United States
Environmental Protection
Agency

EPA 905-K-19-001
April 2019

Application of Quality Assurance and Quality Control Principles to Ecological Restoration Project Monitoring




Product of the Interagency Ecological Restoration Quality Committee under the direction of the U.S. EPA

ACKNOWLEDGMENTS

This guidance was developed collaboratively by the U.S. Environmental Protection Agency (EPA) Great Lakes National Program Office (GLNPO), U.S. Geological Survey (USGS), and U.S. Army Corps of Engineers (USACE). Direction and input was provided by Louis Blume (GLNPO), Karen Rodriguez (GLNPO, retired), Dr. Martin Stapanian (USGS, retired), and Dr. Timothy Lewis (USACE, retired). Material was drafted by the following staff from EPA, USACE, USGS and CSRA LLC, a General Dynamics Information Technology company (CSRA):

EPA: Louis Blume

USACE: Dr. Timothy Lewis and Frank Veraldi

USGS: Dr. Martin Stapanian

CSRA: Dr. Craig Palmer, Lynn Walters, Joan Cuddeback, Brick Fevold, Dr. Robert Brent, Molly Middlebrook Amos, Rob Sutter, Judy Schofield, Doran Stegura, Ken Miller, Justin Telech and Adam Bucher

We wish to acknowledge the contributions of EPA, and in particular, Louis Blume for funding and overseeing development of this guidance, organizing and hosting meetings that led to its development, and sponsoring training sessions held in conjunction with the guidance development process. We also wish to acknowledge the support provided by members of the Interagency Ecological Restoration Quality Committee (IERQC). Members of this committee provided case studies, references, and other information provided in this document. They also provided valuable review and feedback during its development. Individual members of this committee are shown below.

Interagency Ecological Restoration Quality Committee Members	
Organization	**Name**
USACE	Timothy Lewis
	Frank Veraldi
EPA, GLNPO	Louis Blume
	Karen Rodriguez
U.S. Forest Service	James Blehm
USGS	Martin Stapanian
CSRA (providing contract support to EPA GLNPO)	Adam Bucher
	Judy Schofield
	Molly Middlebrook Amos
	Craig Palmer

The U.S. Fish and Wildlife Service (USFWS), National Oceanic and Atmospheric Administration (NOAA), and National Fish and Wildlife Foundation (NFWF) also contributed towards the development of this document through their support to the Great Lakes Restoration Initiative and the IERQC.

Finally, we wish to acknowledge the technical reviews conducted by Anna Lopata, USFWS; Bahram Gharabaghi, University of Guelph; Bill Route, U.S. National Park Service; Bradley Potter, USFWS; Brook Herman, USACE; Dav Parry, Indiana Department of Environmental Management; Don Uzarski, Central Michigan University; Emily Silverman, USFWS; Ingred Karklins, Environmental Survey Consulting; Jason Morrison, U.S. Forest Service; John Shuey, The Nature Conservancy; Lauren Overdyk, Credit Valley Conservation; Lynde Dodd, USACE; Matt Cooper, Northland College; Paul Bollinger, Bollinger Environmental, Inc.; Raymond D'Hollander, Parsons Corporation; Robin Weber, Narragansett Bay National Estuarine Research Reserve; Roy Moser, Credit Valley Conservation; Valerie Brady, University of Minnesota-Duluth; whose thoughtful comments contributed greatly to the quality of the guide.

This document can be cited as: U.S. Environmental Protection Agency. 2019. *Application of Quality Assurance and Quality Control Principles to Ecological Restoration Project Monitoring*. Publication No. EPA/905/K-19/001. Chicago, IL: Great Lakes National Program Office.

DISCLAIMER

This document was prepared with support by CSRA under their Scientific & Technical Support contract with EPA (contract number EP-C-17-024).

These guidelines were collaboratively developed by the U.S. Environmental Protection Agency (EPA), U.S. Geological Survey (USGS), and U.S. Army Corps of Engineers (USACE) to help implement effective quality assurance and quality control (QA/QC) strategies for monitoring ecological restoration projects conducted under the Great Lakes Restoration Initiative (GLRI). This document does not impose legally binding requirements on EPA, states, tribes, or the regulated community; and it may or may not be applicable to a particular situation depending on the circumstances. Federal and state decision makers retain the discretion to adopt approaches on a case-by-case basis that may differ from this guidance where appropriate. Any decisions regarding a particular restoration project should be made based on the applicable statutes and regulations. Therefore, interested parties are free to raise questions and objections about the appropriateness of the application of this guide to a particular situation, and the project sponsor will consider whether the recommendations or interpretations in this guide are appropriate in that situation based on the law and regulations.

Mention of trade names, products, or services does not convey official approval, endorsement, or recommendation by the Interagency Ecological Restoration Quality Committee (IERQC).

CONTACT INFORMATION

For additional information, questions, or comments about this document, please contact Louis Blume (EPA) using the information provided below.

Louis Blume
U.S. EPA
77 West Jackson Boulevard
Chicago, IL 60604-3507
Tel: 312-353-2317
blume.louis@epa.gov

TABLE OF CONTENTS

Acknowledgments ii

Disclaimer iii

Contact Information iv

List of Exhibits viii

Acronyms and Abbreviations xi

Executive Summary xiii

Chapter 1 Introduction 1-1

- 1.1 Background 1-1
- 1.2 Purpose and Intended Audience 1-2
- 1.3 Guidance Scope 1-2
- 1.4 Content and Organization 1-3
- 1.5 Application of QA/QC to Ecological Restoration Projects 1-5
- 1.6 Quality Assurance Roles and Responsibilities 1-6

Chapter 2 Fundamental Principles Concerning Quality Assurance / Quality Control (QA/QC) and Ecological Restoration Project Monitoring 2-1

- 2.1 What is Quality? 2-1
- 2.2 Benefits of and Challenges to Implementing QA/QC in Ecological Restoration Projects 2-4
- 2.3 Graded Approach to the Application of QA/QC 2-7
- 2.4 QA/QC Documentation 2-8
- 2.5 Data Quality Indicators 2-9
- 2.6 Sources of Variability: Sampling and Measurement Error 2-11
- 2.7 Decision Error 2-13
- 2.8 Developing a Monitoring Strategy 2-14
- 2.9 Additional Readings 2-18

Chapter 3 Planning for Data Collection 3-1

- 3.1 Restoration Project Goals 3-2
- 3.2 Restoration Project Objectives 3-4
- 3.3 Sampling Objectives 3-8
- 3.4 Data Quality Indicators and Acceptance Criteria 3-14
- 3.5 Use of Existing Data 3-27
- 3.6 Planning for Data Collection – Checklist 3-33
- 3.7 Additional Readings 3-34

Chapter 4 Preparing for Data Collection 4-1

- 4.1 Standard Operating Procedures 4-1
- 4.2 Training and Certification of Field Personnel 4-12

4.3 Preparing for Field Logistics 4-19
4.4 Arranging Laboratory Analyses 4-27
4.5 Preparing for Data Collection – Checklist 4-31
4.6 Additional Readings 4-32

Chapter 5 Quality Control During Field Activities 5-1
5.1 Field Practices and QA Crews 5-1
5.2 Quality Control Field Checks 5-3
5.3 Use and Reporting of QC Check Results 5-20
5.4 Quality Control during Field Activities – Checklist 5-24
5.5 Additional Readings 5-25

Chapter 6 Data Review 6-1
6.1 Planning Data Review Activities 6-1
6.2 Data Verification and Validation 6-10
6.3 Handling Data Discrepancies and Errors 6-27
6.4 Data Certification 6-32
6.5 Data Review – Checklist 6-34
6.6 Additional Readings 6-36

Chapter 7 Data Assessment, Analysis and Reporting 7-1
7.1 Planning Data Assessment, Analysis and Reporting Activities 7-2
7.2 Assessing Impacts of Data Quality on Use 7-3
7.3 Analyzing and Interpreting Data 7-18
7.4 Use of Analyzed Data within the Continual Planning Process and Adaptive Management Process Cycles 7-24
7.5 Preparing and Reviewing Project Reports 7-27
7.6 Data Assessment, Analysis, and Reporting – Checklist 7-33
7.7 Additional Readings 7-35

Chapter 8 The Relationship between Quality Management and Adaptive Management Strategies 8-1
8.1 Definition 8-2
8.2 Role of Adaptive Management for Ecological Restoration Projects 8-3
8.3 Practicalities of Adaptive Management in Ecological Restoration Projects 8-6
8.4 Incorporating QA/QC Data into Adaptive Management 8-8
8.5 Additional Readings 8-9

References References-1

Appendix A: Data Management Best Practices for Ecological Restoration Projects A-1
A.1 Data Management Planning A-3
A.2 Data Acquisition and Collection A-11
A.3 Data Processing A-17

A.4 Data Summary and Analysis A-23
A.5 Data Preservation A-25
A.6 Data Sharing and Publishing A-30
A.7 Metadata A-33
A.8 Quality Assurance in Data Management A-36
A.9 Backup and Secure Data A-37
A.10 Additional Readings A-38
A.11 Appendix A References A-38

Appendix B: The Assessment of Data Quality Indicators in Ecological Restoration Monitoring B-1
B.1 Measurement Scales and their Statistical Properties of Value B-3
B.2 Data Collection and Measurement Error B-5
B.3 Preparing Data for Quality Assessment B-7
B.4 Precision, Bias, and Accuracy B-8
B.5 Completeness B-17
B.6 Detectability B-18
B.7 Representativeness and Comparability B-19
B.8 Measuring Repeatability B-19
B.9 Additional Readings B-21
B.10 Appendix B References B-22

Appendix C: Quality Assurance Project Plan (QAPP) Template for Ecological Restoration Projects C-1
Section A – Project Management C-2
Section B – Data Generation and Acquisition C-11
Section C – Assessment and Oversight C-16
Section D – Data Validation and Usability C-17
Tables C-19
Exhibits C-22

Appendix D: Quality Assurance Project Plan (QAPP) Review Checklist for Ecological Restoration Projects D-1

Glossary Glossary-1

LIST OF EXHIBITS

Exhibit 1-1. Relationship between the Monitoring Project Lifecycle and the Plan/Do/Check/Act Quality Management Lifecycle 1-4

Exhibit 1-2. Example Organizational Chart for an Ecological Restoration Project....1-7

Exhibit 1-3. Example Quality Assurance Roles and Responsibilities for Restoration Project Team Members .1-8

Exhibit 2-1. Quality Assurance and Quality Control Comparison 2-3

Exhibit 2-2. Total Quality Costs (adapted from Project Management Institute 2014)....2-7

Exhibit 2-3. Common Data Quality Indicators for Environmental Monitoring Data....2-9

Exhibit 2-4. Influence of Precision and Bias on Accuracy 2-10

Exhibit 2-5. Common Sources of Error in Environmental Sampling/Monitoring Programs 2-12

Exhibit 2-6. Types of Decision Error 2-13

Exhibit 2-7. Example Power Curve 2-17

Exhibit 3-1. Process for Establishing Data Quality Criteria 3-1

Exhibit 3-2. Example Restoration Goals and Corresponding SMART Restoration Project Objectives.......3-7

Exhibit 3-3. Example Sampling Objectives for Corresponding Restoration Project Goals and SMART Restoration Project Objectives 3-11

Exhibit 3-4. Types of Data Frequently Collected in a Field Setting for Ecological Restoration Monitoring 3-16

Exhibit 3-5. Example Variables and Acceptance Criteria for Precision, Bias and Accuracy 3-19

Exhibit 3-6. Example Acceptance Criteria for Representativeness, Comparability, Completeness and Detectability for Plant Cover Data 3-23

Exhibit 3-7. Example Stepwise Procedure for the Selection of Acceptance Criteria for an Ecological Restoration Monitoring Effort 3-25

Exhibit 3-8. Examples of Existing Data 3-27

Exhibit 4-1. Recommended SOP Contents....4-4

Exhibit 4-2. Example Applications of Selected SOP Items 4-5

Exhibit 4-3. Example Data Collection SOPs Needed to Support Sampling Objectives....4-9

Exhibit 4-4. Repeatability Statistics for Tree Crown Density and Crown Dieback 4-13

Exhibit 4-5. Training and Certification for Observer-Determined Data Collection....4-18

Exhibit 4-6. Planning and Preparation for Field Logistics....4-19

Exhibit 4-7. Example Selection of Alternate Sample Locations 4-21

Exhibit 4-8. Example Field Operation Supplies and Materials for Vegetation Plots or Avian Surveys 4-23

Exhibit 4-9. Example Completed Data Collection Form 4-24

Exhibit 4-10. Steps for a Successful Laboratory Contract* 4-30

Exhibit 5-1. Good Field Practices during Routine Data Collection 5-2

Exhibit 5-2. Characteristics, Purpose and Timing of Hot Checks 5-4

Exhibit 5-3. Example Hot Check Review Sheet 5-7

Exhibit 5-4. Characteristics, Purpose and Timing of Calibration Checks 5-8

Exhibit 5-5. Comparison of Cold, Blind and Precision Checks 5-11

Exhibit 5-6. Example Cold Check Data Comparison – Tree Species Identification 5-14

Exhibit 5-7. Summary of QC Checks for Observer-Determined Data 5-17

Exhibit 5-8. QC Strategies for Stable Variables 5-19

Exhibit 5-9. Iterative Process Incorporating Results of QC Checks 5-23

Exhibit 6-1. Example Strategies for Conducting Data Review Activities at Each Stage of the Data Collection, Reporting, Transcription and Management Process 6-3

Exhibit 6-2. Example List of Materials and Documents Needed to Review Data 6-7

Exhibit 6-3. Example Variable-Specific Data Verification and Validation Procedures 6-19

Exhibit 6-4. Length-Weight Relationships (inches-pounds) for Large Wild Sport Fish 6-22

Exhibit 6-5. Using Compliance Checks to Verify Ecological Restoration Monitoring Data 6-23

Exhibit 6-6. Using Range Checks to Validate Ecological Restoration Monitoring Data 6-24

Exhibit 6-7. Using Consistency Checks to Validate Ecological Restoration Monitoring Data 6-25

Exhibit 6-8. Identifying, Handling and Documenting Questionable Data 6-28

Exhibit 6-9. Example Data Flagging Codes 6-31

Exhibit 7-1. Examples of Potential Limitations on Data Use as Identified During Data Review Efforts that Affect All DQIs[1] 7-5

Exhibit 7-2. Project Specifications for Example Scenarios 1 and 2[1] 7-9

Exhibit 7-3. Potential Data Analysis Approaches for Ecological Restoration Projects 7-21

Exhibit 7-4. Example Project Lifecycle with Key QA Components 7-25

Exhibit A-1. Data Management Lifecycle A-1

Exhibit A-2. Comparison of Three Computer Environments Commonly Used to Manage Information A-6

Exhibit A-3. Example Process Flow Chart for Quality Review of Primary Data A-9

Exhibit A-4. Data Sources Acquired by a Typical Ecological Restoration Project A-12

Exhibit A-5. Structural Elements that Define a Comprehensive Standard Operating Procedure A-13

Exhibit A-6. Essential Event-Related Data and Their Recommended Data Formats for Recording. A-14

Exhibit A-7. Important Considerations for Identifying Processing Needs for Several Types of Data Commonly Acquired During an Ecological Restoration Project A-18

Exhibit A-8. A Simplified Data Workflow. A-24

Exhibit A-9. File Formats Recommended for Long-Term Storage and Archiving A-28

Exhibit A-10. Example List of Organizations Providing Resources for Publishing and Sharing Environmental Data A-32

Exhibit A-11. Metadata Standards Endorsed by the Federal Geographic Data Commission A-35

Exhibit B-1. Source Partitioning of Total Error in Ecological Restoration Monitoring B-1

Exhibit B-2. Measurement Scales and their Statistical Properties...B-4

Exhibit B-3. Examples of Common Measurements or Observations in each of the Nominal, Ordinal, Interval, and Ratio Scale B-5

Exhibit B-4. Standard Statistical Equations to Assess Bias, Precision and Accuracy...............................B-10

ACRONYMS AND ABBREVIATIONS

AMP	Adaptive Management Plan
ANOVA	Analysis of Variance
ANSI	American National Standard Institute
AOU	American Ornithologists Union
ASQ	American Society for Quality
BACI	Before-After/Control-Impact
CAS	Chemical Abstract Service
CFR	Code of Federal Regulations
COC	Chain of Custody
CSV	Comma-Separated Value
CV	Coefficient of Variation
DBH	Diameter at Breast Height
DMP	Data Management Plan
DMS	Data Management System
DOI	Data Object Identifier (doi)
DQI	Data Quality Indicator
EAB	Emerald Ash Borer
EPA	U.S. Environmental Protection Agency
EU	Experimental Unit
FIA	Forest Inventory and Analysis
FGDC	Federal Geographic Data Committee
FQA	Floristic Quality Assessment
FQI	Floristic Quality Index
GIS	Geographic Information System
GPS	Global Positioning System
GL-DIVER	Great Lakes DIVER Explorer Query Tool
GLHHFTS	Great Lakes Human Health Fish Tissue Study (conducted by U.S. EPA, OW)
GLNPO	Great Lakes National Program Office (part of the U.S. EPA)
GLRI	Great Lakes Restoration Initiative
GRTS	Generalized Random Tessellation Stratified
H_A	Alternative Hypothesis
H_0	Null Hypothesis
IBI	Index of Biotic Integrity
IERQC	Interagency Ecological Restoration Quality Committee
ISO	International Organization for Standardization
ISBER	International Society for Biological and Environmental Repositories
ITIS	Integrated Taxonomic Information System
IUPAC	International Union of Pure and Applied Chemistry
LTER	Long-Term Ecological Research
M-IBI	Index of Macro-Invertebrate Biotic Integrity

MAIS	Macroinvertebrate Aggregated Index for Streams
ME	Mean Error
MOA	Memorandum of Agreement
MOU	Memorandum of Understanding
MSE	Mean Square Error
N	Nitrogen
NARA	National Archives and Records Administration
NOAA	National Oceanic and Atmospheric Administration
NO_3	Nitrate
NFWF	National Fish and Wildlife Foundation
NGO	Non-governmental Organization
OMB	U.S. Office of Management and Budget
OSTP	U.S. Office of Science and Technology Policy
OW	Office of Water (part of U.S. EPA)
P	Phosphorus
PDCA	Plan Do Check Act
PDR	Portable Data Recorder
QA	Quality Assurance
QAOT	Quality Assurance Oversight Team
QAPP	Quality Assurance Project Plan
QC	Quality Control
QMP	Quality Management Plan
QMS	Quality Management System
QS	Quality System
RC	Reed canarygrass
RDBMS	Relational Database Management System
RMSE	Root Mean Square Error
SD	Standard Deviation
SMART	Specific, Measurable, Achievable, Results-Oriented, and Time-Sensitive
SOP	Standard Operating Procedure
TXT	Tab-Delimited Text
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VAR	Variance
WGS	World Geodetic System
XML	Extensible Markup Language

EXECUTIVE SUMMARY

This guidance is intended to assist managers of ecological restoration projects with developing and implementing effective quality assurance (QA) and quality control (QC) strategies. If designed and implemented properly, such QA/QC approaches will improve the quality of data collected, increase the certainty of project decision making, and ultimately save time and money. Although many resources are available to assist project managers with quality systems, this guidance focuses specifically on applying QA/QC concepts to monitoring the effectiveness of ecological restoration projects, with the recognition that these projects have unique QA/QC challenges. Anticipated additional users of this guidance include ecological restoration specialists and stakeholders representing federal and state agencies, non-governmental organizations (NGOs), civic and local groups, and the academic community. Guidance is provided on QA/QC considerations throughout project planning and preparation, as well as data collection, review and evaluation. Details, instructions, resources and examples are provided within each of the individual chapters. Because every restoration project is unique and requirements vary widely among organizations, the information is provided in a guidance document rather than an instruction manual. Notably, we have included information about the philosophy behind the recommended QA/QC strategies so that users can adapt the recommendations to the particular needs of their project and funding organization.

Chapter 1 provides the background, purpose and scope of the guidance document as well as a summary of the content and a description of the project and quality management lifecycles within which the monitoring and QA/QC activities are conducted within an adaptive management framework. Information that can be used by project planners and others to define the QA/QC roles and responsibilities of individuals involved throughout an ecological restoration project is also provided.

Chapter 2 provides a summary of fundamental principles that underlie much of the remaining chapters. It serves as a primer for readers with limited backgrounds in concepts pertaining to quality management or statistics and a quick reference tool or refresher for those with more experience in these fields. As such, it addresses basic quality management and statistical principles and considerations, including the intent and distinction between QA and QC activities, potential implementation challenges, the graded approach to quality management, documentation requirements, use of data quality indicators (DQIs), sources and types of errors to consider, and a high-level summary of aspects to consider when developing a monitoring strategy for ecological restoration projects.

Chapter 3 provides specific guidance and examples for planning data collection activities, including establishing appropriate restoration project goals, objectives and strategies; using project objectives to determine sampling objectives (which in turn informs the sampling design); and defining associated data quality acceptance criteria. Prior to initiating an ecological restoration project, project managers should determine the type, amount and quality of data needed to support decision making, beginning with determining general restoration project goals that convey the project's purpose and direction and describe expected results. **Project goals** are used to determine specific and quantitative **project objectives** that provide the basis for planning restoration strategies, including treatment and maintenance, as well as monitoring that can be used to evaluate project success. Project objectives also provide the basis for developing **sampling objectives**, which are clear, succinct statements defining the ecological attributes monitored, the magnitude of change desired, and the acceptable risks associated with making incorrect decisions. These sampling objectives are used to develop sampling designs, determine sample sizes, and establish necessary data quality criteria. Data quality should be assessed according to DQIs of precision, bias, accuracy, completeness, comparability, detectability and representativeness. For each observation or measurement, project planners should define acceptable limits for DQIs that are needed to meet stated sampling objectives. **Chapter 3** concludes with guidance on QA/QC strategies that project planning teams should address when using **existing data** to support planning or supplement new data that will be generated during the project.

Chapter 4 describes a suite of QA strategies that project planning teams should address before data collection crews are deployed to the field. Recommended strategies include preparing for data collection by identifying, developing or modifying **standard operating procedures (SOPs)** that are tailored to the needs of the project, verifying that personnel are properly trained and certified, and preparing for field logistics. All SOPs, manuals or other written procedures should be (1) designed to meet the project's sampling objectives and data quality criteria and (2) standardized to ensure reproducibility and minimize errors. Project personnel collecting the data should be adequately **trained and certified** and should be able to demonstrate competency. Project managers should allow adequate time for training and certification in the project timeline, confirm that the training is relevant to the field location and conditions, and document all training and certification records. With respect to **field operation plans**, project personnel should address site permits, schedules, equipment, supplies and other field logistics before a sampling season is scheduled to begin. Before work starts, field crews should have information on sampling locations, SOPs, QA plans, and approaches to address unforeseen circumstances.

Chapter 5 recommends and describes several QC checks (hot checks, calibration checks, cold checks, blind checks and precision checks) that can be implemented prior to and during data collection to ensure that (1) field activities conform to requirements specified in project planning documents, and (2) the quality of collected data meets sampling objectives and acceptance criteria for DQIs. These QC checks provide a means for evaluating the ability of routine field crews to collect data as well as the precision, bias, and overall accuracy of these data.

Chapter 6 provides guidance regarding the review of ecological restoration monitoring data. Data generated and collected during these projects form the basis of critical decisions, including whether objectives were achieved and what adaptive management strategies might be needed to improve project outcomes. Data quality review is crucial for supporting such decision making. Throughout this process, data reviewers reconcile the data with pre-established requirements and acceptance criteria to evaluate data quality, identify limitations, and assist managers in understanding any data uncertainties. Data review should involve identifying possible data discrepancies or errors, deciding whether to accept, correct or flag the data, instituting any necessary corrective actions, and documenting resulting decisions and actions.

Chapter 7 discusses various aspects of data assessment, analysis and reporting, including the QA/QC strategies that are important to ensure data are used and analyzed appropriately, analysis techniques are properly selected and executed, and reports accurately reflect project results. Guidance is provided on data assessment, data analysis and project reporting.

Chapter 8 provides a discussion of **adaptive management** and, specifically, the relationship between quality management and adaptive management strategies. Adaptive management provides a framework for structured decision making while ensuring sufficient flexibility for restoration project managers to adjust restoration actions as needed throughout the project lifecycle. The success of adaptive management in ecological restoration projects will be impacted by certain considerations, including the need for accurate monitoring baselines; the limitations of surveillance monitoring; and the application of modeling, data substitution, and recordkeeping strategies. Project planners and managers can help improve the effectiveness of an adaptive management framework by establishing clear objectives and ensuring the implementation of robust QA/QC activities and documentation throughout the quality management or project lifecycle.

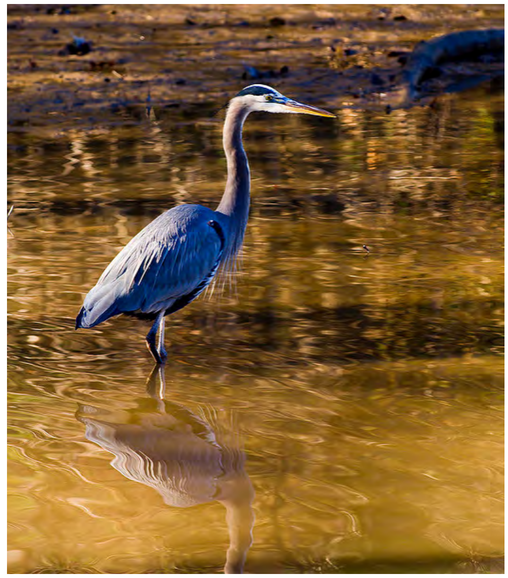
Checklists are provided at the end of **Chapters 3** – **7** to provide a summary of key take-away messages and serve as quick reference tools concerning quality management strategies associated with planning data collection activities (**Chapter 3**), preparing to implement the plans (**Chapter 4**), collection of data and samples in the field (**Chapter 5**), verifying and validating the quality of resulting data (**Chapter 6**), and assessing, analyzing and reporting results of the validated dataset (**Chapter 7**).

A suite of appendices are also included at the end of this guidance. **Appendix A** builds on the guidance and information provided in **Chapters 1** – **8** by providing additional information on important data management considerations that should be addressed during project planning and throughout project implementation. **Appendix B** supplements the information in **Chapter 7** by providing guidance on statistical procedures that are commonly used to evaluate the reliability of data acquired during ecological restoration monitoring. **Appendix C** provides a template that can be used as a tool to document project-specific quality management strategies in a **Quality Assurance Project Plan (QAPP)**. The template is designed to comply with *EPA Requirements for Quality Assurance Project Plans* (EPA 2001), but is tailored to better fit the needs of projects involving ecological restoration and/or the control of invasive species. The template reflects recommendations provided throughout this guidance document, and it includes cross-references to specific locations in this guidance where each topic is addressed. Finally, **Appendix D** provides a checklist that can be used to assist with the review of QAPPs.

In summary, the QA/QC principles described in this document include (1) defining and documenting ecological restoration project goals, project objectives, and sampling objectives, (2) designing and implementing a monitoring program that will provide data needed to determine if the objectives have been met, (3) identifying and implementing QA practices and QC checks to ensure the plan is properly followed and data quality targets are achieved, and (4) reviewing the quality of data to confirm it is sufficient for the intended data use. Application of these principles are valuable only if the collected data are used in a way that allows restoration ecologists to confirm project success and draw on lessons learned, determine if adjustments to the restoration or monitoring designs are needed, and/or implement adjustments to improve overall project or program outcomes.

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND



(**EPA 2013**)

Government agencies and other organizations direct substantial resources towards addressing serious threats to ecosystems such as habitat loss, invasive species, toxic pollutants, shifts in wildlife populations and alterations to natural water levels and flow regimes. Since being launched in 2010, for example, more than 2,000 projects have been funded in support of the Great Lakes Restoration Initiative (GLRI) Habitat and Wildlife Protection and Restoration and Invasive Species focus areas.[1] Other projects are conducted each year by a diverse range of federal, state, and local agencies and non-governmental organizations (NGOs) interested in protecting, monitoring, or improving ecosystems outside the GLRI purview.

Considerable resources are needed to plan and implement these ecological restoration projects and, after restoration activities have been implemented, additional resources are needed to assess their effectiveness in achieving the desired outcomes (Thayer et al. 2003). The success of each project depends on a number of factors, not the least of which is the quality of the ecological data that are used to (1) define pre-restoration conditions, (2) ensure planned activities are implemented correctly, and (3) assess post-restoration success. Although practitioners and decision makers rely heavily on the quality of these data,

- ecological data collection activities are inherently difficult to control, and
- little guidance exists on strategies for mitigating this challenge in the field or determining if the resulting data are reliable enough to support sound decisions. In the absence of such guidance, many projects are compromised by poor or incomplete data.

In June 2012, the U.S. Environmental Protection Agency (EPA) convened an Interagency Ecological Restoration Quality Committee (IERQC) to address this challenge. The IERQC provides a collaborative environment to share quality-related concepts, practices, guidance, methods and tools to ultimately improve ecological restoration projects. Although the committee's focus is on projects that are funded by the GLRI, tools developed by the committee are also applicable to ecological restoration projects undertaken for other purposes.

---

[1] The number of projects supporting these focus areas can be obtained from information on EPA's website dedicated to the Great Lakes Restoration Initiative (https://www.glri.us/projects).

1.2 PURPOSE AND INTENDED AUDIENCE

This guidance is intended to encourage and facilitate the adoption of effective quality assurance (QA) and quality control (QC) strategies in support of ecological restoration projects. Anticipated users include ecological restoration specialists and stakeholders representing federal, state and tribal agencies, NGOs, civic and local groups, and the academic community. Although it is assumed that users will have some background in and knowledge of basic ecological restoration practices and QA/QC concepts, **Chapter 2** includes a brief review of QA/QC principles that are discussed throughout the remainder of the document.

The practices, procedures, information, and concepts outlined in this guidance can provide the following benefits to practitioners and stakeholders:

- Save time and resources by enhancing the consistency of documentation and procedures in current and future projects.
- Improve data quality for ecological measurements and observations, aid in evaluating project success, and incorporate long-term effectiveness monitoring as feedback to adaptive management.
- Encourage a common approach to QA/QC across multiple entities involved in ecological restoration projects to improve data comparability over time and support comparison of various restoration strategies.
- Serve as a consolidated collection of the best QA/QC practices for ecological restoration projects across multiple agencies.

Section 2.2 provides a more in-depth discussion of the potential benefits that can be realized from implementation of effective quality management strategies in monitoring programs. It also discusses the importance of considering the total cost of quality over the life of a project, a concept that involves considering the total cost of (1) QA/QC investments made before and during the project to prevent or mitigate problems and (2) resources incurred during and after the project to address problems and failures. Much of the guidance in **Chapters 3 – 7** is focused on the first half of the equation (QA/QC investments to prevent problems) in order to avoid problems and failures that may prove to be far more costly in the long run (e.g., costs associated with re-work, scrapping data or an entire project, further degradation of ecological resources or wasted financial resources that can occur when incorrect conclusions are made based on flawed data). Project planning teams should carefully consider the information offered in this guidance and select the QA/QC strategies that best meet their project needs and resources (see **Section 2.3** Graded Approach to the Application of QA/QC).

1.3 GUIDANCE SCOPE

This document presents QA/QC best practices compiled from the IERQC agencies; it reflects the combined knowledge and experience of IERQC members and provides guidance on how to:

- apply basic QA/QC concepts,

- establish quality goals and objectives,
- implement QA/QC practices to achieve quality objectives,
- monitor the quality of data collection activities,
- verify and validate the quality of data collected,
- incorporate quality management principles into data analysis and reporting activities,
- apply adaptive management approaches, and
- implement best practices for information management.

The guidance includes decision trees, examples to illustrate implementation of the concepts, and a template designed to assist project planning teams in documenting the QA/QC strategies they intend to use for ensuring the reliability of ecological data generated during their projects. The guidance also includes a companion checklist to assist managers and others responsible for reviewing and approving such planning documents, as well as key references and links to federal agency guidance documents, checklists, programs and efforts.

Use of Terminology

Because it is intended to serve as an interagency tool, this guidance avoids relying on terminology used by a single agency or organization. All QA-related terms are defined to ensure a common understanding among users.

We emphasize that the guidance addresses only those aspects of ecological restoration projects that involve the collection, analysis and use of monitoring data. It does not address other phases of ecological restoration processes, such as site assessment, engineering and construction, surveillance monitoring, and implementation of restoration activities. This guidance serves as a tool to assist users in determining the QA/QC strategies that should be employed to ensure that the data collected to evaluate the efficacy of the restoration activities are of sufficient quality to support project goals and decisions. The primary focus is on QA/QC strategies for data gathered in the field and, in particular, observer-determined (i.e., visual or sound) data that are obtained using "best professional judgment" (e.g., Mack 2001). In some cases, related topics are introduced but not covered in-depth. For example, ecological restoration projects rely on effective sample tracking procedures and often involve the collection of samples that are subsequently shipped to a laboratory for chemical (or other) analysis. Because these practices are not unique to ecological restoration projects, and because QA/QC strategies for such practices are widely addressed elsewhere (e.g., EPA "Quality" website, U.S. Geological Survey (USGS) "National Water-Quality Assessment Biological Protocols" website, EPA "Good Laboratory Practices" website, international standard on general requirements for the competence of testing and calibration laboratories (ISO 2017)), they are covered in this guidance only for context and illustrative purposes.

1.4 CONTENT AND ORGANIZATION

Ecological restoration projects require the collection of data before, during, and after restoration activities. The project lifecycle for such data collection is no different than the lifecycle for other project activities: you should **plan** your efforts, **prepare** for data collection, **collect** the data, **review** the data to verify that it meets your needs, **evaluate** the results, and make any adjustments in monitoring or project design through an adaptive management framework. As shown in **Exhibit 1-1**, each phase of this lifecycle aligns with the **Plan-Do-Check-Act (PDCA) cycle** that forms the basis of many Total Quality Management systems. Sometimes referred to as "plan–do–check–adjust," PDCA is an iterative four-step model for defining new or improved processes and implementing continuous improvement of processes and products (ASQ 2018). It is also known by other names such as the plan–do–study–act (PDSA) cycle, the Shewhart cycle, or the Deming cycle, and in each case, the word "cycle" is sometimes replaced with the word "circle." Regardless of the specific nomenclature, ecological restoration projects have ample opportunities to incorporate the PDCA model into the broader project lifecycle.

Exhibit 1-1. Relationship between the Monitoring Project Lifecycle and the Plan/Do/Check/Act Quality Management Lifecycle

Chapter 2 provides a brief overview of quality-related principles that underlie the remaining chapters of this guidance. **Chapters 3** – **7** present key QA/QC strategies to be considered during each of the Plan, Prepare, Collect, Review and Evaluate phases of an ecological restoration project. **Chapter 8** discusses how the QA/QC strategies described in the preceding chapters support implementation of effective adaptive management strategies for ecological restoration projects. Four appendices are provided at the end of the guidance. **Appendix A** discusses best practices for managing monitoring data, **Appendix B** provides guidance on statistical procedures that are commonly used to evaluate the quality of monitoring data, **Appendix C** provides a template for documenting project-specific QA/QC plans, and **Appendix D** provides a checklist designed to facilitate the review of such plans.

All project activities should be carefully planned and documented before data collection begins, and then implemented throughout the project lifecycle. In fact, some organizations will not allow data gathering activities to begin until the QA/QC strategies for **all** phases of the project lifecycle have been documented and approved in a signed quality planning document.

Note that the project and PDCA management lifecycles illustrated in **Exhibit 1-1** above are not intended to represent an endless cycle of the same project. The dotted arrow leading into the "Plan" component of the project lifecycle is intended to illustrate how knowledge gained from a project can be used to support the process of planning for improvements within the project or for a similar project. This concept of integrating improvements into a project or similar projects is consistent with the use of adaptive monitoring and adaptive management strategies as described in **Chapter 8**.

1.5 APPLICATION OF QA/QC TO ECOLOGICAL RESTORATION PROJECTS

The notion of applying quality management principles to environmental programs is not new, and tools for doing so have long been available for many types of environmental applications— most notably those involving the collection and analysis of samples for chemical parameters or the use of environmental technology. Many of these concepts, however, have not been widely applied or adopted for ecological restoration monitoring projects. Because much of the data gathered involve field observations (e.g., visual and/or auditory identifications of species, visual estimates of canopy cover), some ecological restoration practitioners assume that such field observations are not subject to evaluations of data quality (Stapanian et al. 2016). To the contrary, all data, including field observations, have some level of associated uncertainty that can and should be evaluated. (The degree of allowable uncertainty will be determined by the intended use of these data.) Field observations can and should be standardized in how they are collected, furthering comparability between crews, sites and years.

In developing this guidance, we have built upon QA/QC strategies that are widely used by a variety of organizations that collect samples for chemical analysis, adapting them where needed to support the unique challenges associated with field data gathered during ecological restoration projects. Towards that goal, this guidance:

- presents well-established principles to aid users in explicitly defining restoration goals and objectives for each project;
- recommends the use of a systematic planning process to develop sampling objectives that will support the project objectives and be used to determine a sampling design for the monitoring program and to identify quality requirements for data that will be collected;
- recommends the use of data quality acceptance criteria that specify the level of quality needed for each measurement or observation, and data quality indicators (e.g., precision, bias, accuracy, representativeness, comparability, completeness, detectability) that can be used to determine if this level of quality has been achieved;
- advocates the use of standard operating procedures (SOPs), training and certification, audits and inspections, data verification, data validation and data management procedures as effective strategies for assuring and controlling the quality of ecological restoration project data;
- advocates the integration of all components of the project lifecycle, including QA/QC applications into an overarching decision-support environment, most commonly referred to as Adaptive Management; and
- recognizes the importance of incorporating climate resiliency strategies in project quality design and decision making (EPA 2014a).

1.6 QUALITY ASSURANCE ROLES AND RESPONSIBILITIES

This section provides information that can be used by project planners and others to define the QA/QC roles and responsibilities of individuals involved in an ecological restoration project. Everyone involved in the project bears some responsibility for ensuring and controlling quality at various stages of restoration, ranging from those who define the requirements to those who are responsible for implementing those requirements.

All restoration projects require a clear delineation of the project's organization and how responsibilities are assigned within that organization. This includes identifying:

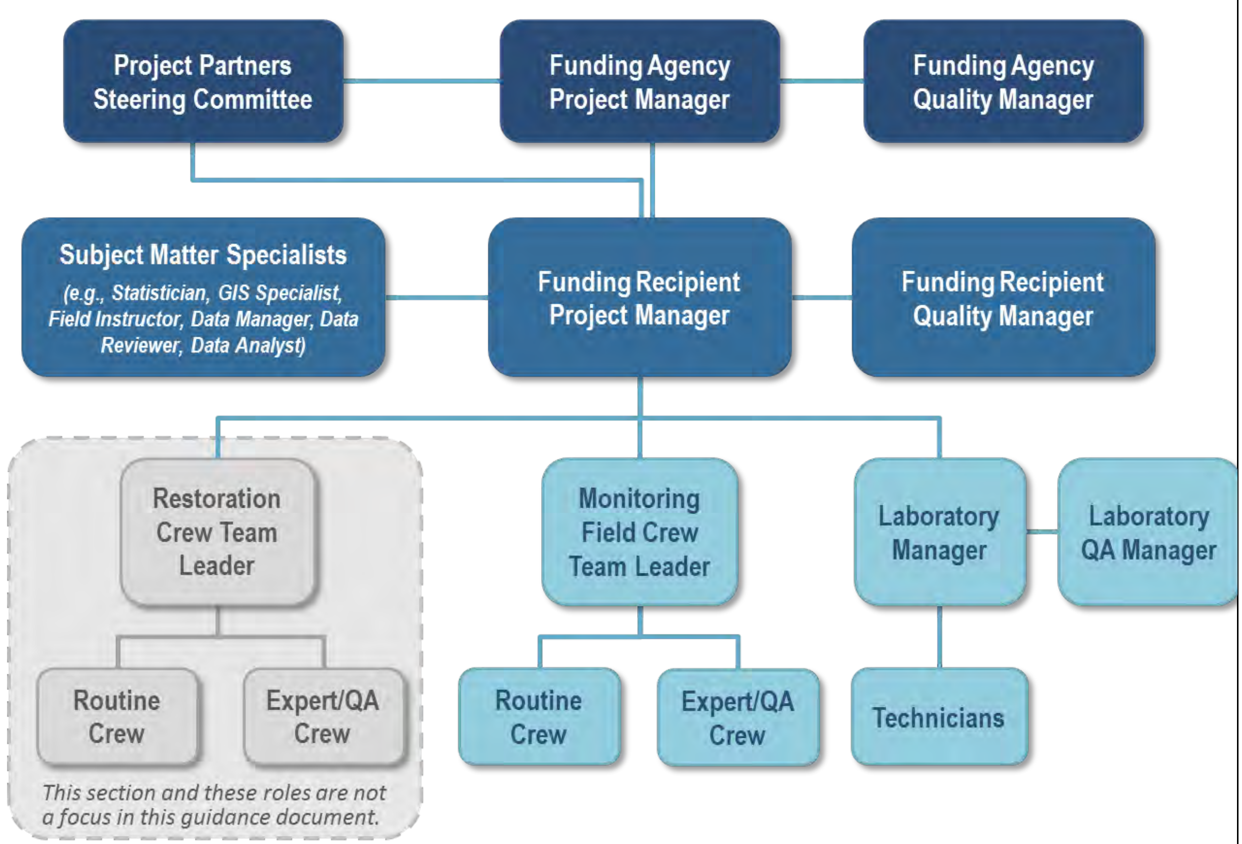
- each organization involved in the project;
- functional groups within the project;
- roles within each functional group;
- key staff involved within each functional group;
- project responsibilities associated with each role; and
- designated authority(ies) for making modifications and adapting when necessary to address unforeseen problems along with responsibilities for:
  - communicating those changes to the project team, and
  - updating project planning documents, forms, data systems, and other materials to reflect the modifications.

All individuals supporting an ecological restoration project must fully understand their roles and responsibilities and to whom they should be reporting. They should also be familiar with who is responsible for making specific decisions related to financial matters, field activities or other issues. Defining roles and responsibilities is a primary component of the project planning process and helps project planners build a cohesive team with clear and effective communication methods. Since every project is unique, the specific roles and responsibilities will be influenced by several factors, including the project size and scope, the organizations involved, and the skills of staff members. For example, some projects implemented by smaller organizations with limited resources may require an individual to assume more than one role, while others may have additional roles that are not represented in this section (or are represented in this section but have a different description).

Note: While there is no doubt that primary responsibilities have to be defined, defining roles too narrowly can have a negative effect on quality by isolating specific individuals or groups and discouraging members from looking at quality concerns outside of their own group. Hierarchies often deemphasize the idea that quality-related responsibilities are shared responsibilities. In some cases, the less rigid the organizational structure, the better an organization is able to work collaboratively. This benefits data quality through all stages of the project lifecycle when a focus on quality strategies is an organizational goal.

The organizational chart shown in **Exhibit 1-2** outlines common roles and **Exhibit 1-3** provides examples of QA/QC responsibilities for the project team members who fulfill those roles. The roles and responsibilities depicted in these exhibits are for ***illustrative purposes only*** and are intended to serve as examples to provide context for subsequent discussions throughout this guidance document. Note that the QA/QC staff shown in **Exhibit 1-2** are independent of the staff responsible for data collection. Because QA and QC are critical tools for preventing and detecting fraud, QA staff may interact with – but should ideally operate independently of – the staff involved in data collection.

Exhibit 1-2. Example Organizational Chart for an Ecological Restoration Project



NOTE: *This figure serves as an example of organizational structure for an ecological restoration project for illustrative purposes only. The generalized structure is used as a guideline for discussions throughout this document. Note that references to the "planning team" typically refer to roles within the top two rows of this chart with contributions from other roles across the entire organization.*

Exhibit 1-3. Example Quality Assurance Roles and Responsibilities for Restoration Project Team Members	
Role	**Example Responsibilities**
Funding Recipient Project Manager	• Coordinates development of project plans and associated restoration goals, project objectives, sampling objectives and monitoring strategy • Reviews, approves and submits QA/QC documentation and updates to the funding agency for review and approval • Distributes approved QA/QC documentation and updates team members • Ensures project team members receive training on QA/QC requirements • Selects and approves changes to SOPs • Assists with QA review of existing data • Addresses deviations from planned activities and approves corrective actions • Ensures QA/QC requirements are met for all project data • Coordinates development of data management plan (DMP) and ensures the plan is implemented • Reviews and certifies project database for quality and completeness • Identifies opportunities for quality improvement • Completes and delivers project reports, along with certified data and metadata • Establishes technical and QA requirements for laboratory analysis and procures laboratory services
Funding Recipient Quality Assurance (QA) Manager	• Provides technical input for development of QA/QC documentation • Reviews and approves QA/QC documentation and oversees any revisions • Provides independent oversight for project activities affecting data quality • Verifies that field and laboratory QA/QC procedures are implemented as planned • Assists with field and laboratory assessments (e.g., QC checks/audits) • Reviews QC check results against data quality requirements • Ensures that corrective actions are implemented as needed to meet QA requirements • Ensures that QA/QC problems, disputes or deficiencies are resolved • Assists with QA review of project data • Ensures that data and records are in compliance with the QA/QC documentation

Exhibit 1-3. Example Quality Assurance Roles and Responsibilities for Restoration Project Team Members

Role		Example Responsibilities
Subject Matter Specialist(s) *(Ecologists, Engineers, Taxonomists, Geographic Information System (GIS) Specialists, Statisticians, etc.)*		• Consults on design of restoration plan and management prescriptions • Consults on sampling design and statistical analysis • Consults on effective monitoring strategies • Creates and interprets land cover information needed for project plan • Assists with training staff in data collection, management and review • Assists with review of project data • Assists with data analysis and preparation of project reports
Data Manager		• Assists with developing and/or selecting data management system (DMS) • Assists with downloading, reviewing and posting data, metadata and reports • Maintains DMS • Develops electronic data collection forms with built-in QC checks
Restoration Crew	Restoration Crew Team Leader	• Ensures restoration efforts are performed according to restoration plan specifications • Provides updates and reports to project manager regarding progress
Restoration Crew	Restoration Crew	• Implements planned restoration activities according to specifications • Implements corrective actions
Restoration Crew	Construction Oversight Specialist(s)	• Provides oversight and observation of implementation of restoration prescriptions or actions • Provides feedback regarding quality issues related to construction activities
Monitoring Field Crew	Monitoring Crew Team Leader	• Trains field staff to collect data with assistance of subject matter specialists and project manager • Acquires, maintains and calibrates field equipment • Ensures that monitoring protocols are followed by all monitoring team members • Reviews the results of collected data to ensure completeness and legibility • Maintains contact with project manager regarding issues or concerns affecting data quality • Ensures data entry and transfer to the project database is completed correctly

Exhibit 1-3. Example Quality Assurance Roles and Responsibilities for Restoration Project Team Members		
Role		**Example Responsibilities**
Monitoring Field Crew	Monitoring Routine Crew Leader	• Serves as leader for crews of two members or more • Supports and assists routine crew with data collection; provides decision authority • Reviews completed data forms and collected samples prior to submittal
	Monitoring Routine Crew	• Implements SOPs to collect monitoring data • Collects and handles samples and specimens • Downloads electronic data from data loggers, digital cameras and other electronic equipment
	Monitoring Expert/QA Crew	• Conducts QC checks • Reports potential impacts affecting data quality • Ensures that QA/QC problems, disputes, or deficiencies are resolved • Evaluates whether reported data meet quality objectives
Laboratory	Analytical Lab Manager	• Ensures laboratory QA/QC procedures are followed • Reviews laboratory data • Approves laboratory data and associated reports prior to submission
	Analytical Lab QA Manager	• Provides independent oversight for laboratory activities affecting data quality • Verifies that QA/QC procedures are implemented as planned • Assists with laboratory assessments (e.g., QA reviews/audits) • Ensures corrective actions are implemented as necessary to maintain QA standards • Ensures that QA/QC problems, disputes, or deficiencies are resolved • Evaluates whether reported data meet quality objectives • Assists with QA review of laboratory data to ensure the laboratory quality specifications have been met
	Analytical Lab Technician(s)	• Analyzes samples • Conducts laboratory QA/QC procedures • Ensures data sheets are complete and legible

CHAPTER 2 FUNDAMENTAL PRINCIPLES CONCERNING QUALITY ASSURANCE / QUALITY CONTROL (QA/QC) AND ECOLOGICAL RESTORATION PROJECT MONITORING

This chapter provides a brief review of fundamental principles that underlie much of the guidance and terminology in the remainder of this document. As such, this chapter serves as a quick reference tool and a:

- primer for readers with limited backgrounds in concepts pertaining to quality management (which includes quality assurance and control) or statistics, and a
- refresher for those who have more experience in either field.

Sections 2.1 – **2.5** provide an overview about quality management terminology and concepts, which are essential for practitioners who wish to apply the concepts in this guidance. **Sections 2.6** – **2.8** describe sources of variability (also known as error) that can impact data quality, types of decision error that can result from poorly designed monitoring programs or data of insufficient quality, and statistical principles related to the development of effective monitoring strategies.

2.1 WHAT IS QUALITY?

Numerous definitions are currently in use to describe the term "quality," and these definitions vary widely in length, complexity and clarity. For the purposes of this document, we have avoided relying on terminology that is used by a single agency or organization. Instead, definitions for QA-related terms used in this guidance are provided in a **glossary** to ensure a common understanding. For the general term "quality" we adopted the International Organization for Standardization (ISO) definition that "***quality is the degree to which a set of inherent (existing) characteristics fulfills requirements***" (ISO 2015a).

2.1.1 The Data Quality Act

Data Quality Act requirements apply to all data and other information generated during federally-funded projects, including ecological restoration.

The Data Quality Act, also referred to as the Information Quality Act, was passed by the U.S. Congress as a two-sentence rider to a 2001 appropriations bill (Section 515 of the Consolidated Appropriations Act of 2001 (Pub.L. 106–554)). The Act instructs the U.S. Office of Management and Budget (OMB) to issue guidelines that:

- "Provide policy and procedural guidance to federal agencies for ensuring and maximizing the quality, objectivity, utility, and integrity of information including statistical information disseminated by Federal agencies" and
- "Establish administrative mechanisms allowing affected persons to seek and obtain correction of information maintained and disseminated by the agency that does not comply with the guidelines."

In response, the OMB issued its *Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity of Information Disseminated by Federal Agencies*.[2] In doing so, it defined quality based on the following three characteristics:

- **Objectivity:** (1) The information itself must be accurate, reliable and unbiased, and (2) the manner in which the information is presented must be accurate, clear, complete and unbiased.
- **Utility:** The information must be useful for the intended users.
- **Integrity:** The information may not be compromised through corruption or falsification, either by accident, or by unauthorized access or revision.

Note that the OMB definition of quality is consistent with and can be viewed as an elaboration of the ISO definition cited above, in that any data that meet OMB's requirements for objectivity, utility and integrity can be said to fulfill requirements and thus be of acceptable quality.

It also is important to note that U.S. federal agencies are required to adopt standards for data quality that are consistent with the OMB definition and to develop processes for reviewing the quality of all information before it is disseminated. These agencies also are required to establish administrative mechanisms that (1) enable the public to seek and, where appropriate, obtain corrections to disseminated information that does not comply with the OMB guidelines; and (2) provide an appeals process for those who disagree with an agency's verdict on a data-quality challenge.

In other words, *all data and other information generated during federally-funded ecological restoration projects are subject to the requirements of the Data Quality Act*. Although the specific processes for complying with the Act vary among agencies, all agencies are responsible for disseminating data that meet OMB quality requirements concerning objectivity, utility and integrity. This guidance is designed to provide tools that will assist in fulfilling these responsibilities.

2.1.2 What is the Difference between Quality Assurance and Quality Control?

The terms **quality assurance** (QA) and **quality control** (QC) are often used interchangeably. Although related, they address different aspects of quality management. Exact definitions vary among organizations, but most recognize that QA is focused on preventing problems, while QC is focused on identifying defects and confirming that project requirements are met. As a result, many people view QA as process-oriented and QC as product-oriented.

For the purpose of this guidance, we have adopted the following definitions for these concepts, drawn from both ISO and the American Society for Quality/American National Standard Institute (ASQ 2014) standard that addresses quality systems for environmental data (ASQ 2014; ISO 2015a):

[2] The final guidelines and subsequent corrections were printed in the Federal Register on January 3, 2002 (67 FR 369-378) and on February 5, 2002 (67 FR 5365), respectively.

Quality Assurance: Part of quality management focused on providing confidence that quality requirements will be fulfilled (ISO 2015a).

Quality Control: Part of quality management focused on fulfilling quality requirements (ISO 2015a). Quality control includes technical activities that measure the attributes and performance of a process, item, or service against defined standards to verify that they meet the stated requirements established by the customer (ASQ 2014).

Exhibit 2-1 provides additional information to help understand these concepts as applied to ecological restoration monitoring activities.

Exhibit 2-1. Quality Assurance and Quality Control Comparison

	Quality Assurance	Quality Control
Features	• Process oriented • Focuses on preventing deviations from project objectives and requirements (proactive) • Involves identifying measurable quality requirements needed to support project objectives and specifying the measurements used to verify that these requirements have been met • Involves developing plans, processes and procedures before implementing data collection and management activities • Involves assessing processes to detect deviations and areas for improvement, and identifying corrective actions to address findings	• Product oriented • Focuses on identifying deviations from project objectives and requirements (reactive) • Involves performing QC checks during monitoring and data management activities, and assessing results to determine if plans, processes and results meet requirements • Involves collecting data using modified or corrected processes to verify that changes are yielding the desired results

Exhibit 2-1. Quality Assurance and Quality Control Comparison		
	Quality Assurance	**Quality Control**
Examples	• Documenting measurable objectives, data quality indicators and acceptance criteria, and specific strategies in QA plans that will be used to ensure collected data will support project objectives • Documenting site- or project-specific procedures (e.g., Standard Operating Procedures (SOPs), methods, guidance, maps) that describe what data to collect, and where, how and when to collect the data. Includes templates, forms, checklists and other tools for documenting and managing results • Identifying training, certifications, equipment, etc. that are needed to ensure the data collected will support project objectives • Documenting procedures for data reduction, data analysis, and data management to control errors and ensure data integrity during transcription, transfer and storage • Identifying recommendations for improving process controls and criteria based on results of process audits and analysis of data quality	• Collecting QC data for each data quality indicator as a tool to determine if specified criteria have been met • Reviewing field and laboratory records to verify that data reflect the required locations, procedures, calculations and frequencies • Verifying that staff have the required experience and training, as well as access to necessary information and equipment before allowing them to collect data • Examining the final dataset to verify it accurately reflects project results • Using QC data to determine overall data quality and evaluate outliers

2.1.3 Role of QA/QC in a Quality Management System

Collectively, an organization's policies, processes and procedures for implementing quality management activities are known as a **Quality Management System (QMS)** or Quality System (QS). As described by the American Society for Quality, a QMS is the "blueprint" or framework by which an organization applies sufficient QA/QC practices to produce results that meet or exceed the organization's objectives and expectations (ASQ 2014). The QMS encompasses both management and technical activities pertaining to planning, implementing and assessing environmental programs within the organization's mission and scope.

2.2 BENEFITS OF AND CHALLENGES TO IMPLEMENTING QA/QC IN ECOLOGICAL RESTORATION PROJECTS

As discussed in **Section 2.1.1**, the Data Quality Act and subsequent OMB guidelines require U.S. federal agencies to adopt standards for data quality and develop processes for reviewing the quality of all information before it is disseminated. Several U.S. federal regulations also require contractors and grantees to develop and implement quality documentation when receiving federal funds (e.g., 2 Code of Federal Regulations (CFR) 1500.11, 40 CFR 35, 48 CFR 46). Beyond these legislative and regulatory requirements, a more obvious need exists for developing and applying QA/QC strategies to ecological restoration projects — ***taxpayers and project sponsors want to know that their money is being put to good use, and QA/QC strategies are designed to ensure that happens***.

Prescribed burn in Dow Field, Nichols Arboretum, Ann Arbor, Michigan. This burn was a training exercise for students in an ecological restoration course at the University of Michigan. Photo Credit: Bob Grese

To be effective, quality must be *planned* into a project. All project planning activities involve a trade-off between the project's scope (design), cost and schedule. These trade-offs are often referred to as the "triple constraints of project management" or the "project management triangle," in which each side of the triangle represents a constraint. A change to one side will affect the other two, and quality is impacted by decisions about all three. In recent years, this project management triangle has been updated to include six constraints that include quality, risk and resources, in addition to the original three (cost, scope and schedule). In this new model, quality is not simply impacted by changes to other project constraints; it is considered a constraint itself (Project Management Institute 2014). Regardless of which model one prefers, it is clear that quality plays a significant role in project planning and is subject to competing pressures.

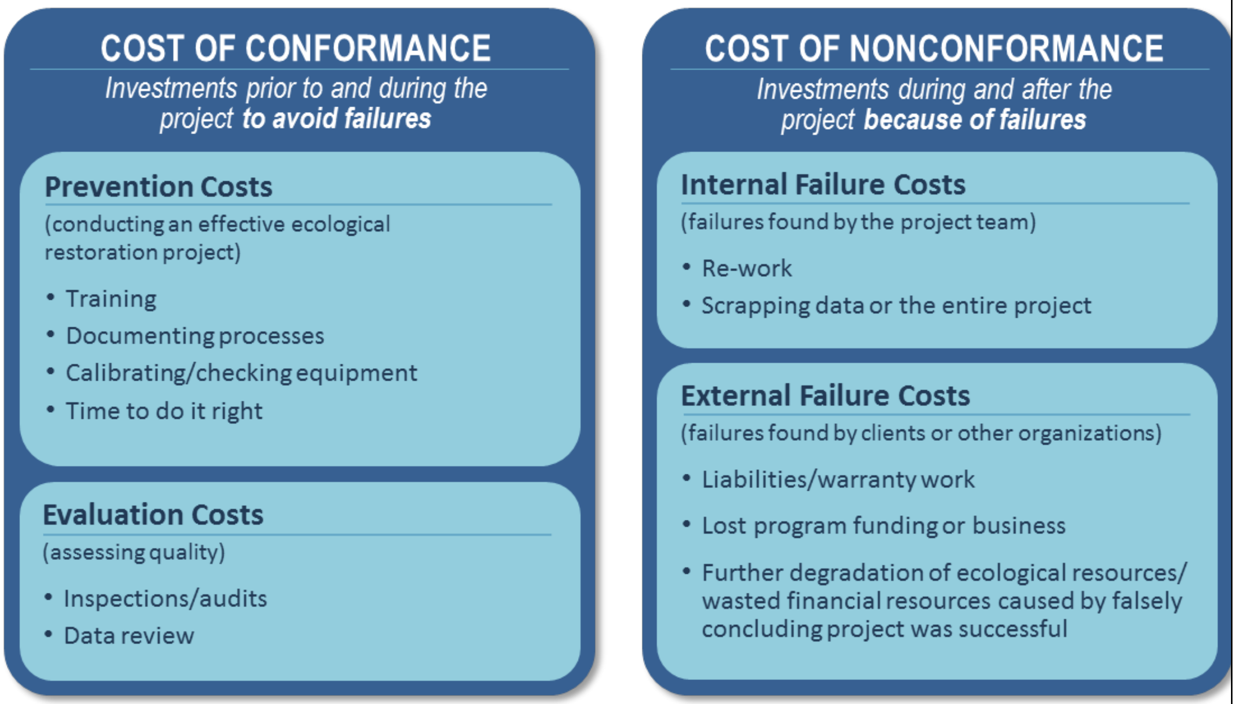
Project managers, including those responsible for ecological restoration projects, are often under intense pressure to deliver results within a specified timeframe and/or budget. When the project scope cannot be accomplished on time and within budget, managers may be tempted to reduce costs by eliminating or reducing the level of QA/QC. Such a strategy is ill-advised, in that doing so may solve short-term needs, but create longer term problems. The following quote from the well-known architect Frank Lloyd Wright underscores this point: "*You can use an eraser on the drafting table or a sledge hammer on the construction site*." This concept is known as the **cost of quality**, which recognizes the cost of NOT creating a quality product or service. Note that the term "cost of quality" is often misunderstood. It is not the price of creating a quality product; it is a methodology for quantifying the total cost of QA/QC activities and deficiencies in the quality of a product or service (ASQ 2017). If work has to be re-done, the cost of quality increases.

Examples of this in ecological restoration projects include:

- repeating ecological measurements or observations made by an improperly trained field crew;
- re-entering project data into a compromised database;
- falsely concluding that a project was successful when it was not, leading to further ecological degradation of and wasted financial resources; or falsely believing that a project was unsuccessful when it was actually successful, resulting in continued expenditures in project design and failure to implement successful designs at other sites (Stapanian et al. 2016; Stankey et al. 2005);
- assuming project success within a shorter time period of project funding, instead of providing for long-term maintenance and ensuring the preservation of ecological benefits; and
- failing to incorporate restoration design elements that take into account the effects of climate change on the ecological system being restored.

To avoid these problems, planning teams must carefully consider the total quality-related costs incurred over the life of the project. These include costs for investing in measures to prevent nonconformance with project requirements, costs associated with evaluating the quality of project activities and results, and costs associated with failing to meet project requirements. Examples of such costs are shown in **Exhibit 2-2** below.

Exhibit 2-2. Total Quality Costs (adapted from Project Management Institute 2014)



2.3 GRADED APPROACH TO THE APPLICATION OF QA/QC

In a well-designed QA/QC program, the cost of conforming to requirements is lower than the cost of non-conformance. Accordingly, this guidance advocates a **graded approach** to the application of QA/QC, which is consistent with the quality management philosophy adopted by ASQ, ANSI, EPA and others. As stated in the ASQ/ANSI E4 standard (ASQ 2014), the graded approach *"is the process of applying management controls to an activity according to the intended use of the results and the degree of confidence needed in the quality of the results."* In other words, the level of QA/QC performed should be commensurate with such factors as the project goals and objectives, project importance, risks associated with decision errors, resources and schedules.

Although many governmental agencies encourage the use of a graded approach, there are no national implementation guidelines. This is largely because its application varies according to the unique needs of each organization. For example, some organizations are focused on regulatory development, others on compliance monitoring or enforcement, and others on non-regulatory monitoring activities. Organizations also differ in the maturity of their quality system and in the resources that are available to support development and implementation of an objective approach. In addition, the diversity of project types to which a graded approach may be applied is so extensive that it essentially precludes development of one-size fits all criteria (Blume et al. 2013). This is true even within large organizations. Users of this guidance should consult their funding organizations to determine if the organization has an established protocol for applying the graded approach; if no such protocol exists, users should work with the funding organization to develop an approach that is appropriate for their project. In doing so, organizations should bear in mind that, although a lack of QC data does not necessarily mean that project data will be of poor quality, it does limit the ability to document or defend the reliability of the data when used to support project decisions.

2.4 QA/QC DOCUMENTATION

Documentation of organizational and project-specific policies, requirements and procedures is a key requirement of any quality system. Exact approaches to addressing these requirements vary among organizations, and can take the form of various names and formats including, for example, Quality Manuals, Quality Plans, Quality Management Plans, Quality Assurance Project Plans, Quality Assurance Program Plans and Quality Control Plans. Some organizations incorporate their quality management strategies in broader documents such as study plans, research and surveillance plans, project plans and data management plans.

For simplicity, this guidance document generally relies on the approach advocated by the ASQ and EPA, which requires a:

- **Quality Management Plan (QMP)** to document an organization's quality management policies and how the organization will plan, implement, and assess its quality system, and a
- **Quality Assurance Project Plan (QAPP)** to document the specific QA/QC strategies that will be used for each unique project or service (ASQ 2014; EPA 2000a, 2000b, 2008).

The QAPP (or equivalent document), when combined with other supporting documents discussed throughout this guidance (e.g., SOPs, data management plans), represents a project's quality documentation. These project-level documents are then applied under the umbrella of an organization's QMP.

Because organizations differ in their approach to documenting quality management activities, users are encouraged to consult with their sponsoring organizations to determine if specific documentation requirements must be met. As noted in Chapter 1, some organizations will not allow data gathering activities to begin until QA/QC strategies for all phases of the project lifecycle have been documented and approved in signed quality planning documentation. For example, the U.S. Army Corps of Engineers (USACE) relies on use of a Quality Control Plan that documents the roles and responsibilities of individuals involved in each project, projected schedules, and quality management practices. USACE requires all branch chiefs within the applicable USACE District to sign the Quality Control Plan before the construction phase of any project, including ecological restoration projects. The EPA applies a similar concept with QAPPs, which must be signed by the applicable project and QA manager before initiating any work involving the collection, analysis, or use of environmental information or the performance of environmental technology. To facilitate compliance with these requirements, EPA's Great Lakes National Program Office (GLNPO) has developed a QAPP template for use in documenting plans for ecological restoration and invasive species control projects (see **Appendix C**) and a checklist that can be used as a tool when reviewing QAPPs (see **Appendix D**).

2.5 DATA QUALITY INDICATORS

The concept of **quality indicators** also merits some discussion. In a broad context, the term refers to measurable attributes that are used to evaluate the quality of a particular outcome or decision (EPA 2005a). When focused specifically on environmental monitoring data, the term **data quality indicators** (DQI) refers to statistics or other descriptors that are used to evaluate data acceptability or usefulness. Criteria for each indicator are established to define the quality of data that is needed to support a project's objectives. Commonly accepted DQIs include precision, bias, accuracy, representativeness, comparability, completeness and sensitivity (EPA 2002; Taylor 1987). In ecological restoration projects that rely on observer-determined data, the term "detectability" (which includes both sensitivity and specificity), is usually preferred over "sensitivity."

Exhibit 2-3 summarizes how these DQIs are defined for the purpose of this guidance. **Chapter 3** explains how DQIs can be developed to support the unique goals and objectives of ecological restoration projects.

Exhibit 2-3. Common Data Quality Indicators for Environmental Monitoring Data

Data Quality Indicator (DQI)	Description
Precision	The degree of agreement among repeated measurements or observations of the same variable under the same or very similar conditions
Bias	The systematic or persistent distortion of a data collection process resulting in error in one direction
Accuracy	The degree to which a measured or observer-determined value agrees with a known or reference value; includes a combination of random error (precision) and systematic error (bias)
Representativeness	The degree to which data represent the characteristic of a population being assessed
Comparability	Confidence that data can be compared to or combined with other data collected for similar purposes
Completeness	A measure of the amount of valid data obtained from a data collection system compared to the amount that was expected to be obtained under correct, normal conditions
Detectability	A measure of the sensitivity and specificity of the sampling design, measurement procedures, instrumentation and/or data collection personnel in detecting true differences in a target variable at ambient levels or when the measurement or observation of a target variable is dependent upon detecting a rare, cryptic or secretive organism

Note that there appear to be two conflicting definitions of accuracy (Clark and Whitfield 1994). One definition states that accuracy is the same as bias; the other states that accuracy considers both precision and bias (Millard and Neerchal 2001). For the purposes of this guidance document, we have adopted the second definition, which assumes that both precision and bias contribute to accuracy, as demonstrated in **Exhibit 2-4**. This visual representation illustrates how a result with zero bias may not be accurate if the data collection process is not precise.

Exhibit 2-4. Influence of Precision and Bias on Accuracy

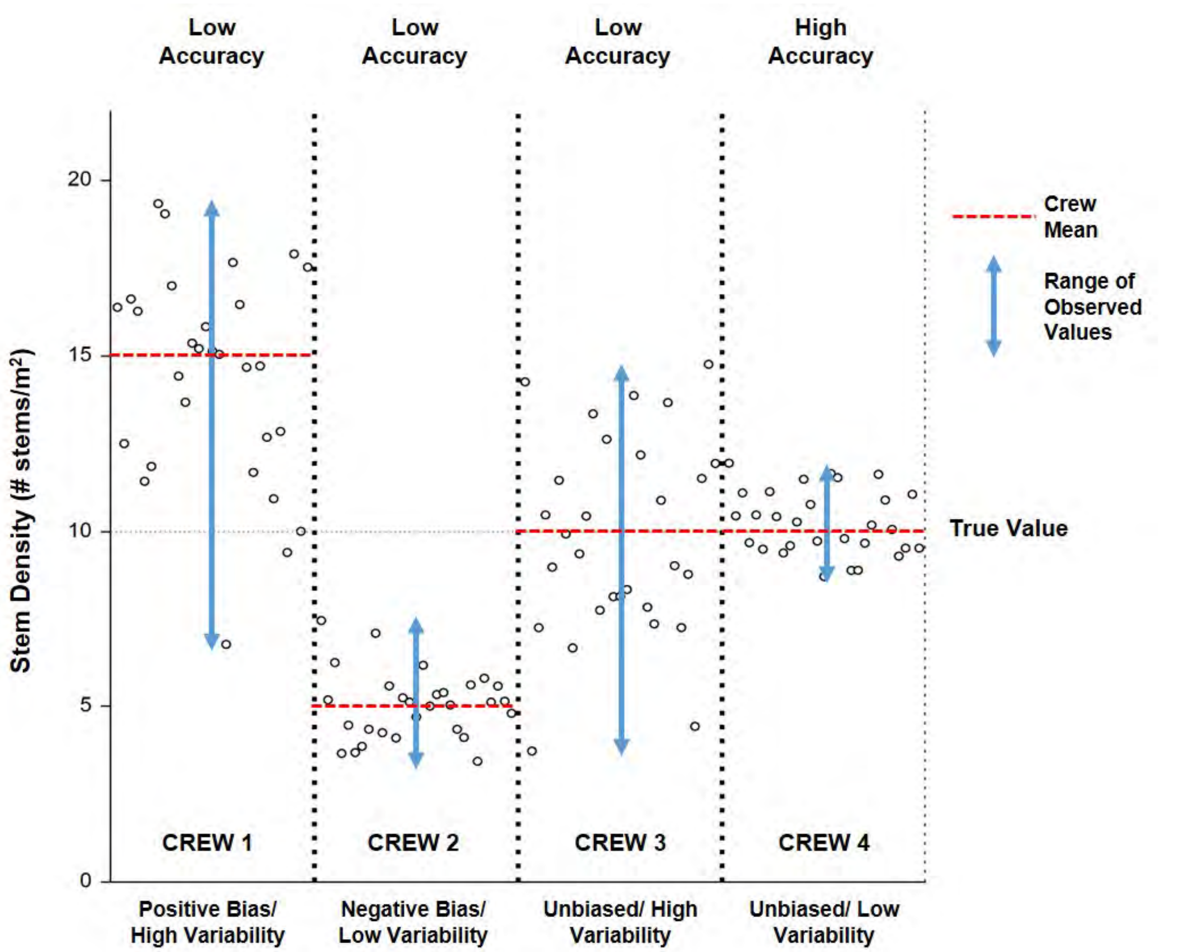


Exhibit 2-4 shows four hypothetical field sampling crews, each with different combinations of measurement precision and bias.

- Crew 1 tended to overestimate the stem density, with a mean close to 15 stems/m^2. Crew 1 measurements also tended to vary widely around that mean, including some results that were below the true value of 10 stems/m^2. Due to the combination of a high bias and high variability, Crew 1's data are inaccurate.

- Crew 2 measurements did not vary widely, with stem densities clustered much more closely to the crew's mean of 5 stems/m^2. However, their mean was well below the true value of 10 stems/m^2. This negative bias renders Crew 2's data inaccurate, despite the low variability of their measurements.

- On average, Crew 3 did not over or under estimate the stem density, with a mean that was approximately equal to the true value of 10 stems/m^2. However, this crew exhibited high variability, such that the results varied from approximately 4 — 15 stems/m^2. As a result of this high variability, Crew 3's data also are inaccurate.

- Crew 4 achieved a mean that was approximately equal to the true value of 10 stems/m^2 with all results tightly clustered around the mean. Because their measurements were unbiased and exhibited low variability, Crew 4's data are considered accurate.

2.6 SOURCES OF VARIABILITY: SAMPLING AND MEASUREMENT ERROR

All data associated with ecological restoration projects are subject to both sampling and measurement error. Project planning teams must be aware of these sources of error and consider their impacts on the level of confidence one can place in the data. Both concepts are illustrated in **Exhibit 2-5**, briefly explained below, and widely discussed elsewhere (e.g., Lohr 2010; Lesser 1999; Gy 1998; Kish 1965).

Sampling **error** can be thought of as the difference between the characteristics identified in a sample of a population (observed or measured values) and the actual characteristics of the entire population (true values).

- For example, in a project to restore shoreline habitats of edible mussels, one might choose to use the number of blue mussels (*Mytilus edulis*) as an indicator of success. Because it is impractical to count every mussel present in a relatively large area, the area is divided into transects or quadrats, and counts of blue mussels within the transects or quadrats are extrapolated to estimate the total number present in the region. The difference between this estimated value and the actual value obtained if one had counted every mussel in the shoreline habitats is defined as the sampling error.

- As another example, consider a project to increase the relative abundance of migratory songbirds within a designated area in a specific timeframe. In this example, sampling error could occur if the sampling design failed to specify sufficient frequencies, times or locations.

Generally, sampling error can be reduced by (1) increasing the number of sample units within the target population (e.g., measuring the number of blue mussels at more plots or transects), or (2) applying a sampling design methodology that more accurately represents the distribution characteristic the target population (e.g., modifying the placement and size/shape of the sample unit).

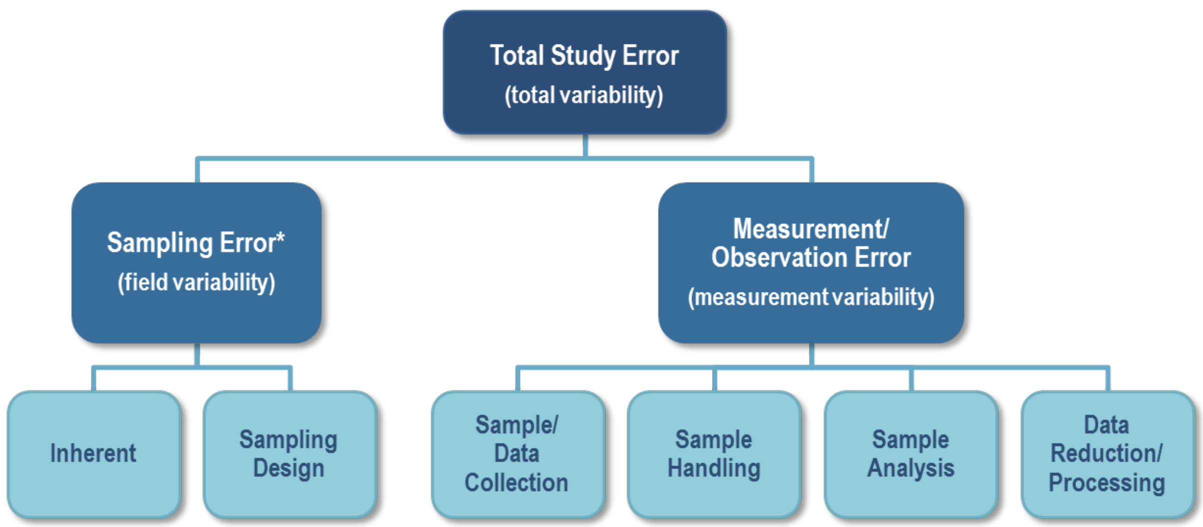
Measurement error refers to the difference between a measured or observed value and the true value, and it is caused by individuals, instruments or processes (e.g., methods, protocols, SOPs) used to obtain the measurements or observations.

- In the blue mussel example, sampling error can occur if the areas selected for sampling do not accurately represent the entire population. In contrast, measurement error can occur when the individuals, instruments or processes used fail to correctly count the number of blue mussels. Examples include cases where mussels are so densely packed together that it is hard to count each one in a given area, or an insufficiently trained crew member cannot differentiate ribbed mussels (a non-target species) from blue mussels. The difference between the actual number of blue mussels present in the area examined and the number of mussels reported represents measurement error.

- In the songbird example, measurement error could occur by misidentifying or miscounting individuals per species, or by failing to detect a species presence.
- For laboratory results, measurement error can be caused by imperfections in the processes or equipment used during field sampling, sample shipping and handling, and/or laboratory analysis.
- Imperfections in data transcriptions and reduction processes also are potential sources of measurement error.

Both types of errors are important to consider when defining specific sampling objectives for a restoration project and developing a detailed study design that can be used to determine if these sampling objectives are met. Where practical, strategies that can control for (or at least minimize) each type of error should be considered in order to increase confidence during decision making. This is particularly relevant in ecological restoration monitoring since it typically includes the collection of diverse types of environmental data. **Chapter 3** provides additional guidance in addressing these concerns during the project planning phase. In addition, **Chapter 6** discusses strategies for identifying and mitigating data reduction and processing errors.

Exhibit 2-5. Common Sources of Error in Environmental Sampling/Monitoring Programs



** Note: The term "sampling error" does not refer to error arising during the physical process of collecting a sample (e.g., collecting a sample that will be subsequently analyzed for phytoplankton counts); such errors are considered to be a component of measurement error.*

2.7 DECISION ERROR

In addition to considering the impacts of sampling and measurement errors as described above, project teams must consider the types of decision errors that may occur during data interpretation. Most monitoring programs are based on classical hypothesis testing and, as shown in **Exhibit 2-6**, hypothesis testing can lead to one of four possible outcomes. Two of the possible outcomes will result in a correct decision, and two will result in an erroneous decision. The nature of these outcomes depends on whether the restoration project objective is based on affecting a change from a baseline condition or meeting a specified threshold. (**Section 3.2.2** discusses the difference between targeted changes and targeted thresholds in greater detail.)

Exhibit 2-6. Types of Decision Error

Conclusions Based on Monitoring Data	**True Condition of the Monitored Ecosystem**	
	No change in the monitored parameter has occurred (null hypothesis)	A change has occurred in the monitored parameter (alternative hypothesis)
Targeted change in the monitored parameter has not occurred	CORRECT DECISION	TYPE 2 ERROR (False Negative/Missed Change, p = β)
Targeted change in the monitored parameter has occurred	TYPE 1 ERROR (False Positive/False Change, p = α)	CORRECT DECISION

In hypothesis testing, a null hypothesis indicates that treatment (restoration activities) did not yield the desired change, and the goal of the test is to demonstrate that either the null hypothesis is supported (i.e., restoration efforts failed to achieve the desired change) or the alternative hypothesis is supported (i.e., restoration efforts did lead to the desired change). Incorrectly concluding that a change has occurred when it has not is known as a Type 1 ("False Positive") error; failing to recognize that a change has occurred is known as a Type 2 ("False Negative") error (Quinn and Keough 2002). The probability (p) of making a Type 1 error is denoted by α, and the probability of making a Type 2 error is denoted by β.

In ecological restoration projects, Type 1 and Type 2 errors are sometimes referred to as "false change" and "missed change" errors, respectively (Elzinga, Salzer and Willoughby 1998). Concluding that a project was successful when it was not (Type 1 error) may lead to further ecological degradation and wasted resources. Alternatively, believing that restoration objectives were not met when they actually were (Type 2 error) may result in additional expenditures associated with redesigning the project as well as a failure to recognize a successful design that could be implemented at other impaired sites (Stapanian et al. 2016; Stankey et al. 2005).

2.8 DEVELOPING A MONITORING STRATEGY

In general, sampling error can be reduced and statistical power increased by choosing an appropriate study design and monitoring strategy (sampling design) to measure change in one or more ecological attributes (Morrison et al. 2008; Zhang 2007). Measurement error can be more easily controlled by planning and implementing the QA/QC practices described throughout this guidance, such as standardization of data collection and management procedures, training staff in the use of the those procedures, conducting QC checks to verify that the procedures are being followed, and ensuring that project data reflect pre-determined standards of quality.

The scope of this guidance document is not intended to include detailed information on study design concepts or on how to develop a monitoring strategy. Project planners should work with a qualified statistician when considering their design and monitoring strategy needs. (For less complex projects, a biologist or ecologist with experience in statistical study design and interpretation may be able to fill this role.) In addition, the monitoring strategy should be designed to support an adaptive management framework as discussed in **Chapter 8**. In lieu of providing detailed guidance on this topic, we recommend considering the following aspects when developing a monitoring strategy:

- **Define the measurements and observations**: Be specific regarding the data to be collected. For example, if you are monitoring for a change in vegetation structure in response to restoration planting, you may be interested in stem density that includes all woody plant species, native or non-native species, or a particular stem height or diameter class (e.g., stems less than 1.4 meters height or ≤ 5 centimeters diameter at breast height). Alternatively, if you are monitoring for a change in wildlife abundance as result of habitat restoration, you may consider measuring bird species absolute abundance, relative abundance, or an index based on the frequency of occurrence for one or more indicator species. The appropriate measurements and observations will be determined based, in part, on the conceptual model imposed (see **Section 3.2.1**) and the selected study design and sampling design strategies. When making these decisions, distinguish between **primary variables** of interest (i.e., those that will be used to determine if objectives have been achieved) and **ancillary variables** that describe who collected the data and when, weather conditions at the time of collection, and other information that can be used to help evaluate data quality and interpret results.

- **Consider the need for baseline and reference condition sampling**: Ecological restoration projects attempt to restore components of an impaired ecosystem to a target condition (see **Section 3.2.2**). In order to demonstrate this transition, baseline condition sampling and reference condition sampling are often necessary components of the monitoring strategy and study design. When conducted, baseline condition sampling is typically performed within the framework of a before-after-control-impact (BACI) study design to assess if the site being restored has achieved a targeted change or is trending toward a targeted threshold condition (Morrison et al. 2008). There are several variations on the application of the BACI study design, including the use of one or more reference sites in addition to the site being restored. A reference site is often selected because it reflects physiographic and ecological characteristics similar to the site being restored, however, it does not receive restoration. When included in the study design, a reference site is typically paired with the site being restored and identical sampling that includes baseline sampling occurs simultaneously at each to monitor change over time. This can be an effective strategy to (1) control experimental bias, and (2) develop the empirical evidence necessary to relate any change in condition of the restored site with the restoration efforts. Such a design consideration can provide data needed to estimate the “effect-size” required to evaluate a project’s sampling objectives, and to support decision making within an adaptive management framework. (Refer to **Chapter 8** for a discussion of adaptive management.) Reference condition sampling can also be conducted at a site that represents optimal, un-impacted, or undisturbed conditions to establish characteristics (benchmarks) that represent the target condition.[3] Establishment and monitoring of such un-impacted reference sites allows the success of the project to be evaluated against how closely the restored site resembles an un-impacted (natural) reference condition (Morrison et al. 2008).

- **Determine the study design***:* Select a study design that is most appropriate to address your project goals and objectives (i.e., hypotheses), and maximizes the ability of producing unbiased and precise estimates of your ecological response. There are three broad categories of empirical research distinguished primarily by elements of research or study design and the degree to which statistical inference can be applied. They include:
    - **Manipulative or true experiment** – designs that include the manipulation of one or more conditions (factors) randomly assigned as experimental treatments and where the treatments, including a control, are replicated,
    - **Quasi-experimental** – designs that include the manipulation of one or more conditions, but typically lack random assignment and/or true replication, and
    - **Mensurative** – designs that lack experimental manipulation and that may or may not incorporate random selection and replication of independent sample units. Depending upon the design elements incorporated, mensurative research can more precisely be defined as observational or descriptive; for environmental monitoring projects, these designs are greatly limited in their ability to make inference regarding causality.

  Ecological restoration can be described as a quasi-experiment given that these projects are based on an assumption that predicts an ecological response to restoration actions. With quasi-experiments, the degree to which statistical inference can be applied is generally limited when compared to a true experiment (e.g., the ability to establish cause-effect relationships). However, the ability to make statistical inference can be increased in quasi-experimental designs by controlling experimental bias and increasing precision in estimates of true effect-size. The latter can

[3] Specifically, the term reference sampling in ecological restoration projects can refer to the use of either (1) a “natural” reference site that represents conditions targeted or used to establish ecological benchmarks of progress toward a targeted state, or (2) a site that has been determined to be similar to the restoration site (pre-restoration) so that it represents the same conditions as the site that is being restored. The latter type is often referred to as a “control” site and receives no restoration. Both sites are monitored in the same way; the difference in change is considered the “effect-size” and accounts for natural variation across the restoration site and the reference (control) site.

be done by including reference condition sampling at one or more randomly selected, independent control sites concurrent with sampling before and after implementing restoration actions. It is important that these control sites are similar to the pre-restoration site in terms of size, geographic setting or proximity, and key ecological characteristics. When these design elements are included in ecological restoration monitoring, they are commonly referred to as a BACI study (see previous bullet). An inherent assumption with BACI designs is that temporal variation for a response variable among control sites that have not been restored will be similar and more consistent than the temporal change in the same variable at the restoration site (Morrison et al. 2008; Block et al. 2001).

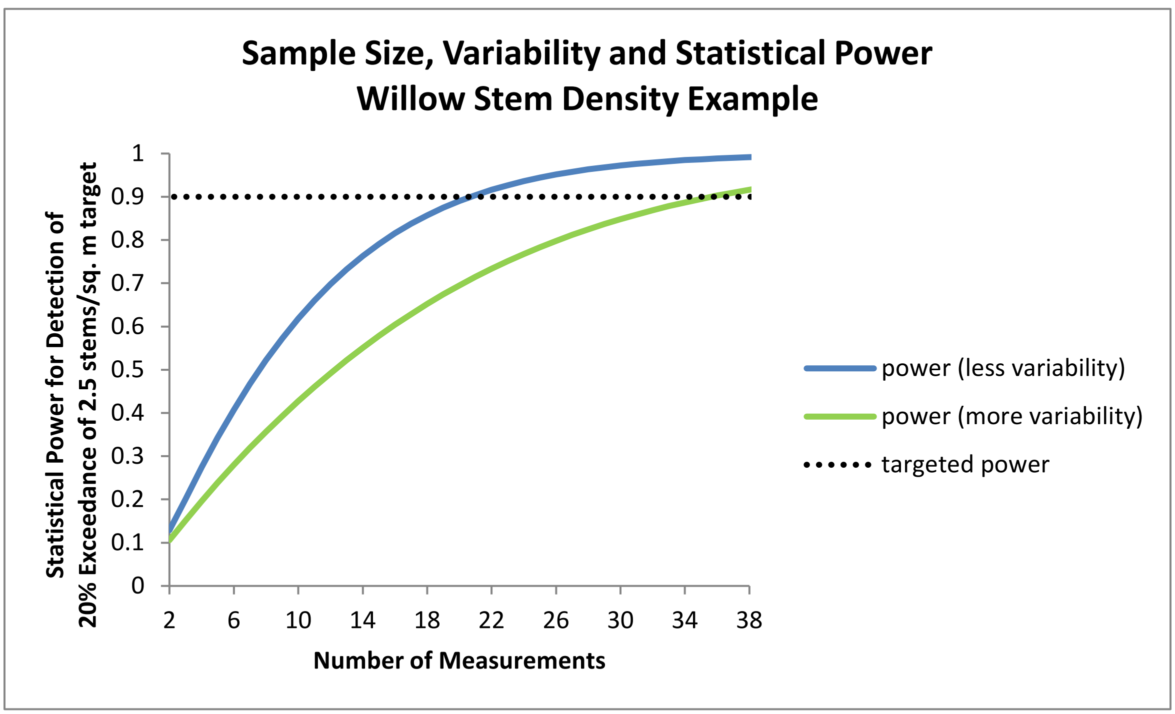
- **Define the sampling units and timeframe for data collection**: Sampling units may be natural (e.g., a tree, a pond) or user-defined (e.g., plots, transects, net hauls, soil cores). The units should not overlap (unless using a hierarchical or nested design), and they may need to meet certain assumptions of statistical independence. To minimize variance, they also should reflect the optimal period of time that sampling can occur and result in consistent estimates for the variable(s) of interest. Sample units should attempt to capture the characteristics and natural variability within the area, target population, community or site of interest rather than simply among sample units. Thus the size, shape and orientation of the sample units are important considerations (Elzinga, Salzer, and Willoughby 1998).

- **Determine the sample size**: The required sample size will depend on the anticipated total variability (sampling and measurement/observation), acceptable error rates (Types 1 and 2), and desired detectable magnitude of change (targeted effect-size or threshold exceedance). Sample size decisions should not be based solely on project budget considerations, as insufficient sample sizes can significantly limit the ability to make informed decisions regarding the project's progress and/or success. **Exhibit 2-7** depicts the relationship between statistical power, variability and sample size for a hypothetical project that seeks to restore optimal willow density (at least 2.5 stems/m^2) along a stream riparian shoreline. The Y-axis shows the statistical power needed to detect a 20% exceedance of the 2.5 stems/m^2 target (with the dotted line depicting the goal of at least 90% power); the X-axis shows the number of measurements that would be needed to achieve the statistical power; and the two curves show the relationship between power and sample size for two levels of variability. For the scenario with lower variability (blue curve), 90% power can be achieved with approximately 21 measurements. For the scenario with higher variability (red curve), 90% power can be achieved with approximately 36 measurements. In the event it is not feasible to increase sampling effort at one or more of the initially selected sites, statistical power can be increased by adding additional reference sites to sample that are in comparable "pre-restoration" condition to the site being restored (Morrison et al. 2008).

- **Choose a sampling design**: There are many different ways to position sampling units within an area that is to be sampled. The different ways of positioning sampling units share three characteristics: (1) random placement (each location has a known probability of being sampled), (2) good interspersion through the area to be sampled, and (3) independence (conditions in one sample unit do not influence conditions in another). Random sampling allows inferences to be made to the area, population, community, or site of interest and reduces bias. Positioning of sample units to ensure interspersion and independence can be done by (1) simple random sampling, (2) stratified random sampling, (3) systematic sampling with a random start, (4) restricted random sampling, (5) multi-stage sampling, (6) cluster sampling or (7) double sampling. Sampling can occur spatially (e.g., across an area) and also temporally (i.e., over time). For example, the Generalized Random Tessellation Stratified (GRTS) sampling approach may be an appropriate and useful strategy, but only for ecological restoration projects that cover a very large geographic area and have the necessary resources and expertise to invest in proper implementation.[4] A statistician can help determine the best sampling design options, but project planners will need to contribute knowledge regarding the biology and ecology of the system to be monitored, as well as practical constraints such as access to property, availability of equipment, and adverse environmental conditions.

- **Identify and document specific procedures**: Although it is usually easier to minimize sources of measurement error than it is to minimize the inherent variability in a sampled population or the error resulting from the sampling design, the ability to minimize error depends on the specific type of data being collected (e.g., observer-determined versus measurements made with a calibrated instrument). **Chapter 4** discusses the importance of providing standard procedures and using trained individuals to collect data in field situations; **Chapter 5** discusses approaches to monitoring data collection procedures and their implementation.

Exhibit 2-7. Example Power Curve



[4] The GRTS sampling approach is a form of probability sampling that results in greater spatial balance (i.e., less clumping), while decreasing the variance and thus increasing statistical power (Stevens & Olsen, 2004). Additionally, sampling locations eliminated by selected criteria (such as placement on a road or other inaccessible site) can be replaced by extra locations generated by GRTS while maintaining a balanced, independent, and random selection process. The GRTS approach is typically applied to large projects, however, and specific skills are required to use the software involved.

2.9 ADDITIONAL READINGS

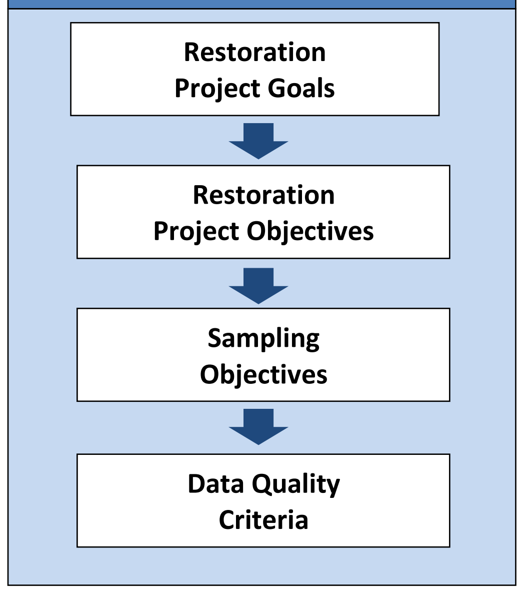
- Christensen, S.W., Brandt, C.C., and McCracken, M.K. 2011. Importance of data management in a long-term biological monitoring program. *Environmental Management*, 47(6), 1112-1124.
- Stokes, E., A. Johnson and M. Rao. 2010. Monitoring Wildlife Populations for Management. Training Module 7 for the Network of Conservation Educators and Practitioners. American Museum of Natural History and the Wildlife Conservation Society, Vientiane, Lao PDR. http://www.fosonline.org/resource/monitoring-wildlife-populations
- U.S. Department of the Interior. 2003. Quality Assurance Guidelines for Environmental Measurements. U.S. Department of the Interior, Bureau of Reclamation, QA/QC Implementation Workgroup. https://www.usbr.gov/tsc/techreferences/mands/mands-pdfs/QualityAssuranceGuidelines_2003.pdf
- U.S. Environmental Protection Agency. 2016. "How EPA Manages the Quality of its Environmental Data." Last modified August. https://www.epa.gov/quality.

CHAPTER 3 PLANNING FOR DATA COLLECTION

We noted in **Chapter 1** that practitioners and decision makers rely heavily on the quality of data associated with ecological restoration projects, but guidance is lacking on how to ensure these data are reliable enough to support sound decisions. In this chapter, we provide guidance on how to address data quality needs early in the planning stage of a project. This chapter provides information and guidance on the processes that can be used to determine the type, amount, and quality of data required to support decision making, including the associated acceptance criteria against which data quality can be assessed.

The process begins with selection of general **restoration project goals**, as described in **Section 3.1**. These goals are then used to determine specific and measurable **restoration project objectives** that provide the basis for planning restoration strategies (**Section 3.2**). These include strategies associated with the restoration process itself, such as treatment and monitoring, as well as monitoring strategies that can be used to evaluate project success. Because the primary focus of this document is on monitoring (rather than restoration) activities, **Section 3.3** includes guidance on how to use the restoration project objectives as the basis for selecting **sampling objectives** which, in turn, are used to determine a sampling design for the monitoring activities and to identify quality requirements for the data that will be collected. Guidance on defining appropriate data quality acceptance criteria is provided in **Section 3.4**. **Section 3.5** describes quality considerations that project planning teams should address if they will use existing (i.e., previously generated) data to support their project planning process or to supplement new data that will be generated by the project team.

Exhibit 3-1. Process for Establishing Data Quality Criteria



Although there may be times when it is necessary to repeat one or more of these steps to address overall project constraints (e.g., schedules, budgets, resources), the process generally flows in a natural progression from setting general restoration goals towards defining more specific objectives and criteria, as shown in **Exhibit 3-1**. It is important to avoid selecting data quality acceptance criteria without first identifying the sampling objectives on which they are based. Similarly, sampling objectives should not be defined without first defining the restoration project objectives the sampling activities are designed to support, and there is little sense in specifying the overall objectives of a restoration project without first understanding the broad goals these objectives are intended to meet. Designing a monitoring strategy in such a "reverse order" may produce data that are of high quality but inadequate for demonstrating how well the project goals and objectives have been met.

3.1 RESTORATION PROJECT GOALS

The planning process begins with the identification of goals that describe the desired future conditions or ideal states an ecological restoration effort will attempt to achieve. Goals should be descriptive and convey a purpose. They should define the general direction for a project but should not define specific desired future conditions in measureable terms. The latter is accomplished through identification of restoration project objectives (**Section 3.2**) that will support the overall goals.

3.1.1 Preparing to Define Restoration Project Goals

When preparing to define goals for a restoration project, it is helpful, if not essential, to have background information on the:

- project location, boundaries, and ownership;
- targets of restoration (e.g., ecosystems, natural communities, rare or protected species);
- threats, need for restoration, and desired state and anticipated benefits;
- current and past condition of the site;
- adjacent land use;
- social, political, and physical context of the project; and
- expectations from funding sources, stakeholders and project staff.

Installation of willow cuttings for revegetation of the riparian area along Elm Creek, Minnesota. Photo Credit: Britta Suppes, Joe Magner, Chris Lenhart

This background information regarding the project site, restoration needs, and planning team members will help set the stage for the selection of restoration goals. In some cases, restoration goals are defined by decision makers in other organizations, and the project planning team is responsible for defining objectives and strategies needed to achieve those goals. For example, a legislature may issue funding to “restore the aquatic habitat of Icky Inlet and make it safe and healthy for recreational activities” and then direct those funds to a federal, state or local agency to manage. When this occurs, project planning teams are responsible for defining specific objectives that can be used to demonstrate the project outcome will support the mandated goals—a process that will be aided by a thorough understanding of the relationship between restoration goals and objectives, as described in **Sections 3.1** and **3.2**.

3.1.2 Defining Restoration Project Goals

The response of ecosystems to restoration activities may take several years to decades to be fully realized. Therefore, it is helpful for planning teams to define restoration goals that represent desired short-term, mid-term and long-term outcomes (NOAA 2013). Short-term goals describe anticipated immediate effects of restoration efforts; long-term goals describe the overall change that is desired, though this change may not necessarily be a direct outcome of the restoration efforts. Mid-term goals describe an intermediate response in the ecosystem (or system being restored) due to project activities. For example, a restoration activity may improve the hydrologic regime for a wetland (short-term) resulting in improved wetland quality (mid-term) and the successful re-establishment of wetland functional processes (long-term). When establishing short-, mid- and long-term project goals, project planners will find it constructive to define them within the context of whether they may be achieved given the scale (extent) of the project and available project resources. Often, project goals that are based on anticipated long-term outcomes may require substantial financial resource inputs and coordination that are beyond the scope of any one restoration project, and achievable only within the context of a larger, over-arching programmatic goal or regional initiative. For example, a programmatic goal may be to restore a federally endangered wetland plant species across its historic range, and to do so will require the coordinated efforts and resources of multiple projects feasible only through a larger programmatic or regional initiative.

Each restoration project goal should include the following four elements (Adamcik et al. 2004):

1) Subject or resource of concern (e.g., the particular species, biotic community, ecosystem process, ecosystem service, habitat type)

2) Attribute of interest for that subject or resource (e.g., species diversity, population size, functioning of an ecosystem process)

3) Conceptual target or condition for that attribute (e.g., optimum, proper, natural, maximum)

4) An action or effort to be made relative to the target (e.g., restore, provide, achieve)

3.1.3 Examples of Restoration Project Goals

"We cannot overemphasize the importance of expressing each and every project goal with a succinct and carefully crafted statement" (Clewell, Rieger, and Munro 2005).

The following are examples of restoration goals that address each of these four elements for hypothetical restoration project sites.

- Restore optimal willow (*Salix* sp.) density along stream riparian shoreline impacted by historical grazing to reduce bank erosion and provide habitat for riparian wildlife species.

- Restore native wet prairie plant species cover to improve floristic quality on a 15-acre wet prairie degraded by historic drainage and invasive reed canarygrass, *Phalaris arundinacea*.

- Establish an urban park woodland with a diversity of native tree species considered to be resilient to the effects of the invasive Emerald Ash Borer (EAB, *Agrilus planipennis*).

Note how succinctly each of these restoration goals addresses the four key elements. In the first example, the stream riparian shoreline is the subject or resource of concern, willow density and stream channel width (erosion) are the attributes of interest, the conceptual target is an optimal willow density that results in reduced stream bank erosion and restored habitat for stream riparian wildlife species, and the action or effort to be made is to “restore” optimal willow density. In the second example, a 15-acre wet prairie plant community is the resource of concern, the attributes of interest are the cover and floristic quality of the plant community, the conceptual target or condition is an improvement to these attributes, and the desired actions are to “restore” the native species and “improve” the floristic quality. Similarly, the urban park woodland is the resource of concern in the third example, a diversity of tree species considered to be resilient to the effects of the EAB is the attribute of interest, the conceptual target is an EAB resilient “native woodland” plant community, and the action to be made relative to the target is to “establish” an urban park native woodland resilient to the detrimental effects of EAB. It is important to note here that, although project goals may address multiple outcomes (e.g., restore optimal willow density and reduce bank erosion), the more focused and specific the goal, the fewer assumptions are needed to establish clear objectives to achieve that goal.

When defining restoration project goals, the planning team should carefully consider what can be realistically accomplished. This includes understanding the importance of defining the conceptual target based on the ecological scale to which the restoration actions will result in a predicted outcome. Some restoration activities may emphasize habitats, such as restoring coastal wetlands, while others may be directed at species, such as promoting the recovery of threatened or endangered species. On a site-level scale, restoration activities may emphasize ecological processes, such as restoring the hydrologic connectivity of an entire watershed. The selection of goals should recognize that an ecosystem may not be able to return to a former state because of unknown stressors or changes in society and the environment (Clewell, Rieger and Munro 2005). Goals may be unrealistic if they are based on an outcome that is beyond the temporal or ecological scale of a project’s influence, and could set the stage for actual or perceived project failure. Development of realistic restoration goals, however, provides a needed framework from which to build specific project objectives.

3.2 RESTORATION PROJECT OBJECTIVES

Once the planning team has defined restoration project goals, team members can determine specific objectives that will support those goals, serve as the foundation for planning restoration and monitoring activities, and provide interim benchmarks (i.e., quantitative endpoints) for each phase of the project as the basis for measuring progress. The team will need to gather information about the targeted ecosystem that can help them define specific components of the restoration project objectives and maximize the effectiveness of subsequent restoration activities. The following subsections describe these processes and provide examples of well-written objectives, each with a specific, measurable basis for supporting the overarching restoration project goals.

3.2.1 Preparing to Define Restoration Objectives

In order to define restoration objectives, the team must gather and evaluate information regarding the environmental stressors that may be compromising biota and other resources at the project site and the ecological resources affected by these stressors (Mulder et al. 1999). Examples of stressors include fire, alteration of hydrologic cycles, habitat fragmentation, sedimentation, road construction and pollution. A pre-restoration assessment of the relevant biotic and abiotic conditions, as well as baseline monitoring data on variables such as water quality, can be very helpful in characterizing both the stressors and the ecological resources affected by them. Other resources that may be helpful include land use plans and knowledge about the life history of species, ecological reference sites, and historical records (Clewell, Rieger and Munro 2005).

We recommend the development of conceptual models as a tool for organizing information and documenting key assumptions (EPA 2006b). Conceptual models are often depicted as a statement or a diagram linking external driving forces and stressors with ecological effects and the measurable or observable attributes that characterize the state of impacted ecological resources. These models are representations of ecosystem components, processes and drivers, and they can facilitate understanding of key ecosystem interactions and function, bring common understanding among interested parties, and clarify assumptions (Ogden et al. 2005; Woodward et al. 2008). Building on the 15-acre wet prairie example in **Section 3.1.3**, the project team has determined that tile drainage and introduction of invasive reed canarygrass (stressors) have resulted in a degraded wet prairie (ecological effect) as measured by the relative cover of existing plant species (attribute). Based on this conceptual model, a reasonable restoration objective might be to increase the relative cover of native wet prairie species in the wetland by X%. Once the objective is defined, specific restoration strategies and activities necessary to accomplish the objective can be defined, and a monitoring program can be designed that will allow project managers to determine if the objective has been met.

3.2.2 Selection of Restoration Objectives

As described previously (see **Section 3.1.2**), restoration project goals identify the resource of concern, attributes of interest for that resource, conceptual targets, and an action relative to that target. Restoration objectives build upon these goals by providing specific measurable targets for desired future conditions. Each restoration objective should be: **s**pecific, **m**easurable, **a**chievable, **r**esults-oriented and **t**ime-sensitive (SMART) (Doran 1981). These attributes should be identified for each variable of interest that is included in a restoration goal. This is accomplished by specifying the direction and quantity of change desired, pinpointing the specific geographic area for the restoration activity, and identifying a time frame (or project phase) to accomplish this change or see the anticipated ecosystem response. SMART restoration objectives, when developed to support short-, mid- and long-term outcomes, are a necessary component of project-level adaptive management (see **Chapter 8**), and provide the quantitative benchmarks or endpoints necessary to support decision making within an adaptive management framework throughout the project lifecycle.

The desired ecological change can be stated in a project objective as either a targeted change from a baseline condition (i.e., an observed trend or improvement) or the achievement of a targeted threshold (Clewell, Rieger and Munro 2005; Elzinga, Salzer and Willoughby 1998).

- **Targeted Change**: A change from a baseline condition would be expressed either as a difference between the results of initial and final data collection efforts (for example, an increase of 10% in population size between baseline and final monitoring efforts) or as an observed trend in results over multiple efforts (for example, an average 2% increase in population size per year). This type of objective is based on a comparison of future monitoring results to baseline conditions.
- **Targeted Threshold:** In contrast, restoration project objectives that define the desired change in terms of a target threshold would define the final condition based on a single numeric goal (e.g., a final population size of X species/acre). In this case, the objective is based on a sampling design and sampling objectives that compare future monitoring results to the specified target or threshold. For this type of objective, it is assumed that prior studies have established that baseline conditions do not meet the target/threshold.[5]

3.2.3 Examples of Restoration Objectives

Exhibit 3-2 provides examples of SMART restoration project objectives that are designed to support the project goal examples provided in **Section 3.1.3**.

Note that in **Exhibit 3-2**, each of the example project objectives directly supports an attribute of interest and conceptual target in its corresponding goal by defining one or more specific outcomes that can be measured or observed within a specific timeframe. For the first project goal, the first objective specifies a measurable amount of shoreline (1,000 linear meters) that will be covered by a specific, measurable amount of willow (average density of 2.5 stems per square meter), and that should be present within a specific timeframe (after two years). The conceptual target identified (an optimal willow density that results in reduced stream bank erosion and restored habitat for stream riparian wildlife species) is addressed by specific, measurable, reportable and achievable objectives. A similar relationship exists between the restoration goals defined in the second and third examples and their corresponding project objectives.

The above examples are for illustrative purposes only, and many projects are likely to have more than one goal, along with several objectives to support each goal. When this is the case, project planners may find it helpful to list the project objectives according to a hierarchy based on whether they address a short-, mid- or long-term goal (outcome). This is particularly relevant when the mid- and long-term outcomes are only possible if and when the short-term outcomes are achieved.

[5] There is some risk in assuming that prior studies have demonstrated that baseline conditions do not meet the desired target or threshold. If effective QA/QC strategies were not used in these prior studies, your decision to initiate a restoration action may be based on faulty initial condition estimates. Refer to **Section 3.5** of this chapter for guidance on evaluating the quality of existing data.

Exhibit 3-2. Example Restoration Goals and Corresponding SMART Restoration Project Objectives	
Project Goal* (from **Section 3.1.3**)	**Corresponding Project Objectives****
Restore optimal willow (*Salix* sp.) density along stream riparian shoreline impacted by historical grazing to reduce bank erosion and to provide habitat for riparian wildlife species	Restore native willow to an average stem density of 2.5 stems per square meter along a total of 1,000 linear meters of riparian shoreline within the toe and transition zones after 2 years
	Reduce the annual rate of stream channel (bank-full width) widening along the restored riparian zone after 6 years, with particular interest in an annual rate reduction of at least 80%
	Increase the relative abundance of migratory songbirds within the 1,000 linear meters of restored riparian habitat area after 6 years, with particular interest in an increase of at least 40%
Restore native wet prairie plant species cover to improve floristic quality on a 15-acre wet prairie degraded by historic drainage and introduction of invasive reed canarygrass, *Phalaris arundinacea*	Increase the total area of wet prairie characterized by saturated soils to greater than 50% within the 15-acre project area after 2 years
	Reduce total cover of reed canarygrass to less than 10% across the 15-acre wet prairie after 8 years
	Increase, by at least 75% over a 12-year period, the total cover of native wet prairie plant species characterized by a floristic quality assessment (FQA) Coefficient of Conservatism score of greater than 5
Establish an urban park native woodland with a diversity of native tree species resilient to the effects of the invasive EAB, *Agrilus planipennis*	Restore 5 acres of urban park woodland with native tree and shrub species where tree species composition reflects less than 20% representation of ash (*Fraxinus* spp.) after 6 years

* *In general, state restoration goals in the positive reflecting a future or target "restored" condition.*

** *Restoration objectives can be stated as a positive or negative change using "absolute" (e.g., 10 mm, 500 mg/L, 2.5 stems/meter^2) or "relative" (e.g., 20%, 50%, 80%) change, and can refer to an ecologically or biologically meaningful effect, often referred to as "effect-size" or "effectiveness criteria." Regardless of whether expressed as absolute or relative, change is usually specific to one direction, i.e., an increase or decrease. The magnitude of the desired change is determined with consideration of the inherent variability of the system under study, including sampling error, measurement error, sample size, and desired statistical power.*

Once restoration project objectives have been defined, the project planning team can use them to:

1) determine the specific remediation requirements, activities, resources and schedules that are needed to accomplish the objectives, and

2) develop a monitoring program that can be used to evaluate the effectiveness of the remediation efforts in meeting those objectives.

The remainder of this chapter addresses the second task, with a specific focus on QA/QC strategies that should be considered when designing the monitoring program.

3.3 SAMPLING OBJECTIVES

As mentioned above, the project planning team will need to create a monitoring program that will allow project managers to determine if the restoration activities were effective in achieving the specified restoration goal(s) and project objectives. Development of such a monitoring program will require:

1) identification of specific sampling objectives (which also can be thought of as "monitoring objectives") and

2) development of a detailed sampling (monitoring) plan that will provide data that can be used to determine if the sampling objectives are met.

Both activities require some understanding of the sources of variability that can arise in any monitoring program, and of the types of decision errors that may result from the monitoring data (see **Sections 2.6** and **2.7**, respectively, for a brief overview of these concepts). Given the significant amount of resources invested in ecological restoration projects and the importance of monitoring data in determining project success, we strongly recommend that project planning teams consult with an experienced statistician for assistance.[6]

3.3.1 Establishing Sampling Objectives

As discussed in **Section 2.7**, Type 1 and Type 2 errors can lead to wasted resources, further degradation, and missed opportunities. Therefore, sampling objectives should clearly state the level of uncertainty that stakeholders are willing to accept for making an incorrect decision.

Type 2 errors are also dependent on the size of the change that actually occurred. Consequently, when establishing sampling objectives, project planners need to determine the size of an effect (effect size) that will be meaningful, and recognize that the "false negative" (Type 2/missed change) error rate will reflect a change of this size or greater. In other words, the probability of concluding that no change had occurred when in fact a change of at least this size did occur would be less than or equal to the Type 2 error rate. Monitoring programs, therefore, should be designed to ensure a sufficient sample size and yield enough usable data to (1) allow a high probability of identifying when the specified change occurs, and (2) avoid the additional costs and resources that would be needed to detect a smaller (and not necessarily meaningful) difference at the same high probability.

The established meaningful effect size needs to be compatible with the restoration project objectives. Specifically, if an objective is expressed as a change between a baseline and final condition, then the effect size must be a specific amount of change, expressed as either an absolute, relative, or standardized effect size that is consistent with the restoration goal.[7] Similarly, if the objective is defined as a comparison to a target or threshold, the effect size would be a difference (either absolute or relative) from that target/threshold. The decision of selecting the appropriate effect size is complicated

[6] In accordance with the graded approach discussed in **Chapter 2**, a biologist or ecologist with experience in statistical study design and data interpretation may be sufficient for less complex monitoring projects.

[7] Targeted changes specified in absolute terms are expressed in directly measured units, such as mm, mg/L or total count. Targeted changes specified in relative terms are expressed as a percent difference from the baseline. Targeted changes specified in standardized terms are expressed as a unitless metric, standardized based on the observed variability.

by federal requirements to consider the potential for increased variability in system response due to effects of regional climate change (EPA 2014a). In theory, such effects might be assumed to apply equally across different sites within a region (e.g., a site subject to ecological restoration activities as compared to a reference or control site). However, the effects could vary considerably over time, reducing the level of precision in estimating change as a result of restoration actions.

Sampling, Measurement and Decision Errors – Summary

Sampling and Measurement Errors (see Section 2.6)

- Sampling error refers to the difference between the characteristics of a sample of a population (observed or measured values) and the actual characteristics of the entire population (true values). Sources of sampling error include the natural variability within the sampled population, the sample collection design, and the number of samples taken.
- Measurement error refers to the difference between an observed or measured value and the true value. For data collected in the field, it is caused by imperfections in the field crew processes, crew expertise and equipment. Measurement error in laboratory results may be caused by imperfections in the processes or equipment used during field sampling, shipping and handling, and laboratory activities. Imperfections in data transcription and reduction processes also are potential sources of measurement error.
- Project planning teams must be aware of sampling and measurement errors and consider their impacts on the level of confidence one can place the collected data.

Decision Error (see Section 2.7)

- Type 1 errors involve incorrectly concluding that a project achieved its desired outcome even though it did not. These "false change" errors can lead to further ecological degradation and wasted resources.
- Type 2 errors involve incorrectly concluding that a project failed to achieve its intended target when it actually did. Such "missed change" errors may result in unnecessary project redesign expenditures and failure to implement a successful design at other impaired sites.
- Sampling objectives should clearly state the level of uncertainty that the stakeholders are willing to accept for making an incorrect decision.
  - The probability of making a Type 1 error is denoted by α; the probability of making a Type 2 error is denoted by β
  - When defining sampling objectives, project planning teams must balance potential consequences associated with each type of error against project constraints (e.g., schedule, budgets and resources) and a study design aimed at minimizing sources of error.

Consider once again our hypothetical example of a project objective to increase the number of migratory songbirds within the restored shoreline after a six-year period. The effect size of this increase would need to be a difference between baseline abundance and the abundance after six years. Now suppose that historical knowledge of bird activity indicates that, to meaningfully increase the songbird population, the abundance needs to increase by at least 40% in order to avoid misinterpreting effects due solely to the inherent variability of the system.[8] In our example, stakeholders want to be sure that the chances of missing a change of 40% or greater are small, so they specify a Type 2 error rate of 20% (e.g., no more than a 20% probability of missing a 40% or greater increase in songbird abundance). Although a smaller than 40% change in abundance could be detected with a lower probability,

[8] Determination of meaningful effect size generally requires a combination of best professional judgment and available study data or literature concerning the variables of interest in similar environments.

stakeholders in our hypothetical project are interested in a reasonable probability of detecting a change that is considered to be biologically meaningful. In addition to specifying the biologically meaningful effect size and Type 2 error rate, our hypothetical stakeholders want to be at least 95% confident they will not falsely conclude there was a change when, in fact, there was no difference in abundance. In other words, the stakeholders want to limit the Type 1 error rate to 5% and the Type 2 error rate for a 40% or greater change to 20%. The sampling strategy would then be designed to collect sufficient data to meet these requirements.

3.3.2 Examples of Sampling Objectives

The goal in developing effective sampling objectives is to avoid ending up with an inadequate sampling design that would make it difficult to determine whether a restoration project objective has been met. Towards this goal, well-defined sampling objectives specify (1) the degree of change that must be detected to define project success, and (2) the degree of certainty needed when stating that the change has been detected. **Exhibit 3-3** provides example sampling objectives that might be derived to support the example restoration project goals and objectives presented in **Sections 3.1** and **3.2**, based on traditional hypothesis testing approaches such as those discussed in **Chapter 2**. (Although Bayesian Methodology and other approaches may be appropriate alternatives to traditional hypothesis testing, discussion of such strategies is beyond the scope of this document.)

Ideally, the specific information required to develop sampling objectives can be derived from the restoration project objectives. This information includes the target population or resource of interest, along with its geographic location, attributes of interest, and the anticipated direction, degree and time frame for the response. Note that:

- restoration goals describe *why* a restoration activity is being conducted;
- restoration project objectives delineate *what* needs to be measured or observed; and
- sampling objectives provide additional information that planners will use to decide *how*, *where*, and *when* data are to be collected, and *how man*y samples are required or needed.

Finally, it is important to recognize that, although sampling objectives serve as the basis for designing a monitoring strategy, these two components are often developed in an iterative manner. For example, when designing the strategy, the project planning team may determine that it is not possible to achieve the original sampling objectives within budget constraints. In this situation, the sampling objectives may need to be modified to reflect the financial limitations (e.g., accepting a lower level of confidence that the desired change will be detected or accepting a higher risk of falsely concluding that a change has occurred). At times, it may even be necessary to revisit and re-scope the project objectives to reflect the constraints (e.g., reduce the size of the restoration area or reduce the magnitude of change desired).

Exhibit 3-3. Example Sampling Objectives for Corresponding Restoration Project Goals and SMART Restoration Project Objectives			
Restoration Goal (from **Section 3.1.3**)	**Corresponding Restoration Project Objectives**	**Statistical Interpretation of Project Objective**	**Corresponding Sampling Objectives** *The results of this monitoring effort will…*
Restore optimal willow density along stream riparian shoreline impacted by historical grazing to reduce bank erosion and to provide habitat for riparian wildlife species	Restore native willow to an average density of 2.5 stems per square meter (m^2) along 1,000 linear meters of riparian shoreline within the toe and transition zones after 2 years	Objective Type: Target Threshold Null Hypothesis (H_0): $Dens_{yr2} \le 2.5$ stems/m^2 Alternative Hypothesis (H_A): $Dens_{yr2} > 2.5$ stems/m^2 Risk of Type 1 Error: $\alpha = 0.05$ Risk of Type 2 Error: $\beta = 0.10$ (when $Dens_{yr2}$ is at least 20% greater than the target 2.5 stems/m^2) $Dens_{yr2}$ is the mean native willow stems density after 2 years of implementing restoration effort.	Demonstrate achievement of a mean density of 2.5 stems/m^2 (with 90% certainty or statistical power when the true density is at least 20% greater than the targeted 2.5 stems/m^2) along 1,000 linear meters of riparian shoreline within the toe and transition zones after 2 years of restoration effort, with a 5% chance (α) of incorrectly concluding that the 2.5 stems/m^2 objective was reached when it in fact was not.
	Reduce the annual rate of stream channel (bankfull width) widening along the restored riparian zone after 6 years, with particular interest in a reduction of at least 80%	Objective Type: Baseline Comparison H_0: $Rate_{yr1} \le Rate_{yr6}$ H_A: $Rate_{yr1} > Rate_{yr6}$ Risk of Type 1 Error: $\alpha = 0.05$ Risk of Type 2 Error: $\beta = 0.20$ (when $Rate_{yr6}$ at least 80% lower than $Rate_{yr1}$) $Rate_{yr1}$ and $Rate_{yr6}$ are the annual rate of stream channel widening at year 1 (before restoration) and year 6 (after restoration), respectively.	Demonstrate a reduction in the rate of stream channel widening (with 80% certainty when the rate is at least 80%) along 1,000 linear meters of riparian shoreline after 6 years of restoration effort, with a 5% chance (α) of incorrectly concluding that the rate has been reduced when in fact it did not.
	Increase the relative abundance of migratory songbirds within the 1,000 linear meters of restored riparian habitat area after 6 years, with particular interest in an increase of at least 40%	Objective Type: Baseline Comparison H_0: $Abund_{yr1} \ge Abund_{yr6}$ H_A: $Abund_{yr1} < Abund_{yr6}$ Risk of Type 1 Error: $\alpha = 0.05$ Risk of Type 2 Error: $\beta = 0.20$ (when $Abund_{yr6}$ is at least 40% greater than $Abund_{yr1}$) $Abund_{yr1}$ and $Abund_{yr6}$ are mean abundance year 1 (before restoration) and year 6 (after restoration).	Demonstrate an increase in migratory songbirds (with 80% certainty when the increase is at least 40%) within the 1,000 linear meters of restored riparian habitat after 6 years of restoration effort, with a 5% chance (α) of incorrectly concluding that the abundance had increased when it in fact did not.

Exhibit 3-3. Example Sampling Objectives for Corresponding Restoration Project Goals and SMART Restoration Project Objectives

Restoration Goal (from **Section 3.1.3**)	**Corresponding Restoration Project Objectives**	**Statistical Interpretation of Project Objective**	**Corresponding Sampling Objectives** *The results of this monitoring effort will…*
Restore native wet prairie plant species cover to improve floristic quality on a 15-acre wet prairie degraded by historic drainage and introduction of invasive reed canarygrass, *Phalaris arundinacea*	Increase total area of the 15-acre wet prairie characterized by saturated soils (SS) to greater than 50% within the project site after 2 years	Objective Type: Target Threshold H_0: $SSCover_{yr2} \leq 50\%$ H_A: $SSCover_{yr2} > 50\%$ Risk of Type 1 Error: $\alpha = 0.05$ Risk of Type 2 Error: $\beta = 0.20$ (when $Cover_{yr2}$ is increased to 60% or greater) $SSCover_{yr2}$ is the mean percent cover of saturated soils after 2 years	Assess whether the relative cover of saturated soils has been increased to 50% or greater within the project site after 2 years (and demonstrate with 80% certainty an increase greater than 60%), with a 5% chance (α) of incorrectly concluding that the relative cover has increased when in fact it did not.
	Reduce total cover of reed canarygrass (RC) to less than 10% across the 15-acre wet prairie after 8 years	Objective Type: Target Threshold H_0: $RCCover_{yr8} \geq 10\%$ H_A: $RCCover_{yr8} < 10\%$ Risk of Type 1 Error: $\alpha = 0.05$ Risk of Type 2 Error: $\beta = 0.20$ (when $RCCover_{yr8}$ is reduced to 5% or less) $RCCover_{yr8}$ is the mean percent cover of reed canarygrass after 8 years of restoration effort	Assess whether the total cover of reed canarygrass has been reduced to less than 10% across the 15-acre wet prairie after 8 years of restoration effort (and demonstrate with 80% certainty a reduction in total cover to 5% or less), with a 5% chance (α) of incorrectly concluding that the percent cover has decreased to below 10% when in fact it did not.
	Increase, by at least 75% over a 12-year period, the total cover of native wet prairie plant species characterized by an FQA Coefficient of Conservatism score greater than 5	Objective Type: Baseline Comparison H_0: $FQCover_{yr1} \leq Cover_{yr12}$ H_A: $FQCover_{yr1} > Cover_{yr12}$ Risk of Type 1 Error: $\alpha = 0.05$ Risk of Type 2 Error: $\beta = 0.20$ (when $FQCover_{yr12}$ is at least 75% or greater than $FQCover_{yr1}$) $FQCover_{yr1}$ and $FQCover_{yr12}$ are mean relative cover (of species with FQA CC>5) at year 1 (before restoration) and year 12 (after restoration), respectively	Assess whether the total cover of native wet prairie plant species with FQA Coefficient of Conservatism scores greater than 5 has increased after 12 years of restoration effort (and demonstrate with 80% certainty if it has increased by at least 75%), with a 5% chance (α) of incorrectly concluding that the relative cover has increased when in fact it has not.

Exhibit 3-3. Example Sampling Objectives for Corresponding Restoration Project Goals and SMART Restoration Project Objectives			
Restoration Goal (from **Section 3.1.3**)	**Corresponding Restoration Project Objectives**	**Statistical Interpretation of Project Objective**	**Corresponding Sampling Objectives** *The results of this monitoring effort will…*
Establish an urban park native woodland with a diversity of native tree species resilient to the effects of the invasive EAB, *Agrilus planipennis*	Restore 5 acres of urban park woodland with native tree and shrub species where tree species composition reflects less than 20% representation of ash (*Fraxinus* spp.) after 6 years	Objective Type: Target Threshold H_0: $AshComp_{yr6} \geq 20\%$ H_A: $AshComp_{yr6} < 20\%$ Risk of Type 1 Error: $\alpha = 0.05$ Risk of Type 2 Error: $\beta = 0.20$ (when $AshComp_{yr6}$ is less than 10%) $AshComp_{yr6}$ is the mean species abundance of *Fraxinus* spp. relative to non-*Fraxinus* spp. abundance after 6 years of restoration effort	Assess whether the tree species composition of an urban park native woodland has less than 20% representation in total abundance by *Fraxinus* spp. after 6 years of restoration effort (and demonstrate with 80% certainty when the composition is less than 10%) and accept a 5% chance (α) of incorrectly concluding that the cover decreased to below 20% when in fact it did not.
Note: *In general, state restoration goals in the positive, reflecting a future or target desired condition. Avoid reference to or use of specific intermediate steps necessary to achieve the goal.*			

3.4 DATA QUALITY INDICATORS AND ACCEPTANCE CRITERIA

In **Section 3.3,** we discussed the importance of defining sampling objectives that specify the degree of certainty needed to support decisions based on the monitoring data collected. We also noted that sources of uncertainty include the sampled population—largely addressed through the project's sampling design—as well as the data collection processes that will be used. The next step in controlling overall error is to address the data collection process itself. This begins with identifying the quality of data that is needed to evaluate whether or not you have achieved your sampling objectives (i.e., how good must your data be in order to achieve the desired levels of certainty in your decisions?).

In **Section 3.4.4**, we present a stepwise procedure for determining data quality acceptance criteria and provide an example application of that procedure. Before doing so, however, it is important to review the types of data being collected (**Section 3.4.1**) and how acceptance criteria for different data quality indicators are described (**Sections 3.4.2** and **3.4.3**). The discussion builds on the text in **Section 2.5**, where we introduced precision, bias, accuracy, representativeness, comparability, completeness and detectability as commonly accepted data quality indicators (DQIs) for environmental monitoring data (see **Exhibit 2-3** for definitions of each term). In this section, we discuss acceptance criteria as performance goals for individual DQIs.

The practice of using DQIs to set data quality acceptance criteria is well established for data generated using laboratory methods for chemical and physical analysis of environmental samples. In contrast, the use of DQIs has been less widely adopted for data that are generated primarily using methods of visual- and/or aural-assessment (observer-determined) and best professional judgment. We believe that ***project planning teams can and should develop acceptance criteria for the collection of <u>all</u> data, including observer-determined data, as a means of ensuring and documenting that decisions are based on acceptable levels of measurement error***; the remainder of this section provides guidance for doing so. Data quality acceptance criteria for laboratory measurements are discussed here only for context and with an understanding that specific guidance is available elsewhere (EPA 2003a, 2006a; Cross-Smiecinski and Stetzenbach 1994).

3.4.1 Types of Data

Before considering how to establish acceptance criteria for each DQI, it is helpful to review the different types of data that are often collected in support of ecological restoration projects. For the purposes of this guidance, and as shown in **Exhibit 3-4,** these types of data are categorized as:

- Species, Taxa or Group, or Community Classification,
- Class or Categorical Assignment,
- Numerical Rank Assignment, and
- Numerical Estimate.

These categories apply to all types of information that is typically targeted during ecological restoration monitoring, including primary or ancillary variables of interest, **stable variables** that can be expected to produce the same result when measured repeatedly over a fixed period of time, and **transitory variables** that are affected by stochastic processes and easily biased by the presence of an observer, the sampling activities, or other disturbances.

Project planners should be aware of the statistical properties imposed on data when deciding how to quantify an ecological variable (or type of data it represents), including any implied limits in measurement precision as result of the method used to quantify the variable (i.e., based on an observer's best professional judgment or by use of a graduated device or calibrated instrument). For example, distance measurements made using observer-based judgement and recorded as numeric rank values (e.g., intervals of 0-10m, 10-20m) are less precise than measurements recorded as discrete numeric values (e.g., to the nearest whole 1-meter integer), and both are less precise than continuous numeric distance measurements (e.g., fractions of a meter) determined using a graduated measuring tape, an optical or digital rangefinder, or global positioning system (GPS) device. In practice, an observer or crew will often combine the use of best professional judgment and a graduated measuring device or electronic instrument as part of a standard procedure to quantify a given variable. Examples include the use of a straight ruler or digital caliper to determine the length of an anatomical feature in order to distinguish between similar plant or animal species, a quadrat frame to interpret vegetation ground cover, a spherical densiometer to assess canopy cover, a Secchi disk to interpret depth of water transparency, or standard reference material (e.g., color chart) to interpret the percent of organic matter contained in a soil sample. When such combined practices are utilized, project planners should clearly define standard procedures to minimize the potential compounding of measurement error and its effects on measurement precision. **Appendix B**, **Section B.1** provides additional information regarding measurement scales and their statistical properties.

Exhibit 3-4. Types of Data Frequently Collected in a Field Setting for Ecological Restoration Monitoring

Type of Data*			Description	Examples
CATEGORICAL		Species, Taxa or Group, or Community Classification	Taxonomic or vernacular names representing a nominal variable that uniquely distinguishes an observable and identifiable organism, group of organisms, or natural community based on phenotypical traits or community compositional characteristics	*Salix interior*, *Salix* sp., sandbar willow, shrub, scrub-shrub wetland, or *Hexagenia limbata*, *Hexagenia*, burrowing mayfly, mayfly
CATEGORICAL		Class or Categorical Assignment	Discrete, mutually exclusive descriptive (non-numeric) categories of an observable and identifiable ecological attribute or condition; may be represented by a nominal or ordinal variable	Gender (male/female), age (juvenile/adult), abundance (none, few, many), substrate type (gravelly, sandy, silty, organic muck)
CATEGORICAL	QUANTITATIVE	Numerical Rank Assignment	Numeric values assigned to describe the relative condition of an observable attribute, object or organism; represents estimates of an ordinal or interval variable scaled along an arbitrary numeric gradient	Plant vigor (1= <25% live tissue, 2= 25-50% live tissue, etc.), wind speed (e.g., Beaufort wind scale), plant cover (1= <25%, 2=25-50%, etc.)
NUMERICAL	QUANTITATIVE	Numerical Estimate	Quantitative estimates of variables expressed as either a discrete or continuous numeric value determined by: (1) an **observer's judgment** of the absolute (count) or relative frequency (rate, percentage, and proportion) of occurrence of an observable and identifiable ecological feature; organism; condition; or unit of length, area, volume or weight; or (2) a **scientific instrument** associated with manufacturer's specification of limits of precision and accuracy	Observer's judgment: precise count (e.g., 7 stems) or estimates of total count (e.g., 300 seagulls), or units of length (e.g., 25 m), area (e.g., 10 m^2, 22% cover), volume (10 mL or 1 cubic yard) or weight (e.g., 5 grams or 1 lb) Scientific instrument: a positive or negative value (e.g., ± 0.00) interpreted from an analog display or transcribed from a digital display

***Types of data listed are intended to reflect actual variables being assessed by an observer (or crew) and recorded on a data collection form, and are organized in approximate order of measurement scale as presented in **Appendix B**, **Exhibit B-2**.

Each type of data has unique characteristics and, therefore, presents unique challenges for establishing data quality acceptance criteria. For example, a laboratory chemist may be able to test measurement accuracy by using standard reference materials to spike a known amount of a chemical into a sample and comparing the known amount to the amount measured. However, it would not be feasible to spike a known quantity or quality into an observation of an ecological attribute such as the categorical determination of a plant community type. What is feasible is to employ a combination of descriptive references (including standard operating procedures) and illustrative keys (e.g., soil color chart) to standardize observer-determined data. Recommendations on how to establish acceptance criteria for the different types of data common to ecological restoration projects are provided in **Sections 3.4.2** through **3.4.4**.

3.4.2 Acceptance Criteria for Precision, Bias and Accuracy

The DQIs of precision, bias and accuracy were discussed previously in **Section 2.5**. In summary:

- **Precision** is a measure of the degree of agreement among data collection efforts under identical or very similar conditions. When data collection relies upon observer-determined methods, precision is commonly estimated by comparing the data collected independently by two or more crews or crew members for the same ecological parameter or attribute. Within-crew precision can be estimated for a single crew, or a single crew member, by having the crew (or crew member) collect measurements or observations at the same sampling unit more than once. A true value is not needed to estimate precision.

- **Bias** is a measure of a systematic or persistent misrepresentation of a data collection process or effort that results in error in one direction. Generally, bias includes a directional component (whether the estimates are higher or lower than the true value being assessed) and a magnitude (the amount that the estimate differs from the true value).

- **Accuracy** is an evaluation of the degree of the closeness of the data to known or reference values and includes a combination of random error (precision) and systematic error (bias) components. (Refer to **Exhibit 2-4** for a graphic display of the impacts of precision and bias on accuracy.)

Due to the difficulty in determining a “true value” for many ecological attributes or variables, values collected by expert or QA crews often serve as surrogates to true values, and accuracy and bias are commonly estimated by comparing results from routine crews to expert crews. This approach is discussed in detail in **Chapter 5**. In some cases, it may be possible to evaluate accuracy and bias using an independent method for a subset of sites or monitoring events that is more accurate and precise (referred to here as a “reference method”). Although more complete or accurate methods may be available for many ecological variables, these methods may not be practical because they are too time consuming, too costly, or cause damage to the sampled environment. This is often the case when sampling objectives require estimating transitory variables, such as wildlife response to habitat restoration efforts or stable variables that require a large number of samples to be representative of the area under study. For these circumstances, use of a reference method across a subset of sample units can be an effective approach. Examples of how a “reference method” approach might be implemented in different situations include the following:

- **Percent cover, density or abundance estimates**: If the “standard” methods used in a particular project involve visual estimates representing a numerical estimate of percent cover or abundance of a given sessile species or slow moving organism (e.g., plants, mussels), then actual counts of individuals for a smaller set of representative plots or subplots might be used as a “reference” method to evaluate the accuracy (and precision) of the visual estimates.

- **Biotic index estimates**: Estimates of biological indicators often employ sub-sampling to economize the sampling effort required to determine species composition. For instance, aquatic macroinvertebrates are often sampled using dip-nets as part of standard procedures for calculating a biological index that is indicative of water quality. Methods typically require that captured invertebrates be picked from vegetative debris and deposited in a sample vial until a certain number of individuals are counted (e.g., 200 individuals) or for a pre-determined duration of time. All macroinvertebrates collected in the vial are then later identified and taxonomically sorted and counted to estimate the relative proportion or taxonomic composition of the macroinvertebrate community in the sampled area. A reference method approach would involve repeating this procedure for a subset of samples or sites by conducting complete counts for all taxa in the entire dip-net sample, recording the total time required (to normalize sample effort), and comparing the results to the estimates produced using routine methods.

- **Biomarker measurements**: Biomarkers and non-lethal tissue sampling methods are often used to model environmental levels (concentrations) of industrial contaminants or exposure risk for certain types of organisms. These non-lethal methods are preferred for large studies where the environmental impact of wide-scale lethal sampling of organisms would create undue harm or be detrimental to a species' population viability. In these cases, more invasive or potentially lethal sampling methods could be used in a subset of locations to evaluate the accuracy of the less-invasive routine method. An example would be the routine use of fish biopsy plugs for monitoring mercury exposure coupled with targeted whole-body analysis to evaluate accuracy and bias.

Exhibit 3-5 shows that acceptance criteria for precision, bias and accuracy of observer-determined data generally consist of two components: an error tolerance specification and an expected frequency of compliance in meeting that specification (Westfall and Woodall 2007). Error tolerance is defined as the expected range for repeated measurements or observations, and is necessary to assess the repeatability of a procedure. The expected frequency of compliance (or "compliance rate objective") is dependent on how difficult it may be to achieve the desired error tolerance for a given variable of interest, the level of confidence necessary for a particular variable, or the variable's importance in defining restoration success. When applied together, the error tolerance objective and the compliance rate objective provide a means for assessing precision, bias and accuracy.

Specific examples of quality acceptance criteria for these DQIs also are provided in **Exhibit 3-5** for several types of variables. For example, a project planning team may propose to assess the degree to which a routine crew or crew member correctly assigns a forest classification type by having an expert independently evaluate 10% of the areas assessed by the routine crew. If the expert's results confirm the routine crew's results (i.e., 100% agreement at least 95% of the time), the crew's results are considered to be accurate and reliable. In contrast, if the expert results confirm the crew's results only 20% of the time, the crew's results would be considered inaccurate and unreliable.

Such assessments also can be examined on the basis of individual crew members, rather than as a whole. Imagine, for example, a project in which the expert results confirm the crew results (100% agreement) 82% of the time. Further examination of the data indicates that a single crew member's results are responsible for all of the non-compliant pairs. If that crew member is consistently making the same type of mistake (e.g., consistently misinterpreting the scale on an analog instrument), the crew member is contributing to bias in the data. If that crew member is making different types of mistakes (e.g., interpretation, instrument calibration or sensor positioning errors), the crew member is contributing to imprecision (and possibly bias) in the data. Both types of error (bias and imprecision) contribute to inaccuracy in the overall dataset.

Exhibit 3-5. Example Variables and Acceptance Criteria for Precision, Bias and Accuracy

Variable Assessed		Type of Data	Error Tolerance Objective	Compliance Rate Objective	Description
Observer-Determined	Forest type	Species, Taxa or Group, or Community Classification	100% Correct	95%	100% agreement in forest type classification identified by routine and QA crews, 95% of the time (or 1 error allowed per 20 sample units)
Observer-Determined	Fish species identification	Species, Taxa or Group, or Community Classification	100% Correct	95%	100% agreement in fish species identified by routine and QA crews, 95% of the time (e.g., 1 error allowed per 20 sample units)
Observer-Determined	% cover bare soil (11 classes)	Numerical Estimate	±10% (or ±1 class)	90%	Estimated percentages of bare soil must fall within ±10% (or ±1 class) of a QA expert's estimated value, 90% of the time (e.g., 1 error allowed per 10 sample units)
Observer-Determined	Bird abundance (3 categories)	Numerical Rank Assignment	100% correct	90%	100% agreement in rank assignments for bird abundance between routine and QA crews, 90% of the time (or 1 error allowed per 10 sample units)
Field Measurements	Secchi disk depth	Numerical Estimate	±10 cm	90%	Estimated Secchi disk depth must fall within ±10 cm of a QA expert's estimated value, 90% of the time (or 1 error allowed per 10 sample units)
Field Measurements	Dissolved oxygen	Numerical Estimate	±0.5 mg/L	90%	Concentrations of dissolved oxygen must fall within ±0.5 mg/L of duplicate measurements, 90% of the time (or 1 error allowed per 10 sample units)
Laboratory	Macroinvertebrate taxonomic identification	Species, Taxa or Group, or Community Classification	100% correct	95%	100% agreement in macroinvertebrate identification between routine and QA expert results, 95% of the time
Laboratory	Total phosphorus	Numerical Estimate	±1 µg/L or ±5%	95%	Concentrations of total phosphorus must fall within ±1 µg/L or ±5% of duplicate measurements, 95% of the time
Laboratory	Moisture content	Numerical Estimate	±3%	95%	Percentages of moisture content must fall within ±3% duplicate measurements, 95% of the time

Once again, project planners are advised to work closely with a statistician when determining acceptance criteria. These criteria should be stringent enough to protect against errors that adversely affect interpretation of the data. Poor precision could mean that assumptions made when developing the sampling design are not being met, resulting in weaker than expected statistical power. A systematic error could directly affect the comparison of results to a target threshold. Another way of saying this is that the magnitude of the measurement error for a particular performance criterion or variable has the potential to mislead or even mask accurate interpretation of true estimates and accurate understanding of whether the project objective has been achieved. For example, if a routine field crew is able to consistently achieve a minimum error tolerance objective of ±10% when assessing percent cover of bare soil, project planners should consider establishing a target change in % bare soil cover based on an effect size that is substantially greater than 20% (i.e., the total width of a ±10% error tolerance objective). Doing so recognizes the possibility that, by chance alone, the routine field crew results could demonstrate a bias toward an outer limit of the error tolerance even though the crew has successfully achieved that objective.

As shown in **Exhibit 3-5**, tolerance and compliance rate objectives can be applied to field and laboratory measurements, as well as observer-determined results. Note, however, that many of these measurements are also well-suited for other types of quality assessment strategies. When measuring total phosphorus, for example, field crews may be asked to collect extra volume for a certain percentage of the field samples. The laboratory divides this extra volume into three aliquots – one that is analyzed as received, and two others that are spiked with a known amount of phosphorus. After the spiked samples are analyzed, measurement bias can be determined by comparing the measured value to the theoretical "true" value (which is based on the known amount spiked into the samples), and precision can be evaluated by comparing the relative percent difference of the measured spike values. Such use of spiked and duplicate samples is a common means of evaluating measurement error in the laboratory. For large projects involving multiple sampling events and analytical batches, these QC data can be included in assessments of overall accuracy. Strategies for assessing the quality of these types of measurements are widely addressed elsewhere and, therefore, are not the focus of this guidance.

Observer-Determined Measurement Examples

Transitory vs. Stable Variables

Transitory Variables:

- **Species detection and identification**
- **Estimates of non-persistent herbaceous ground cover**
- **Plant or animal surveys involving lethal or destructive physical sampling**

Stable Variables:

- **Stationary and physical ecological features such as tree canopy cover**
- **Stem density of persistent vegetation**
- **Frequency of plant species occurrence**
- **Soil texture**

As noted previously, observer-determined results often target variables that represent ecological phenomena that are considered transitory in time and space. If monitoring of transitory variables is required, project planners should consider planning for the following activities:

- Conduct classroom or simulated field trials to estimate observer accuracy, bias and precision (and for potential use in determining data quality acceptance criteria).

- Use multiple routine field crew members (e.g., double-observer) to produce paired datasets for assessing precision.
- Pair routine field crew members with experts to collect paired datasets that can be used to assess accuracy and bias.
- Collect duplicate samples or retain samples to allow for repeated measurements to estimate accuracy, bias and precision.
- Collect voucher specimens or samples to support observer-determined data, serve as standard reference materials, and/or facilitate crew member training.
- Periodically assess observers' ability to meet acceptance criteria.

3.4.3 Acceptance Criteria for Representativeness, Comparability, Completeness and Detectability

Also discussed in **Section 2.5**, there are the commonly accepted DQIs of representativeness, comparability, completeness and detectability.

Representativeness is determined by the degree to which data represent the characteristic of a population being assessed (EPA 2002), and planning teams should strive to ensure sampling designs are based on sampling units that represent the population of interest. Failing to do so can have devastating consequences on the utility of the data collected, regardless of how precise, unbiased and accurate the data may be. Selection of unrepresentative streams in the Pacific Northwest, for example, was shown to be a contributing factor in the subsequent collapse of the salmon stocks, as only high quality streams that were not representative of all streams in the region were selected for monitoring. Unaware of this inadequacy in their sampling design, fishery managers overestimated the overall productivity of the region's salmon stocks, leading to decisions that ultimately failed to protect the resource (Siitari, Martin, and Taylor 2014). Similarly, if a certain plant species is known to be uncommon in a project area but the abundance recorded is high, those data should be confirmed through the collection of voucher specimens or additional sampling within the overall study area (Stapanian et al. 2016). Plant images also can be used for authentication by experts and can be sent as attachments to text messages to expedite identification or verification of the species.

Comparability expresses the confidence with which the data can be compared to or combined with other data collected using similar procedures. Within a given project, comparability among crew members and over time can be achieved by thorough training and strict adherence to standard operating procedures (SOPs), as described in **Chapter 4**.

- In some cases, it may be possible to combine datasets that were generated using different methods, but comparability of the methods should be carefully assessed before doing so. Field calibration studies that include evaluations of the quality (e.g., precision and accuracy) of data generated by multiple methods are a useful means of evaluating comparability. One such example is an interagency calibration study (described in **Section 4.4.1**) that was designed to compare Lake Erie fish abundance estimates generated by multiple agencies using different SOPs and trawl vessels

(Tyson et al. 2006). Results of that study provide a means for adjusting data collected by some of the agencies based on a procedure designated as the "standard" while also preserving each agency's ability to continue using procedures that are consistent with their own historical data.

- Another important consideration for ecological restoration projects is the comparability of taxonomic data. In general, project planning teams can promote comparability by using the most current and regionally accepted taxonomic systems. In some cases, however, it may not be possible to crosswalk historic taxonomic data with current keys, particularly when certain taxa have been split into multiple groups; in such circumstances, datasets need to be maintained at the lowest possible taxonomic resolution that is consistent between historic and current data.
- For long-term monitoring projects, the project planning team needs to consider and implement strategies that will allow older baseline monitoring data to be compared with monitoring data gathered using updated methods or taxonomic systems. In the context of long-term monitoring projects, planners also may discover that historical datasets used to define baseline conditions have become less comparable due to changes in the stability of conventional indicators of condition or health as a result of climate change or other impacts on the ecological system of study. For example, measures such as floristic quality index (FQI) and other indicators of biotic integrity (IBIs) developed in relation to existing disturbance regimes may become less comparable (and potentially less relevant) moving forward in time.

Completeness is the proportion of collected data that can be considered valid and usable relative to the amount required in the sampling plan, with the remainder considered as missing. The concepts of "valid" and "usable" may vary depending on project objectives and the user of the data. Sampling designs often require a certain number of samples to ensure that sampling objectives related to Type 1 and Type 2 errors can be met. Logistical and safety considerations or unplanned events (e.g., flooding) can limit the ability to collect all monitoring data as planned. In other words, (1) a minimum number of results are often required to provide the statistical power needed to support restoration project decisions, and (2) logistical, safety, or other considerations may prevent the required number of samples from being obtained. In addition to the amount of data that could not be collected or used, completeness also can be affected by the nature of invalid or missing data and whether they are "missing at random." A large number of missing observations from the same subarea or time of day could limit the representativeness of the data, even if the overall completeness goal (based on total number of samples and measurements) was met. Project planning teams should mitigate these types of problems by pre-determining contingency measures that can be taken to ensure that the minimum amount of useful data needed to support decision making is obtained. Examples might include proactively identifying alternate sampling strategies or one or more "backup plots" to be sampled in case planned study plots cannot be accessed.

Detectability is a measure of the sensitivity and specificity of the sampling design, measurement procedures, instrumentation and/or data collection personnel in detecting true differences in a target variable at ambient levels or when the measurement or observation of a target variable is dependent upon detecting the true occurrence of a rare, cryptic or secretive organism. Detectability is typically expressed as a minimum absolute value ("lower detection limit") or as an estimate of probability between zero and one ("probability of detection"). The ability to correctly identify the true presence or absence of an ecological condition (e.g., species presence/absence, disease prevalence, water quality impact) is represented by the combined attributes of measurement sensitivity and specificity. **Measurement sensitivity**, also called the true positive rate, is the proportion of positives correctly determined as positive (e.g., the field crew correctly detects the true presence of species X or the true proportion of water samples that are impacted by a disturbance). **Measurement specificity** represents the proportion of accurately determined true negatives or, in other words, the proportion of negatives or absences that are correctly identified as negatives or absences (Gitzen 2012; Drew, Wiersma, and Huettmann 2010).

Exhibit 3-6 provides examples of suggested acceptance criteria for the DQIs of representativeness, comparability, completeness and detectability, when estimating areal cover of plants.

Exhibit 3-6. Example Acceptance Criteria for Representativeness, Comparability, Completeness and Detectability for Plant Cover Data

Data Quality Indicator	Example Acceptance Criteria
Representativeness	All recorded plant species and their frequencies of occurrence accurately reflect those typically found throughout the study area of interest. A cumulative species-area curve will be generated and evaluated to determine minimum sample-size requirements.
Comparability	All individuals collecting data have been trained, certified and determined competent to implement SOPs according to the project quality objectives.
Completeness	Valid and usable data are collected and reported for at least 95% of the sampling units for each sampling period.
Detectability	Targeted species presence and absence, regardless of abundance, are correctly detected 95% of the time.

As noted previously, representativeness, comparability and completeness must be built into the sampling design through careful selection of the locations to be sampled, number and size of the sampled plots, and procedures used by the field crews. Detectability is similar, in that a poorly designed study or a poorly trained crew may be incapable of detecting the presence or absence of a targeted species or condition. The need to design the sampling strategy around these four DQIs, however, does not preclude the development of qualitative or quantitative data quality acceptance criteria for each. As shown in **Exhibit 3-6**, it is possible to establish quantitative acceptance criteria for representativeness, completeness and detectability. The table also presents examples of qualitative criteria that can be used to verify that requirements designed to promote representativeness (i.e., a statistically sound sampling design) and comparability (i.e., confirmation of crew competency) have been met. In some cases, development of quantitative criteria for comparability also may be possible. Each ecological restoration project is different, and the acceptance criteria used to ensure that collected data are of sufficient quality should be uniquely tailored to specific project needs.

Graded Approach to QC

When selecting acceptance criteria and corresponding QC checks (described in Chapter 5), project planning teams should consider adopting a graded approach (Section 2.3) that:

- **Reflects the unique circumstances of their project, and**
- **Strikes an appropriate balance in the cost of quality equation (Section 2.2) such that the cost of QA/QC practices needed to ensure conformance with project requirements does not outweigh the costs of non-conformance (e.g., unreliable data, further degradation or wasted resources arising from incorrect conclusions).**

3.4.4 Stepwise Procedures for Determining Acceptance Criteria

We concluded the previous section by advising project planning teams to establish acceptance criteria that are tailored to the unique needs of their ecological restoration project. In this section, we suggest the following simple, stepwise approach as guidance for determining these acceptance criteria:

1. State project and sampling objectives in quantitative terms (SMART restoration project objectives and associated sampling objectives) as described in **Sections 3.2** and **3.3**.

2. List and describe each planned observation or measurement (i.e., target variable) and its units for data collection.

3. For each of these observations or measurements, identify the DQIs (i.e., precision, bias, accuracy, representativeness, comparability, completeness and detectability) that will be used to evaluate results.

4. For each planned observation or measurement, state the acceptance criteria associated with each DQI. These acceptance criteria should be stringent enough to control measurement error while also being achievable by properly trained staff using well-defined procedures.

5. Describe how quality will be evaluated. Refer to **Chapter 5**, Quality Control during Data Collection, for a discussion regarding tools such as calibration plots, hot checks, cold checks, blind checks and precision checks to evaluate data quality.

An example of how this stepwise procedure might be followed is shown in **Exhibit 3-7**. For illustrative purposes, this example builds on the first example project and sampling objectives presented in **Exhibit 3-3**. As noted in the exhibit, it is important not only to select acceptance criteria for each DQI, but also to determine how these acceptance criteria will be evaluated during and after data collection.

Exhibit 3-7. Example Stepwise Procedure for the Selection of Acceptance Criteria for an Ecological Restoration Monitoring Effort

Step	Example Approach to Accomplish This Step	
1. State objectives	Project Objective	Restore native willow to an average stem density of 2.5 /m^2 along 1,000 linear meters of riparian shoreline within the toe and transition zones after 2 years.
	Sampling Objective	The results of this monitoring effort will demonstrate the achievement of a mean density of 2.5 stems/m^2 (with 90% certainty or statistical power when, in fact, it is at least 20% greater than the target) along 1,000 linear meters of riparian shoreline within the toe and transition zones after 2 years, and with a 5% chance (α) of incorrectly concluding that the 2.5 stems/m^2 objective was reached when it, in fact, was not.
2. Identify target variables and corresponding units	Observations and Measurements	Willow stem density will be measured on thirty (30) 1m x 3m rectangular plots with plot markers geo-referenced using sub-meter accuracy GPS equipment.
3. Identify the DQIs that will be used to define data quality and determine usability	Precision	Defined collectively in terms based on error tolerance + frequency of compliance for each variable of interest.
	Bias	
	Accuracy	
	Representativeness	The degree to which data will represent the characteristic of the population being assessed.
	Comparability	The confidence that data collected in the project can be compared to or combined with other data collected for similar purposes.
	Completeness	The amount of valid data obtained from the project compared to the amount that was expected to be obtained under correct, normal conditions.
	Detectability	The sensitivity and specificity of the sampling design, measurement procedures, instrumentation and/or data collection personnel in detecting true differences in a target variable at ambient levels or when the measurement or observation of a target variable is dependent upon detecting the true occurrence of a rare, cryptic or secretive organism.

Exhibit 3-7. Example Stepwise Procedure for the Selection of Acceptance Criteria for an Ecological Restoration Monitoring Effort

Step	Example Approach to Accomplish This Step		
4. Select acceptance criteria for each DQI	Precision	Error Tolerance and Frequency of Compliance	*Willow Shrub ID (Genus and criteria):* • Genus (Salix) Level: 100% correct (error tolerance) 95% of the time (frequency of compliance) • Species level: 100% correct (error tolerance) 90% of the time (frequency of compliance) *Willow Shrub Stem Count*: ±10% (error tolerance) 95% of the time (frequency of compliance) *WGS84 GPS Position:* Latitude/Longitude Horizontal Accuracy within ±0.5 meter (error tolerance) 95% of the time (frequency of compliance)
	Bias		
	Accuracy		
	Representativeness		Data are obtained in accordance with a statistically sound sampling design, are complete and meet minimum data quality acceptance criteria for precision, bias, accuracy and detectability.
	Comparability		Data are determined to be representative and have been collected using equivalent procedures.
	Completeness		A minimum of 95% of plots provide valid data for each target variable.
	Detectability		*Willow Shrub ID:* Species level ID correctly identified 90% of the time when willow is truly present or not identified when truly absent. *Willow Shrub Stem Count:* A basal stem is counted 95% of the time when it is truly present, regardless of abundance, or is not counted when truly absent.
5. Describe how achievement of acceptance criteria will be evaluated	Precision		Conduct QC field checks (described in **Chapter 5**) for each target variable to estimate within- and between-crew precision, bias and accuracy and compare to established acceptance criteria.
	Bias		
	Accuracy		
	Representativeness		Obtain independent statistical review of sampling design, verify specified procedures were followed, and verify that acceptance criteria for precision, bias, accuracy and detectability were achieved for each target variable.
	Comparability		Verify that data are representative and were collected using equivalent procedures.
	Completeness		Calculate percent completeness among plots for each sample year to determine the amount of usable data (see **Chapter 6**) meeting or exceeding data quality acceptance criteria.
	Detectability		Evaluate QC data to estimate false positive and false negative rates for each target variable and compare to established acceptance criteria.

3.5 USE OF EXISTING DATA

Nearly all ecological restoration projects rely on existing data to facilitate project planning or to supplement data collected by the project team. The term **existing data** refers to any data that were not directly and specifically generated to support the purpose or decision at hand. This may include data obtained from the published literature; data obtained from other divisions within your organization; data obtained from other federal, state, or local agencies; and even data collected by your own organization for a completely different purpose. (See **Exhibit 3-8** for additional examples.) Other commonly used terms to describe existing data include "acquired data," "data from other sources," "historical data," "secondary source data" and "tertiary source data."

Exhibit 3-8. Examples of Existing Data

- Data collected by or for someone other than your organization and not under your organization's control
- Data collected by your organization or others for a purpose other than the current intended use
- Data published in the literature
- Voucher samples or specimens collected during prior studies
- Models and results from models developed by other organizations or for a different purpose
- Queries of states, organizations, trade associations, etc.
- Includes, but is not limited to, any of the following data that were not generated by or for your organization to support the decision at hand:
    - GIS data
    - Maps
    - Classification of habitat types
    - Economic and statistical data
    - Land use data
    - Field or laboratory results
    - Conceptual ecological models
    - Census data
    - Citizen science/crowd sourcing (e.g., eMammal, eBird, iNaturalist)

In many cases, existing data may be the only data available to determine historical or baseline conditions of the ecosystem being restored or monitored. In other cases, a different organization may already be gathering data similar to the data you need to support your project. Appropriate use of existing data can save time, money and other resources. Appropriate use, however, requires careful planning and subject matter expertise to ensure the data are both relevant and of sufficient quality to meet the needs of your project.

When conducting your own data gathering activities, you design the project in a way that focuses on collecting exactly what you need, the way you need it; in doing so, you are able to consider each of the DQIs described above (i.e., precision, accuracy, representativeness, comparability, completeness and detectability) and build them into your study design. This is not the case with existing data, and information about these indicators is often not published with the dataset. Even when information is available to demonstrate that data are of sufficient quality for their originally intended use, careful investigation of the methodology that was used may indicate that the data, while good, are not directly relevant to or appropriate for your project needs.

> **– Tip –**
> **EPA's *Assessment Factor Guidance: A Summary of General Assessment Factors for Evaluating the Quality of Scientific and Technical Information* (EPA 2003b) is a helpful resource for planning how to evaluate the quality and relevance of existing data.**

The DQI that is of particular critical concern when considering the use of existing data is comparability. Are the existing data comparable to the primary data collected? Common factors to consider when evaluating this comparability include, but are not limited to, the methodology used, timing, location, target populations, measurement error, and detection, quantitation or reporting limits. For example, imagine that you are designing a program to monitor the long-term effectiveness of ecological restoration projects in a geographically large area (e.g., coastal wetlands of western Lake Erie). It may be helpful to identify existing data that describe baseline conditions in the area, but it is also critical to ensure that the existing data are available on a geographic scale that allows for detection of statistically-significant differences over the time period of interest. As another example of geographic comparability, it is essential to verify that the location is correct if secondary data will be combined with more contemporary data by geographic coordinates. Plotting the points on a digital high-resolution map prior to use helps ensure that the data were actually collected in proximity of the current restoration project area.

Similarly, if different methodologies were used to collect the existing data than are planned for primary data collection, it could produce a systematic bias that leads to an erroneous conclusion that there was a change in the baseline condition when there was not (a Type 1 error). It may be beneficial to examine the methods used in past monitoring efforts and, if found to be acceptable, adopt the same methods for the current project. Doing so helps managers of new monitoring efforts protect project resources and alleviates the data comparability problem.

From a quality perspective, it is tempting to assume that data from the published literature and or government databases are reliable. Unfortunately, this is not always the case. Articles published in peer reviewed journals are often retracted, and even more are "corrected" after publication (Fang, Steen and Casadevall 2012). Even if an article has been corrected, the original version is often widely available. A 2012 study of 1,779 articles published in MEDLINE between 1973 and 2010, and subsequently retracted, revealed that 289 of the articles were still available on a non-publisher website; 27 of these were available in multiple locations (Davis 2012). Transparency and completeness also are concerns when relying on secondary data. In November 2015, researchers reported that they examined 100 studies in seven leading evolutionary and/or ecology journals with policies that require researchers to publicly archive data necessary to replicate study results. The research team found that more than half of the archived datasets were missing data or contained insufficient metadata (Roche et al. 2015). Data available in government databases also may require some investigation to verify they are of sufficient quality for your use. Some government databases capture data that are reported to the government by regulated entities, rather than data that have been generated and carefully evaluated by the agency that manages the database. In other cases, results may reflect average values compiled from multiple sources rather than independent measurements or observations (Kelly and Walters 2014). It is important to understand the impacts of such data manipulations on your project objectives. For these reasons, we recommend that users investigate existing data carefully to fully understand what is being reported; in many cases, this may require contacting the authors or managing agency for additional information.

Planning how you will use existing data is no less important than planning how you will collect new data, and the remainder of this section describes strategies to consider. While they may require a greater investment up front, these strategies are designed to reduce overall project costs by avoiding resources wasted in gathering existing data that, at best, are not useful and, at worst, can lead to inaccurate conclusions or inappropriate actions. An added benefit is that these strategies can increase the comparability and transparency of your project (Kelly and Walters 2014).

***Identify and document your project objectives*.** Note that this strategy (along with many others) also is required when planning to collect new data (see **Sections 3.1** and **3.2**). It is not possible to identify and gather the data you need without first knowing your project objectives, including any decisions that need to be made and the risks of reaching an inaccurate conclusion.

Determine and document the type of data you need and where you might find them. This seemingly simple activity actually involves a number of steps to ensure that your efforts are focused only on data that will directly support your project needs. These include:

- **Data Needs**: Prepare a detailed list of the specific data elements needed to support the project goals and objectives, and describe the scope of each element. For example, if you anticipate needing data that reflect a full range of conditions (e.g., multiple seasons, multiple species), include such details in your project plan. If your project includes development of one or more databases to capture existing data from other sources, identify and define each database field. The intent is to ensure that all individuals involved in data gathering and handling understand exactly what data are needed and to avoid misunderstandings about what a particular data element means.

- **Potential Data Sources**: Identify potential sources of existing data that that might support your project objectives. Examples include topographical maps, photographs, land use databases, data from studies previously conducted in the area of interest, meteorological data, published literature sources, etc. If literature searches are required, describe the search engines that will be used and key search terms. If databases will be used, describe each database in terms of who developed and operates it, the type of data it contains, and any search/query parameters to be used when extracting data from that source. Similarly, describe any other potential sources of data and the rationale for considering or using them. If you plan to obtain data by contacting specific individuals or organizations, document these plans.

- **Potential Data Constraints**: Identify any legal, security or other restrictions that might limit your application of or access to the data you need, and determine if these constraints can be resolved. Geospatial and remotely sensed data typically are made available with associated metadata documentation that can provide very detailed descriptions. Metadata often define use and/or application constraints that may include statements qualifying any limitations based on temporal variation, sensor detection limits, atmospheric or location error, or an inappropriate maximum scale of application. Other constraints associated with geospatial or remotely sensed data may relate to lack of "ground truthing" or other applications (e.g., simulation modeling) used to validate model results.

- **Criteria for Selecting Data Sources**: If you are able to identify a number of potential data sources, define criteria that you will use to determine which sources are most likely to meet your needs and prioritize their use. These source selection criteria will vary according to the unique needs of your project; examples include the comparability, reliability, applicability, format, access constraints, or even the quantity of data available in the candidate source. Regardless of the criteria you choose, explain the rating system that will be applied. For example, a project team may choose to use the age of the source as a criterion for applicability, with a qualitative rating scale in which data that are less than 3 years old are rated high, data between 3 and 8 years old are rated medium, and older data are rated low because they may be less representative of current conditions. As another example, the project team may apply a rating approach to the format of the data source, with electronically available sources rated higher than sources containing data that must be entered manually.

- **Data Value Selection Strategy**: Once you have screened potential data sources, you may find that several of the sources yield values for the data element(s) you need, only one source provides values for the data elements of interest, no sources yield values for the data elements of interest, or some sources address multiple data elements of interest. Therefore, it is helpful to define and document criteria and procedures that your project team can use to determine which value(s) are most appropriate for use. For example, if water quality measurements are available for your project site, and these data represent state monitoring results as well as volunteer monitoring data, will you prioritize one set of values over the other or capture all of these data?

- **Resolution of Data Gaps**: Projects that rely on existing data are often cyclical because it is difficult to gather all the data needed in a single step. This is true whether the existing data are being used for project planning purposes (e.g., to determine baseline conditions or determine project scope) or during project implementation (e.g., to fill gaps in data that will be collected by the project team). Initial data gathering efforts often yield important information, but also (1) leave gaps for data that are not available or could not be located and/or (2) reveal additional data needs that were not previously considered. For this reason, it is useful to establish a process that the team can follow to identify and address those gaps. Doing so during the planning stage will help the project team prepare for rather than respond to unanticipated data needs during or after project implementation.

- **Documentation and Recordkeeping**: We recommend that you also plan how you will document the results of your source selection process, including any sources that you decided against using and the rationale for not using them. Failure to do so can lead to accusations of "cherry picking" the data. This is especially important for projects that may face legal challenges and federally-funded projects that are subject to Data Quality Act requirements.

Identify and document how you will manage the data you gather. In most cases, data gathered from different sources reflect a variety of formats, reporting conventions, and other differences that require manipulations to make the data suitable for use in your project. The project planning team should identify standard conventions and data handling procedures in advance to ensure that all project team members understand and implement what is necessary to achieve project objectives.

- **Standardization of Data Elements**: Data gathered from multiple sources are often presented in different units and may be associated with a data element code or identity based on different nomenclature systems. Examples include, but are not limited to, the following:
    - Some datasets may present spatial data in degrees, minutes and seconds, while others present the same information in decimal degree format. Additionally, latitude and longitude values can be based on different geodetic systems. The most widely used is World Geodetic System (WGS), used by the Global Positioning System and last updated in 2004 (WGS 84, also known as WGS 1984, EPSG:4326). Earlier schemes included WGS 72, WGS 66, and WGS 60. Positional data extracted from existing sources that predate implementation of the 2004 standard will likely need to be converted to ensure data comparability, as will data extracted from sources that use an entirely different system.
    - Taxonomic nomenclature is a common type of data element in ecological restoration. In order to standardize the representation of species taxonomic identification within and across data management systems, the use of standardized numeric codes (e.g., Taxonomic Serial Number maintained by the Integrated Taxonomic Information System (ITIS)), alpha-numeric codes (e.g., Symbol Code maintained by the U.S. Department of Agriculture (USDA) Plant Database), or alpha codes (e.g., "alpha-code" listing maintained by the American Ornithologists Union (AOU)) can facilitate accurate comparisons and data element documentation. In addition to standardization of taxonomic codes, project teams also may need to consider inconsistencies in taxonomic resolution. Example considerations include using the lowest common resolution among available datasets, excluding data that are not at the appropriate resolution, or using multiple resolutions with appropriate adjustments to indicators or metrics.
    - Chemical data are often reported using different nomenclature, including trade names, International Union of Pure and Applied Chemistry (IUPAC) names, Chemical Abstract Service (CAS) names and CAS numbers. Project teams should standardize nomenclature to harmonize organic and inorganic chemical data that may be gathered and used in the project. For example, including a CAS number field in every record containing chemical data provides a means for comparing data for the same compound from different sources, even when each source uses a different naming convention.
    - Project teams also should identify the standard units that will be used for each data element and the specific processes that will be used to make any necessary conversions or comparisons. In doing so, project teams should consider simple imperial/metric conversions (e.g., ounces to grams) as well as the practical ability to convert all units and element identifiers to a common

standard. For example, some chemical results may be reported in wet weight, while others are reported in dry weight; these results are not directly comparable without additional information that may or may not be available.

- **Data Capture:** Planning activities should include consideration and documentation of the processes that will be used to manually enter data obtained from existing sources (i.e., data entry), and/or to merge or upload data from existing electronic sources into the project database. Both types of activities provide ample opportunities for error, including transcription errors associated with data entry and large-scale errors that can arise during file transfers when delimiters are not properly placed. Data gathering activities should include steps to both mitigate these problems and verify that errors have not occurred.

- **Data Storage and Manipulation:** Project planning teams should identify how existing data and its associated metadata will be stored, who will be responsible for access and maintenance, and how it will be incorporated with other project data. This includes documenting the hardware, software and personnel requirements for managing and incorporating the existing data into the project, and the quality management strategies that will be employed to ensure the integrity of the data is not compromised during data storage, access/retrieval, updates or other manipulation. Additional guidance regarding management of project data is provided in **Appendix A**.

Incorporate data quality validation and data analysis. After all data have been screened, gathered and entered into the database, it is important to examine the overall dataset to confirm it supports the project objectives, and document any quality issues associated with individual or overall results. In some cases, the gathered data may not meet your original quality objectives, but are the only data available. If such a situation arises, it is important to document the data limitations and their associated impacts on data analysis and the resulting decisions or conclusions (e.g., in planning documents, internal project files, data review files and final reports). **Chapter 6** provides additional information on data review and documentation strategies.

The project team also should determine and document exactly how the existing data will be used to support project decisions. This includes identifying and explaining what calculations will be performed (e.g., mean tree diameter, % change in crop cover), the exact data that will be used to perform these calculations, and the methodology for making the calculations. If calculations will be performed after elimination of data outliers, the project plan should define how outliers will be determined and the basis for their exclusion.

Assess the process. Finally, the project team should consider mechanisms that can be used to verify that data are located, extracted and validated in accordance with the project plans. For example, it may be helpful to include periodic assessments of any existing data that have been selected by the team to verify that decisions regarding the utility of the potential data sources, methods for documenting the data sources, and any data quality issues are appropriate. Similarly, it may be helpful to implement manual or automated queries that are designed to help identify errors that might arise from electronic data transfer processes.

3.6 PLANNING FOR DATA COLLECTION – CHECKLIST

The checklist below provides a summary list of overarching principles and aspects that should be considered and implemented when planning for data collection activities. As with any checklist, the listed items should not be interpreted or applied without comprehension of the supporting information. Users of this checklist are encouraged to read and understand the corresponding details that are provided throughout this chapter, and to implement these details using a graded approach that is commensurate with a project's scope, importance and available resources.

PLANNING FOR DATA COLLECTION – CHECKLIST

☐ **Define restoration project goals.**
  ☐ Consider project location, land ownership, restoration targets, current and desired condition, anticipated benefits of restoration, and expectations of funding resources.
  ☐ Develop succinct and clear project goals that include the:
    o subject or resource of concern (e.g., species, biotic community, ecosystem process, habitat);
    o corresponding attribute (e.g., species diversity, population size, process function);
    o conceptual target condition of the attribute (e.g., optimum, proper, natural, maximum); and
    o action to be taken relative to the target (e.g., restore, provide, achieve).
  ☐ Include short-term, mid-term and long-term goals.
  ☐ Ensure goals are realistic (i.e., achievable given site conditions and available resources).
 	
☐ **Define restoration project objectives.**
  ☐ Evaluate and have a clear understanding of the project goal.
  ☐ Assess biotic and abiotic pre-restoration conditions, and develop a conceptual model.
  ☐ Define restoration project objectives for each subject or resource of concern in the project goal.
    o Ensure each objective is specific, measurable, achievable, results-oriented and time-sensitive (SMART).
    o State each objective as either a targeted change from a baseline condition or the achievement of a threshold.
    o Specify the direction and quantity of change desired, pinpoint the specific geographic area, and identify a timeframe.
 	
☐ **Establish sampling objectives.**
  ☐ Consider and have a clear understanding of the project goal and objectives.
  ☐ Determine the effect size (size of change) that will be used to evaluate success and consider the risk of Type 1 and Type 2 errors.
  ☐ Ensure each objective clearly specifies 1) the degree of change that must be detected to define project success, and 2) the degree of certainty needed when stating that the change has been detected.

PLANNING FOR DATA COLLECTION – CHECKLIST
☐ **Determine data quality acceptance criteria.** ☐ Determine the types of data that will be collected (e.g., categorical, numerical), along with the specific data and corresponding units. ☐ Determine the data quality indicators (DQIs) that will be used to evaluate data quality (i.e., precision, bias, accuracy, representativeness, comparability, completeness and detectability). ☐ For each DQI, determine data quality acceptance criteria that are o Stringent enough to control error, and o Achievable by properly trained staff using well-defined procedures. ☐ Determine how DQIs will be evaluated using the acceptance criteria (i.e., what methods and data will be used).
☐ **Will existing (secondary) data be needed to support project planning or decisions? If yes,** ☐ Identify the type(s) of data needed. ☐ Determine criteria that will be used to select existing data. ☐ Identify and select sources of existing data. ☐ Evaluate existing data for use. o Are the data comparable to the primary data (e.g., similar or identical methodology used, location, target populations, measurement error, reporting units and limits)? o Are the data transparent, complete and understood in the context of your intended use? ☐ Are the data of sufficient quality for your intended use?

3.7 ADDITIONAL READINGS

- Canadian Parks Council. 2008. *Principles and Guidelines for Ecological Restoration in Canada's Protected Natural Areas*. Gatineau, Quebec. https://www.pc.gc.ca/en/nature/science/conservation/ie-ei/re-er/pag-pel (online version) or http://www.ccea.org/wp-content/uploads/2015/10/RP_Principles-and-Guidelines-for-Ecological-Restoration-in-Canadas-Protected-Natural-Areas.pdf (pdf version).

- Keenleyside, Karen A., Nigel Dudley, Stephanie Cairns, Carol M. Hall, and Sue Stolton. 2012. *Ecological Restoration for Protected Areas: Principles, Guidelines and Best Practices*. Gland, Switzerland: IUCN. x + 120pp. http://www.ser.org/page/SERDocuments.

- McDonald, Tein, George D. Gann, Justin Jonson, Kingsley W. Dixon. 2016. *International Standards for the Practice of Ecological Restoration-Including Principles and Key Concepts, First Edition*. Society for Ecological Restoration, Washington, D.C. http://www.ser.org/page/SERDocuments.

- Michener, William 2008. *Quantitatively Evaluating Restoration Experiments: Research Design, Statistical Analysis, and Data Management Considerations*. Restoration Ecology 5(4):324-337. doi: 10.1046/j.1526-100X.1997.00546.x.

- The National Academies of Sciences, Engineering and Medicine. 2017. *Effective Monitoring to Evaluate Ecological Restoration in the Gulf of Mexico.* Washington, DC: The National Academies Press. doi: 10.17226/23476. http://dels.nas.edu/Report/Effective-Monitoring-Evaluate-Ecological-Restoration/23476?bname=osb.

CHAPTER 4 PREPARING FOR DATA COLLECTION

In **Chapter 3**, we focused on QA strategies for developing a monitoring program designed to evaluate the effectiveness of ecological restoration activities and help guide future decisions. These strategies begin with carefully defining specific, measureable, achievable, results-oriented and time-sensitive (SMART) project objectives that support the overall restoration project goals, followed by development of sampling (monitoring) objectives and a monitoring program designed to determine if the desired change has occurred within acceptable limits of uncertainty (error). We noted that sources of uncertainty include the sampled population itself (largely addressed through the monitoring program's sampling design) and the data collection processes used. We also recommended that project planning teams identify data quality indicators (DQIs) and corresponding acceptance criteria as QC tools to define and control measurement error. In this chapter, we build on the planning foundation laid in **Chapter 3** by describing a suite of QA strategies that project planning teams should address before crews are deployed to the field. These include:

- identifying, developing or modifying standard operating procedures (SOPs) that are tailored to the needs of the monitoring program (**Section 4.1**);
- verifying that personnel who will be responsible for conducting field activities have received training and demonstrated competency in the activities they will perform before they are allowed to gather data without supervision (**Section 4.2**);
- addressing site permit and other field logistics needs before the sampling season is scheduled to begin (**Section 4.3**); and
- making arrangements for analysis of field samples by laboratories that have demonstrated competency in performing the required determinations (**Section 4.4**).

4.1 STANDARD OPERATING PROCEDURES

Much of the data collected in support of ecological restoration projects is based on best professional judgment, which is prone to measurement error due to subjectivity associated with observer assessments, and the limited ability to quantify and/or control many environmental factors. For ecological restoration monitoring to be effective, SOPs need to be accurate, complete, concise, understandable and available to all project staff prior to data collection and handling activities. The importance of well-written SOPs cannot be overstated; time and resources can be significantly impacted by failing to provide these documents. Similarly, if SOPs are provided, but the instructions are not appropriate, understood and followed consistently, the resulting data will likely be inaccurate and could have significant impacts on the quality of results, conclusions and decisions.

In practice, SOPs may be identified alternatively, as manuals, methods, protocols, work instructions or other names. These documents play a critical role in maximizing the quality of ecological restoration monitoring data by:

- promoting efficiency;

- minimizing miscommunication;
- helping ensure procedures are performed consistently by multiple individuals and over long periods of time (both within and, where applicable, across projects);
- providing a basis for training staff;
- serving as references if confusion arises in the field or during data transfer, reduction, review, extraction or analysis; and
- serving as references to data users.

> **Caution!**
> Even if SOPs fulfill all of the desirable qualities discussed in this section, they are of little value if they are not made readily available to individuals involved in data collection and documentation, personnel are not trained in their use, or the procedures are not followed.

Cumulatively, these SOP attributes increase confidence that (1) any changes detected in the variables being monitored reflect an actual change stemming from the restoration activities and (2) actual changes are not masked by inconsistent or incorrect results (Oakley, Boudreau, and Humphrey 2001). A library of SOPs also can serve as a useful tool for project planning teams. The subsections that follow describe the influence they can have on data quality, characteristics of effective SOPs, recommendations for evaluating and comparing existing SOPs to the project-specific needs, and sources of example SOPs. Although these subsections focus heavily on field and laboratory procedures, SOPs are not limited to data collection activities. For example, the Quality Assurance Oversight Team (QAOT) governed by the Comprehensive Everglades Restoration Plan developed an SOP document to guide QAOT members as they develop and implement SOPs for a variety of procedures and activities. (https://evergladesrestoration.gov/content/qaot/QAOT_SOPs_020918.pdf) SOPs also are useful tools in ensuring the consistency and accuracy of other data handling activities, including compilation of data into project databases, and data review, assessment, and reporting. In general, any activities that are (1) related to the collection, handling, or use of samples or data and/or (2) will be repeated over multiple days or by multiple individuals are candidates for an SOP.

4.1.1 Influence of SOPs on Data Quality

As discussed in **Chapter 3**, project planning teams should identify DQIs and corresponding acceptance criteria to ensure that conclusions and decisions are based on accurate and reliable data; SOPs are a critical tool for controlling data collection processes so that resulting data fall within these established criteria. The influence of SOPs on the ability to meet acceptance criteria for the seven DQIs identified in **Chapter 3** is discussed below.

Representativeness: Ensuring a high level of representativeness depends on designing a monitoring plan that includes sampling locations that have been selected to accurately reflect the population of interest, and careful selection or preparation of SOPs to implement that plan. Project planners should ensure the SOPs allow for collection of data that are representative of the ecosystem being monitored by verifying that the SOPs are (1) consistent with the project goals and the corresponding project and sampling objectives (**Chapter 3**), (2) applicable to the project site locations, (3) applicable to the ecological community and the individual species of concern, and (4) applicable to anticipated ranges in environmental conditions and associated spatial and temporal variability. Project planners may use existing SOPs that have been previously developed for national, regional, or project-specific applications, and adapt those SOPs as necessary to address the specific needs of their project.

Comparability: Many of the variables measured or observed in ecological restoration projects are procedurally defined, meaning that each value is tied directly to the procedure used to collect it. For instance, model results for fish population estimates can differ significantly depending upon whether fish are marked and recaptured using electrofishing or netting. Even slight variations within each procedure (such as the voltage used, the shocking time in electrofishing surveys or net placement) can result in substantial variability. To ensure data comparability within a project, SOPs must be adapted or developed, and followed consistently throughout the project. Strict adherence to SOPs across different field crews, different field sites, and different seasons or years is important in meeting comparability needs. Well-documented SOPs, including those used to select sampling site locations, can assist in evaluating the comparability of data between different projects; an evaluation of the SOPs used can determine whether the results collected can be appropriately compared.

Completeness: SOPs for field and laboratory activities typically include step-by-step procedures for collecting samples or data, as well as forms for recording observations, measurements, and ancillary information. Together, these are important tools in maximizing the percentage of collected data that will be considered valid and usable. The procedures are designed to ensure collection of representative and accurate data when followed correctly, and the reporting forms are designed to facilitate accurate and consistent capture of data, including qualifying or ancillary information such as the date and time of collection, weather conditions, and vegetative status of target plant species (e.g., flowering, fruiting, senescence or die-back). Thus, when used correctly, SOPs can increase the chances of obtaining a complete set of valid data consistent with the monitoring design.

Precision, Bias and Accuracy: Field and laboratory SOPs should include detailed, step-by-step procedural instructions for all activities associated with collecting, handling and shipping samples, making measurements and observations, and documenting results. Before using them in a project, the procedures should be tested to verify that they are clear enough to be understood and applied consistently by different people with different levels of experience. Such testing can help identify areas that require further clarification to minimize bias and enhance precision and accuracy among project personnel. SOPs also should (1) document the acceptance criteria that have been established, and (2) identify the QC checks (see **Chapter 5**) or samples that will be used to evaluate whether the data gathered meet the specified criteria.

Detectability*:* In many cases, the details provided in an SOP can have a direct impact on detectability. Specific criteria for identifying a species, for example, will impact species counts. If the criteria include descriptions or definitions for species identification that are either too limited or too broad, resulting species counts could include false negatives (Type 2 error, or β) or false positives (Type 1 error, or α).

4.1.2 Characteristics of Effective SOPs

Ecological monitoring protocols vary widely in both content and format, which leads to confusion about the information they should contain and how they should be formatted (Oakley, Boudreau, and Humphrey 2001). For the purpose of this discussion, we are referring to any detailed instructions that are designed and implemented to ensure the uniformity and consistency of a specific activity or set of activities. While there is no universally accepted format, good SOPs (or their equivalent) typically include elements and topics such as those shown in **Exhibit 4-1**, and discussed below.

Exhibit 4-1. Recommended SOP Contents		
UPFRONT INFORMATION • Title • Identification number (e.g., SOP FS-34) • Version number, revision date, revision history • Name of the organization • Table of contents • Acronyms, abbreviations, and explanations or definitions of uncommon terms/phrases	**CONTENT** • Purpose, scope and applicability • Schedule and timing of data collection • Health and safety warnings • Cautions and interferences • Required equipment and supplies • Personnel qualifications and responsibilities • Detailed procedures • QA/QC, including o Type and frequency/timing of QC checks o Acceptance criteria o Corrective actions • Data and records management (including data entry; reporting units; data uploading, handling, and storage) • Pertinent references • Charts and maps • Graphic representations (e.g., diagrams, illustrations)	**APPENDICES and ATTACHMENTS** • Data sheets, forms and checklists • Reference tables/materials

Scope and Level of Detail: SOPs vary in scope from those covering a broad range of activities to those targeting a single aspect of the project (e.g., field crew training, establishing and using sampling grids, catching and processing specimens, transcribing data from field forms) or a particular data need (e.g., tree diameter measurements, species counts, laboratory analysis of samples for nutrient concentrations). Regardless of their scope, SOPs should be written in a clear, concise manner that provides an understanding of the processes and corresponding step-by-step procedures that can be understood and applied by those involved in data collection, management and/or use.

Content: To ensure that data meet the quality criteria, it is essential that SOPs include detailed instructions regarding implementation of the procedures as well as the use, maintenance and limitations of any equipment. For example, if requirements regarding the location, time period and weather during which bird species are to be identified and counted are not sufficiently specified or followed, the consistency between results generated by multiple field team members will be compromised, with results potentially duplicated or missed. In cases where equipment is used, SOPs should provide details regarding the equipment specifications, such as minimum optical quality requirements for binoculars, camera resolution, recording quality and length, and minimum units of time.

Detailed step-by-step activities included in data collection SOPs often include the purpose, areal extent and time period in which data are collected. If data are required for a specific set of plant species, for example, the SOP should include the specific area of interest and the time frame during which the species are expected to exhibit key features (i.e., flowers, fruiting bodies and leaf-out). Ideally, and as shown in **Exhibit 4-1**, SOPs will include all corresponding QA/QC procedures, references, reporting forms, units of measure, and quality objectives associated with any data collected. References should be provided for specific field guides and taxonomic keys that will be used. When practical, some of these guides may be included as actual attachments to the SOP, along with standardized field or laboratory data forms.

SOPs should describe procedures for using forms or other data collection and reporting tools. As was noted in **Section 4.1.1**, pre-developed, standardized field reporting forms are often helpful in ensuring the completeness and comparability of project data, as they make it easier for field crews to collect the appropriate data without forgetting or missing an important activity or data element. Laboratory reporting forms can be similarly helpful in standardizing nomenclature, capturing all required data, and presenting summary-level information. Standardized forms provide consistency within and between different field and laboratory crews, and eventually aid in data verification and validation. Field data collection forms often include reference pictures, charts, or tables that can be used to document measurements and observations, and aid in subjective field assessments. For example, pictures of percent ground cover or percent canopy cover can help in calibrating data collection across field crews and across individual field staff. SOPs for ecological restoration projects that use portable data recorders (PDRs) to streamline data capture should include detailed instructions regarding their use. These hand-held electronic data recorders (including smart phones, tablets, and global positioning system (GPS) technology) also can be programmed to include pick lists and QA/QC checks to ensure the data entered are specific (e.g., assigned to one or more of a pre-selected list of options) and reasonable (e.g., within a specified range of temperature or wind velocity). If used, these tools can significantly assist field personnel in meeting acceptance criteria established for DQIs.

In addition to items discussed above, SOPs can include checklists, equations, charts and maps, definitions of numeric or letter codes, reference tables, and graphic representations, all of which facilitate data collection and enhance data quality. **Exhibit 4-2** provides examples of common applications of these SOP items.

Exhibit 4-2. Example Applications of Selected SOP Items

SOP Items	Example Applications
Checklists	Documentation and records management, hiring, procurement and preparation of equipment and supplies, field gear and equipment, scheduling, training, and crew qualifications
Equations	Tree height, tree basal area, horizontal distance, unit conversion

Exhibit 4-2. Example Applications of Selected SOP Items	
SOP Items	**Example Applications**
Charts and Maps	Plot map, including sub-plot, transect, and plot center coordinates; ground cover density determination; vegetation count boundaries; sampling rotations; species counts; land cover type(s)
Definitions, Keys and Codes	Decay class, ground cover substrate classification, % cover class, branch density, soil texture, vegetation type, herbivory, crown class, damage status and location, species abundance, sky conditions, wind speed, background noise, bird detection type, detection symbols, photograph descriptors, data queries
Reference tables	Soil material, environmental features, landforms, insects and disease-causing agents, sampling point locations (and random sample numbers), American Ornithologists Union (AOU) bird codes, U.S. Department of Agriculture (USDA) Plant Database plant symbol codes, National Land Cover Database (NLCD) Classifications
Graphic representations	Tree crown classes, tree form classes, sampling methods, measurement methods, species identification, plant or animal anatomy

SOP Identifiers and Version Control: Regardless of the format and exact content, all SOPs should be treated as controlled documents with a specific assigned document number, version number, and issue and approval date(s) to ensure that multiple users are following the same, current protocols. The SOP number and/or abbreviated title, version number, and date should be captured on each page along with the page number (preferably in a "page # of #" format). Ideally, project managers should complete the following tasks:

- Include a brief "revision history" page that summarizes the changes made to each version of the SOP (typically behind the title page or at the end of the document), which can help users quickly identify areas in which the procedures have changed.
- Ensure that SOPs are peer reviewed and validated prior to use to verify that all procedures are clearly understood, consistently implemented by multiple staff, applicable to the project at hand, and expected to yield the desired results.
- Establish and implement a process for managing and distributing SOPs and other controlled documents so that only the most recent approved versions of the documents are available for use, which facilitates interpretation of the data and ensures consistency when there is a change in data collection personnel.
- Maintain a log of the changes made to an approved SOP in the project files, which can provide valuable information when comparing data collected during different time periods.

4.1.3 Evaluation and Comparison of SOPs

Planning teams involved in selecting, modifying or developing SOPs need to balance efficiency with sufficiency to ensure SOPs are logistically practical, are adequately informative, and facilitate achievement of sampling and data quality objectives while avoiding the collection of redundant or inaccurate data (Stapanian, Bur, and Adams 2007). Planning teams should evaluate SOPs prior to their use to make sure all elements are addressed, activities pertaining to data collection and handling are specified and appropriately detailed, and information about recently implemented procedures or lessons learned has been incorporated.

In some cases, existing SOPs may be readily available for direct application to a project. In other cases, SOPs will need to be developed, or existing SOPs will need to be modified (or partitioned from an SOP designed for broader application) in order to meet the specific project needs, location, schedules, resources and/or objectives (Stapanian et al. 2016). Depending on the unique needs of the project, the planning team can evaluate existing SOPs to determine if they can be used as-is (particularly where consistency with previous efforts is important) or modified to meet the specific needs of the project, rather than creating SOPs from scratch.

As described in **Chapter 3**, acceptance criteria should be project-specific and driven by comprehensive planning that includes restoration goals and corresponding project and sampling objectives. Therefore, the elements of an existing SOP should not drive the QC acceptance criteria for the project. Instead, new SOPs should be developed or existing SOPs adapted to reflect project-specific QC elements and acceptance criteria. Although in some cases it may be advantageous to use QC criteria from existing SOPs that are more stringent than needed, criteria should only be adopted if appropriate given the sampling objectives, schedule and resources.

Existing SOPs

Using and adapting existing SOPs to meet project needs can save time and money, and facilitate data comparisons across multiple projects. Project managers should ensure, however that the SOPs used will meet the specific needs of the project.

Although it might be preferable to have common SOPs that can be used across similar projects, there may be cases where an SOP could and should be enhanced to address a specific project or location. Three examples are provided below.

- Field techniques for counting birds differ between coastal areas, wetlands, and terrestrial environments.
- Gill netting, which is an effective way to assess pelagic fish species populations in open lake waters, would not be practical (or effective) in shallow littoral zones along a lake shore that would require consideration of alternative techniques (e.g., fyke-nets or seines).
- Western U.S. projects address trees that are typically larger than those addressed in other areas; the U.S. Forest Service (USFS) has developed a big tree protocol to address this difference, allowing field staff to remove the use of subplots and address only trees of a certain diameter within the entire larger sample frame.

Planning teams may decide to modify SOPs based on lessons learned. For example, an SOP for collecting understory vegetation in the USFS' National Forest Health Monitoring program originally included estimating the proportion of cover from trees ≥ 3 meters tall in a 1-m^2 quadrat. After the pilot season, it was determined that the precision among crews was unacceptable, and the desired information could be derived from other, more reliable measurements that were being collected at the same site. Removing this measurement saved considerable time and money and provided a more reliable dataset (Stapanian, Cline, and Cassell 1994, 11.1-11.44; Gartner and Schulz 2009, 55-78).

Similarly, planning teams may be confronted with a decision to switch to a newer, cheaper, faster or more accurate procedure. While the decision to switch has obvious advantages, the impact of such changes on the ability to evaluate long-term trends in the data should be carefully considered. Any changes in data collection methodology should be documented and, if possible, a comparison study between the old and the new procedures should be conducted to allow for interpretation of trends and changes using data gathered with both the original and new methodology. Comparison studies are recommended, particularly in cases where long-term use of a given procedure exists or is anticipated. These studies can involve collecting data using both the new and old procedures for one or multiple field seasons. While this will increase the costs and level of effort in the short term, it can provide huge benefits in the long term. Before deciding to modify data collection procedures, planning teams should consult with a qualified statistician and potential data users. In addition, and as noted above, a revision history page should be included to summarize the changes made so that future data users can easily identify and evaluate the impact of any changes that have been made over time.

In large-scale projects involving multiple agencies or parties, it may be impractical for the activities of all participants to conform to the same SOP. In certain cases, results can be "corrected" or adjusted based on a designated standard. An example is provided below.

- In western Lake Erie, catches from annual bottom trawl surveys conducted by several agencies are used to estimate lake-wide abundances of yellow perch (*Perca flavescens*) and walleye (*Sander vitreum*) (Forage Task Group 2013). Each agency uses a different vessel and different SOPs (e.g., combination of net configuration, trawling speed, and time the trawl is on bottom) that reflect agency-specific procedures that have been used for decades. For this reason, combining results is difficult, and an interagency calibration study was performed to address this challenge (Tyson et al. 2006). As a result of the study, one vessel was designated as the "standard" vessel, which allows catches of yellow perch and walleye from the other vessels to be adjusted according to the catch from the standard vessel. Consistency with each agency's long-term data also is maintained because the individual SOPs used by each agency were not changed.

Even in smaller scale projects (e.g., stream reach, coastal shoreline, estuary), certain circumstances may prevent collaborators from complying with the same standards and procedures. Two examples are provided below.

- Restoration of estuarine ecosystems that border two or more political boundaries (e.g., national, state, tribal, county) may require collaborators to comply with policies regarding potential impacts of sampling procedures that risk incidental take of regulated species or disturbance of historic landmarks or archeological sites.

- Physiographic differences between sampling locations may require an allowance for the use of alternative equipment to quantify the same ecological variable. Examples include (1) use of alternate fish-sampling gear as a result of differences in aquatic vegetation structure or water depth, (2) use of alternate methods to monitor coastal wetland bird or amphibian populations across sites that differ significantly in vegetation, or (3) wind or wave energy and its associated impact on species detection while conducting visual and aural surveys.

In any case, it is imperative that differences in procedural standards among collaborators are clearly described and documented for consistent application and implementation to ensure reproducibility and to maintain minimum data quality standards that meet the data quality acceptance criteria.

4.1.4 Examples of SOPs

Exhibit 4-3 lists some of the types of SOPs that might be used to support the example projects discussed in **Chapter 3**, **Exhibit 3-3**. Specific examples of sources of SOPs used in actual ecological monitoring programs are provided at the end of this section.

Exhibit 4-3. Example Data Collection SOPs Needed to Support Sampling Objectives	
Example Sampling Objectives (from Exhibit 3-3)	**Example Corresponding SOPs**
• Demonstrate achievement of a mean density of 2.5 stems/m^2 (with 90% certainty when the true stem density is at least 20% greater than the targeted 2.5 stems/m^2) along 1,000 linear meters of riparian shoreline within the toe and transition zones after 2 years, and with a 5% chance (α) of incorrectly concluding that the 2.5 stems/ m^2 objective was reached when it in fact was not. • Demonstrate a reduction in the rate of stream channel widening (with 80% certainty when the rate is at least 80%) along 1,000 linear meters of riparian shoreline after 6 years, and with a 5% chance (α) of incorrectly concluding that the rate has been reduced when in fact it did not. • Demonstrate an increase in migratory songbirds (with 80% certainty when the increase is at least 40%) within the 1,000 linear meters of restored riparian habitat after 6 years and with a 5% chance (α) of incorrectly concluding that the abundance had increased when it in fact did not.	• Use of GPS and topographic surveys • Plot selection and marking • Field identification, measurement and mapping of native vegetative species • Monitoring vegetative cover • Stream channel measurement and monitoring • Identification and monitoring abundance of migratory songbirds • Data collection and documentation • Photographic image processing and management

Exhibit 4-3. Example Data Collection SOPs Needed to Support Sampling Objectives	
Example Sampling Objectives (from Exhibit 3-3)	**Example Corresponding SOPs**
• Assess whether the relative cover of saturated soils has been increased to greater than 50% within the project site after 2 years (and demonstrate with 80% certainty an increase greater than 60%) with a 5% chance (α) of incorrectly concluding that the relative cover has increased when in fact it did not. • Assess whether the total reed canarygrass cover has been reduced to less than 10% across the 15-acre wet prairie after eight years (and demonstrate with 80% certainty a reduction in total cover to less than 5%) with a 5% chance (α) of incorrectly concluding that the % cover has decreased to below 10% when in fact it did not. • Assess whether the total cover of native wet prairie plant species with floristic quality assessment (FQA) coefficient of conservatism scores greater than 5 has increased after 12 years (and demonstrate with 80% certainty if it has increased by at least 75%) with a 5% chance (α) of incorrectly concluding that the relative cover has increased when in fact it has not.	• GPS use • Plot selection and marking • Prescriptions for herbicide or mechanical control • Identification, measurement and monitoring coverage of saturated soils • Identification, measurement and monitoring vegetative cover, density, species and abundance • Geographic Information System (GIS) data entry and analysis • Voucher specimen identification and processing • Data collection and documentation
• Assess whether the total cover of an established Emerald Ash Borer (EAB)-resilient native woodland has less than 20% representation by *Fraxinus* spp. after 6 years (and demonstrate with 80% certainty when the composition is 10% or less); accept a 5% chance (α) of incorrectly concluding that the cover decreased to below 20% when in fact it did not.	• GPS use • Plot selection and marking • Field identification and counts of native vegetation • Monitoring vegetative cover • Photographic image processing and management • Data collection and documentation

The following examples are not intended to be an exhaustive list of all ecological restoration project SOPs, nor are inclusions intended as a specific endorsement. The information is intended to provide examples of SOPs, field manuals, and other formal protocol formats that may help planning teams in designing SOPs.

- The National Park Service provides a library of SOPs that are specific to ecological monitoring in the Great Lakes, on the Great Lakes Inventory and Monitoring Network website: http://science.nature.nps.gov/im/units/glkn/monitor. From this site, example protocols are available for monitoring amphibians, climate, diatoms, water quality, land birds, land cover and use, persistent contaminants and vegetation.

- A National Parks Service protocol for monitoring land birds at two National Parks includes SOPs for (1) preparations and setting up equipment before the field season, (2) training field crew members, (3) using GPS, (4) establishing and marking sampling plots, (5) conducting variable circular plot counts, (6) documenting habitat variables, (7) managing data, (8) analyzing data, (9) reporting data/results, (10) storing equipment, and (11) revising protocols (Oakley, Thomas, and Fancy 2003). http://science.nature.nps.gov/im/reports/index.cfm?tab=1#products

- The Great Lakes Inventory and Monitoring Network website, http://science.nature.nps.gov/im/units/glkn/monitor/index.cfm, posts SOPs covering numerous topics, including sampling designs, field preparation, hiring and training data collectors, locating sampling points, conducting bird counts, monitoring vegetation, and data management and reporting.

- EPA manages several surveys of the nation's aquatic resources; each survey uses standardized field and laboratory methods designed to result in unbiased estimates. Methods and manuals used in each of these surveys can be found at the following links:
  - https://www.epa.gov/national-aquatic-resource-surveys/ncca for the National Coastal Condition Assessment
  - https://www.epa.gov/national-aquatic-resource-surveys/nrsa for the National Rivers and Streams Assessment
  - https://www.epa.gov/national-aquatic-resource-surveys/nla for the National Lakes Assessment
  - http://water.epa.gov/type/wetlands/assessment/survey/index.cfm for the National Wetlands Condition Assessment

- Environment Canada has compiled a suite of protocols designed to help research teams detect, describe, and report on ecosystem changes and promote standardized study designs, sampling procedures, sample and data analysis, and reporting. These protocols are available at https://ec.gc.ca/faunescience-wildlifescience/default.asp?lang=En&n=E19163B6-1#Ecologicalmonitoringprotocols.

- The U.S. Geological Survey (USGS) Forest Vegetation Monitoring Protocol for National Parks in the North Coast and Cascades Network (2009) (https://pubs.usgs.gov/tm/tm2a8/pdf/tm2a8.pdf) includes 29 SOPs covering everything from records management through project data and posting, and includes SOPs for hiring, orienting and training personnel; establishing and marking monitoring plots; preparing information packets and equipment; recording visit details; measuring and mapping; handling field forms; entering, verifying, reviewing and certifying data; developing metadata; and debriefing and close out.

- Wisconsin Frog and Toad Survey. http://wiatri.net/inventory/frogtoadsurvey/Volunteer/PDFs/WFTS_manual.pdf

- Field and Laboratory Methods for using the MAIS (Macroinvertebrate Aggregated Index for Streams) in Rapid Bioassessment of Ohio Streams. http://www.epa.state.oh.us/portals/35/credibledata/references/MAIS_training_manual_2007.pdf

- Ohio Rapid Assessment Method for Wetlands Quality (Mack 2001).

- Xerces Society-Bee Monitoring Protocol. http://www.xerces.org/wp-content/uploads/2014/09/StreamlinedBeeMonitoring_web.pdf

- Published Bird Survey Protocol. http://images.library.wisc.edu/EcoNatRes/EFacs/PassPigeon/ppv59no03/reference/econatres.pp59n03.rhowe.pdf

4.2 TRAINING AND CERTIFICATION OF FIELD PERSONNEL

Wetland Vegetation Sampling; Environment Canada

Strategies to control the quality of ecological restoration project data begin in the project planning phase and continue throughout all phases of the project's lifecycle. Data quality is particularly sensitive during the data collection phase when personnel are involved in field sampling, measurement and observation activities; these personnel must have the basic skills and training necessary to ensure they are able to safely and accurately perform assigned tasks. Inadequately trained individuals can increase data variability and inflate measurement error, significantly impacting project decision making and outcomes. This is particularly important for observer-determined data that do not rely on a calibrated piece of equipment. Human observation can be subjective and variable by its nature, and proper and continuous training is critical to ensure that data are collected based on objective assessments. Even calibrated instruments can yield improper results when used by insufficiently trained individuals. Ensuring that field crews are properly trained will increase project efficiency and mitigate unanticipated adverse impacts on schedules and budgets. In general terms, appropriate training consists of instruction, practice, and skills evaluation and/or certification prior to data collection. If crew capabilities are not periodically assessed throughout data collection, initial training should be supplemented by periodic refresher or "booster" training. Details regarding these aspects of training are provided throughout this section.

4.2.1 Crew Qualifications

Many ecological restoration projects require field crew members to have a level of existing expertise along with project-specific training. For example, bird surveys often require individuals who are experts in detecting and identifying birds using refined visual and aural skills under less than ideal conditions; studies have shown that human bias is one of the most noteworthy factors affecting the accuracy of trend estimates for songbird populations (Kepler and Scott 1981, 366-371; Baker and Sauer 1995), demonstrating the need for a well-trained and experienced field crew.

Some field data collection activities may require less expertise and skill than others. In forest surveys, for example, assessing crown density (how much light is blocked by the tree crown) is challenging, and focused, extensive training is required. In contrast, assessing crown dieback (estimate of mortality of branches with fine twigs) is often easy for field crews and the percent of such observations within a project's error tolerance limits is usually good. The USFS *Forest Inventory and Analysis (FIA) National Assessment of Data Quality for Forest Health Indicators* concluded that, while training and protocols were producing acceptable levels of repeatability for crown dieback, either more training was needed or the acceptance criteria needed to be reevaluated. **Exhibit 4-4** shows the results of 2,221 data records that were included in this assessment, along with corresponding statistical results.

Exhibit 4-4. Repeatability Statistics for Tree Crown Density and Crown Dieback						
Variable	FIA Region[1]	% within error tolerance	95% Confidence Interval	Mean difference (QA crew – field crew)	RMSE[2]	Records
Crown density	SRS	78.9	75.0 – 82.4	1.0	11.7	493
	NE	60.7	54.6 – 66.6	-2.8	14.9	270
	NC	78.6	75.0 – 81.9	-0.5	11.0	579
	IW	67.8	64.4 – 71.1	0.0	13.4	789
	PNW	67.8	57.1 – 77.2	-3.1	13.0	90
	All	72.2	70.3 – 74.1	-0.4	12.6	2,221
Crown dieback	SRS	97.4	95.5 – 98.6	-0.2	6.3	493
	NE	90.4	86.2 – 93.6	-1.2	8.5	270
	NC	96.9	95.1 – 98.1	0.0	7.4	579
	IW	95.9	94.3 – 97.2	0.9	7.6	789
	PNW	96.7	90.6 – 99.3	-0.9	6.7	90
	All	95.9	94.9 – 96.6	0.1	7.4	2,221

[1]SRS – Southern; NE – Northeast; NC – North Central; IW – Interior West; PNW – Pacific Northwest
[2]RMSE – Root mean square difference *[sic]*
Source: Amacher et al. 2009

As another example, surveys that require field crews to collect material that will be examined later by one or more experts in species taxonomy and identification (e.g., benthic or plankton samples) or analyzed by chemists in a laboratory (e.g., chemical composition of soils sampled from a restored wetland) require individuals who are well-trained in conducting the sampling procedures, but are not necessarily experts in species identification or chemical analysis.

Planning teams should carefully consider the qualifications and skills needed for each field activity, and develop procedures to ensure that the data, voucher specimens and samples will be collected by qualified personnel. Some organizations have found it useful to develop SOPs that are specifically designed to address hiring, training and certification. Such SOPs may include interviewing procedures and appropriate interview questions, certification requirements, assessment of physical capabilities, proficiency assessments and ranking. In addition to practices that focus on qualifications when hiring, organizations should conduct training and periodic assessments to verify that the training programs and specified qualifications are appropriate. Assessments can be as simple as confirming that data collected by staff who have the required qualifications and training meet the specified project needs and data acceptance criteria. Frequent failures in meeting acceptance criteria suggest that the combination of qualifications and training is insufficient, the SOPs are incorrect or inadequate, and/or the acceptance criteria established for the project may be overly optimistic.

4.2.2 Pre-Training Preparation

We recommend that potential field crew members receive and be required to study field manuals, SOPs and project overviews before classroom or field-based training sessions begin. Where applicable, trainees should be provided with any field gear, equipment and a list of species that are likely to be encountered and/or monitored, and should be required to possess prior monitoring experience and knowledge related to any target species in advance of their formal training. Trainees also should be encouraged to reach out to the technical lead(s) prior to the training for clarification of questions they may have regarding the procedures, and should plan to bring equipment, appropriate field clothing, and field guides with them to each day of training. Training will be more effective with such preparation because more time can be devoted to practicing data collection and coordinating crew activities.

4.2.3 Classroom and Field Instruction

It is extremely useful to provide instruction regarding data collection, particularly in regards to visual and audio identification skills in the classroom, with subsequent reinforcement in the field. Participants should be provided with SOPs and lists of any species that will be observed or measured, shown specimens, trained in the use of the SOPs, and trained to observe and recognize species that are likely to be encountered. For example, trainees for the understory vegetation data collection in the USFS FIA Program are supplied with herbarium specimens of the region's common species to study in the classroom, and hone their identification skills each day during a week-long training period at various sites under the supervision of an expert. During classroom training sessions, trainers may note that trainees are weak in certain SOP elements, and should highlight these elements for reinforcement during field training. Training kits, photographs or illustrations, audio recordings of species' vocalizations, and Web-based learning and testing tools also are available and provide an alternate means of instruction (e.g., Bird Studies Canada 2000; Bird Certification Online program).

Field training provides an opportunity for participants to view live specimens, gain competency in the implementation of SOPs, become familiar with equipment, field gear and clothing, and become familiar with crew organization and each crew member's role in the data collection process. Trainees should practice data collection tasks that are relevant to the project, such as:

- preparing and handling voucher specimens;
- collecting data under typical field conditions;
- completing data forms;
- notifying appropriate personnel of unforeseen problems; and
- implementing appropriate procedures or approval processes for mitigating such problems.

Field training

There is no substitute for field training and experience. Field training allows trainees to view live specimens, gain competency with SOPs and equipment, become familiar with field gear and clothing, and become familiar with crew interactions and roles.

We recommend that instructors lead trainees in a mock establishment and monitoring of at least one representative project plot – including site access through data collection and documentation – so that individuals can become familiar with the entire process. We also recommend that instructors assess the accuracy of the data collected during these trial runs and ensure that results fall within the established acceptance criteria prior to completion.

There is no substitute for practicing SOPs in the field to achieve competency in collecting data, and training should provide ample time to include the activities that must occur before and after the data are collected each day (e.g., plot layout, preparing and shipping materials). Although time, budgetary constraints, and sampling objectives may necessitate specialization, we recommend cross-training each crew member in all SOPs relevant to their expertise and qualifications. Ideally, trainees will practice SOPs until they become second nature, going beyond an attempt to just "get it right." For example, EPA's National Aquatic Resource Surveys involve diverse monitoring teams from many offices within EPA, state agencies, and other organizations. All survey partners are required to sign a QA Project Plan (QAPP) and implement the standardized field methods. State, tribal, EPA, contractor, and other field crews are required to take part in standardized and structured training activities prior to the start of field training, and training is supplemented by an on-site field assistance visit/audit of each crew during the first few weeks of sampling. Their training includes:

- classroom/webinar instruction on the objectives of the surveys, the basic protocols and procedures, and all documents relevant to the survey;
- on-site, hands on demonstrations of all methods used for that survey; and
- practice of all methods by each crew with training team oversight to ensure proper implementation.

4.2.4 Training Content

> **Promoting Crew Interest**
>
> **The value of having crew members "buy in" to a project and commit to following SOPs has a large impact on meeting quality objectives and should not be underrated. We recommend that trainers begin training sessions by clearly explaining the importance of the project and the role of each crew member. A prepared and poised trainer can greatly influence participants' commitment to data quality.**

Training should begin with a discussion covering the history, goals and objectives of the project, and an outline of the project design. Crew members are motivated in various ways, and training should be designed to foster each participant's commitment to project objectives. Some are motivated by knowing they are contributing to a larger effort and helping to restore coastal wetlands or reducing the impact of invasive species, for example. Others may be motivated by knowing that their efforts positively impact local communities or Tribal entities who value ecological resources for economic and cultural reasons. Still others may be motivated by the satisfaction that they are generating information needed to update and enhance available datasets containing information for a species or taxon of interest, ensure rigorous analyses, provide cost-effective remediation, enhance program assessment, or evaluate treatment effectiveness. Whatever the reason, training sessions should include (1) a reaffirmation of why the project is important and why high quality data are paramount for project success; (2) a reaffirmation of the importance of each crew member's role; (3) instruction, practice and training in the field and classroom; and (4) evaluation of crew performance and feedback. In other words, staff should understand what they are doing and why. In addition, it is helpful for trainees to learn the rationale behind the SOPs so that they may better adapt to slight changes in circumstance.

Once trainees have had a chance to implement SOPs and practice data collection in the field, project goals and objectives should be reviewed again to provide the crew with a chance to ask questions based on what has been learned and experienced. As noted in **Section 4.2.3**, effective training programs include sessions in both the classroom and the field. For ecological restoration projects, training should provide individuals with information and skills pertaining but not limited to:

- site access and establishing plot boundaries;
- species to be observed, counted, and described;
- variables to be measured or observed;
- methods and strategies for collecting information;
- the rationale supporting collection strategies;
- maintenance and calibration of instruments and equipment;
- methods for collecting samples or materials for further identification by experts or laboratories;
- data recording/entry processes;
- use of standardized data sheets;
- use of handheld equipment, including GPS and PDRs;
- equipment maintenance and calibration;
- procedures for handling data (including samples and specimens) in the field; and
- data backup, entry, verification and validation.

Training should be tailored to address region- and project-specific conditions to provide individuals with a clear sense of what to expect in the field. If the project covers a broad geographic area, training can be tailored to each specific region within the area.

Finally, successful data operations require a culture of safety in addition to a culture of quality. Therefore, all training should include discussions of safety. Trainers should stress the importance of creating a “safety culture” in the field, both at the field sites and during travel to and from the sites. Trainees should learn how to avoid, react to and respond to unsafe conditions; they also should learn how to assess risk, and be briefed on what conditions constitute a safety risk, such as working late at night or working for extended shifts. Although the primary purpose of safety training is to protect crew members, it is worth noting that safe conditions have a significant impact on ensuring data quality; unsafe conditions can easily lead to collection of incomplete, non-representative and/or inaccurate information. Examples of field-related risks that could adversely impact data collection include boat and water safety, vehicular safety, sun exposure and dehydration, hunting activities, hypothermia, allergic reactions to plants or stinging and biting insects, and wild animals.

4.2.5 Certifying Crew Competency

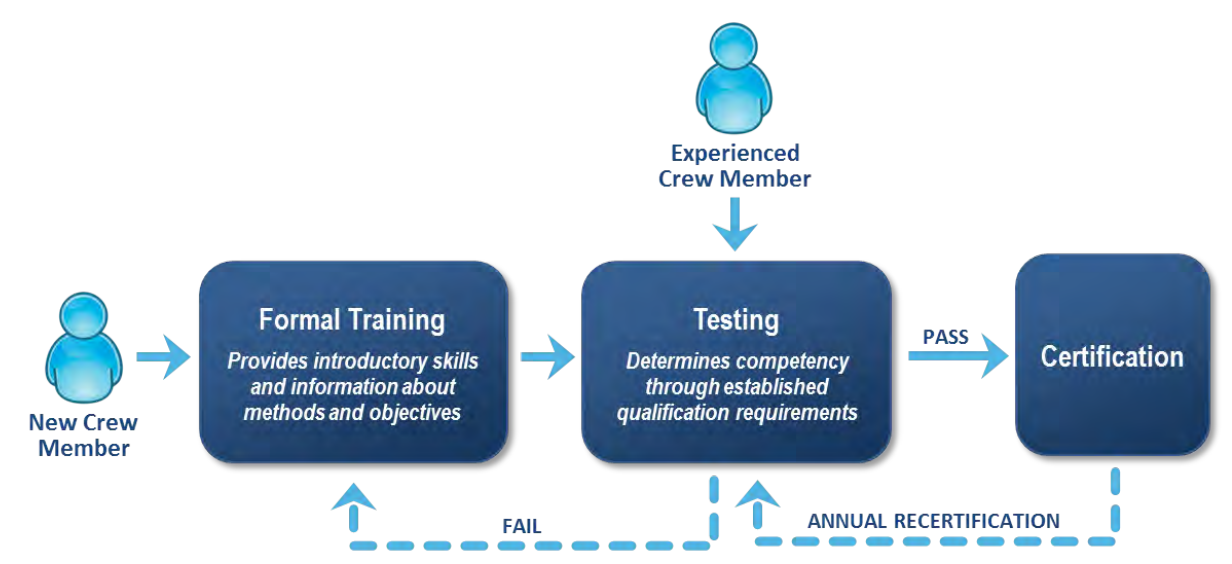
Before beginning actual field work, each new crew member, no matter the level of experience, should be able to demonstrate their ability to collect data of sufficient quality under actual field conditions. Training should include evaluations at the end of each session to rate participants' levels of understanding and proficiency. Various metrics, such as the use of calibration plots and hot checks (see **Section 5.2**) can be used to assess field readiness. During development of forest health indicators for the FIA Program, for example, crew members were certified in understory vegetation when their results agreed with the expert at least 90% of the time on species identification and within 20% on vegetation cover at least 80% of the time (Stapanian, Cline, and Cassell 1994; Stapanian unpublished data). Monitoring of Great Lakes coastal wetlands includes the formal training and certification of all new field personnel regardless of prior experience. For example, the anuran and bird field crews are trained and tested to minimize errors in species identification, data entry and the locating of sampling points with GPS receivers (Uzarski et al. 2017). As another example, crew members who conduct point counts in Great Lakes Network parks are required to complete an online certification program developed by the University of Wisconsin-Green Bay, which allows (1) trainees to certify their skills in identifying birds by sight and sound, and (2) the parks to verify that certification.

Some projects may require that each field crew responsible for collecting observer-determined data on vegetation or animal species include at least one expert skilled in the field of botany or the specific animal taxon or species. Although field crew members with prior experience will not need as much training as new crew members, they will need to be trained regarding the project goals, objectives, SOPs, data acceptance criteria, and location. They also will need to demonstrate sufficient capability for collecting data for the specific project. The USFS often uses hot checks and calibration plots (see **Section 5.2**) during and/or as a last step of training to evaluate crew capabilities prior to actual data collection.

In addition to a hands-on, on-site evaluation and confirmation of crew capabilities prior to actual data collection, it is recommended that all crew members participate in periodic refresher training and recertification. Experienced crew members can assist as additional instructors with less experienced trainees, giving them an opportunity to continue practicing observational skills such as distance estimation, working on identification of birds by call notes and partial songs, and improving species identification and characterization skills. Ongoing training and certification should also be linked to QC checks that are a part of the overall project QA strategies. Hot checks, cold checks, and blind checks are mechanisms for ensuring that data meet the data quality acceptance criteria, but these checks can also provide opportunities for ongoing training. Immediate feedback from a QA crew during a hot check can reinforce training principles. Results from cold and blind checks can assess training effectiveness or determine if refresher training is needed. These checks are described in more detail in **Chapter 5**.

Exhibit 4-5 shows our recommended approach to ensuring that individuals are capable of and certified for data collection in support of ecological restoration projects.

Exhibit 4-5. Training and Certification for Observer-Determined Data Collection



4.2.6 Failure to Meet Certification Requirements

Each crew member will either pass or fail competency testing based on established qualification requirements. If a crew member passes, that individual is certified and can begin data collection, with periodic refresher training and recertification (see **Section 4.2.5**). If a crew member fails, it is recommended that they be retrained and re-assessed for certification a second time. Following the evaluations, time and resources should be devoted to corrective action and improvement to provide an opportunity for participants to correct any deficiencies. Ideally, a proficiency scoring system could be applied to "grade" crew member skills along a numeric or ordinal scale, and the resulting certification values used to assign field crew teams in a way that minimizes effects caused by systematic errors.

As appropriate, individuals failing a second assessment may be re-assigned to non-data collection activities, assigned data collection work that is directly supervised, or released from the project. In some cases, a probationary period may be warranted, with experienced crew members accompanying new members until appropriate certification is obtained. Because failures and their potential impact on data can range from small to large, they are often handled on a case-by-case basis.

4.2.7 Examples

Numerous training programs and opportunities address topics directly pertaining to ecological restoration monitoring. The list below provides just a few examples of training that has been made available by government and private organizations.

- Observers who conduct bird counts using sight and sound in Great Lakes Network parks and the Great Lakes Coastal Wetland Monitoring Program are required to complete a Birder Certification Online program developed by the University of Wisconsin-Green Bay under funding and collaboration from the Wisconsin Department of Natural Resources, the Wisconsin Bird Conservation Initiative, the National Park Service and the U.S. Fish and Wildlife Service. (http://www.birdercertification.org/)

- Environment Canada provides several training modules targeting bird studies. Bird Studies Canada 2000. (http://www.bsc-eoc.org/volunteer/bccws/index.jsp?targetpg=bccwsresources)

- Environmental Canada also provides training kits, photographs or illustrations, audio recordings of species' vocalizations, and Web-based learning and testing tools (e.g., Bird Studies Canada, 2000; Bird Certification Online program).

- The NatureInstruct website training allows trainees to certify their skills in identifying birds by sight and sound. Nature learn is an interactive website to help individuals improve their skills in visual or audial identification of wildlife. (http://www.natureinstruct.org)

4.3 PREPARING FOR FIELD LOGISTICS

The importance of preparing for field logistics before field crews are sent to collect samples and data should not be overlooked. Preparation activities include conducting site reconnaissance and obtaining any required permits (**Section 4.3.1**), organizing and preparing equipment and information needed in the field (**Section 4.3.2**), and supplementing SOPs with site-specific information that will guide crews in their daily efforts at each project site (**Section 4.3.3**). Examples of such activities are provided in **Exhibit 4-6** and discussed further in **Sections 4.3.1** through **4.3.3**.

Exhibit 4-6. Planning and Preparation for Field Logistics

Site Reconnaissance and Permits	Supplies and Equipment	Site-Specific Field Instructions
• Verify suitability of selected sampling sites • Obtain permits and approval of documented compliance with regulations • Obtain site access permission from landowners • Notify local authorities of field activities when sites are located on public lands • Establish a master schedule for routine and QA crew field activities	• Sampling gear, equipment, supplies and checklists • Equipment instructions and manuals • Pre-departure check list • SOPs • Field guides • Species "cheat sheets" • Maps • Data forms • Emergency first aid kit • Emergency radio or cellular device • Permits/site access permission documents	• Overview of restoration goals, project objectives and sampling objectives • Schedules, roles and responsibilities • Data collection locations • General considerations (e.g., site-specific health and safety, site access) • Overview of daily activities • Post data collection activities

4.3.1 Site Reconnaissance, Permits and Master Schedules

Before field data collection begins, site reconnaissance should be performed to confirm the suitability of the selected sampling sites. All of the necessary federal and state permits and landowner access permissions also should be obtained, and a master schedule of activities should be in place that includes information regarding when QC checks will be performed.

Site Reconnaissance: Candidate site locations are typically selected during the monitoring plan design phase (see **Section 2.8**), and may be selected based on previously utilized locations or from maps and GIS data to meet specific project criteria. Ideally, the datums, coordinate systems and selected locations will remain consistent and be verified throughout the design, restoration and post-restoration monitoring phases of the project. Regardless of how the sites are selected, field reconnaissance should be conducted prior to permanently establishing each location. During this reconnaissance, project planners should confirm that the location (1) can be safely and consistently accessed, (2) is representative of the area and variable(s) targeted by the project, and (3) can meet sampling objectives.

Reconnaissance efforts also should verify that all SOPs that will be used are applicable and appropriate for the site conditions. A site's physical and biological conditions can change dramatically throughout a given time period; therefore, it is recommended that site reconnaissance be performed during the same season or seasons in which data collection will occur and that any changes are documented.

Environmental conditions and seasonal impacts such as snowpack, stream flow, water elevations, or dense undergrowth may limit site access, increase safety concerns and/or impact data quality. To offset any likelihood that selected sites might be deemed unsuitable, or that the necessary permits or landowner access cannot be obtained within schedules, project planning teams should consider strategies for selecting equally representative sites that can be used as back-ups, consulting with a statistician as needed. Such pro-active planning to include back-up locations can be critical to ensuring the completeness of both routine and QC data collection (see **Exhibit 4-7**). Note that the elimination of sampling locations should be based on predetermined criteria instead of subjective decisions by field personnel, which can create bias. These criteria can address (1) accessibility such as landowner permission, (2) sample unit characteristics such as trails or other unique disturbances, and (3) sampling areas that meet the project objectives such as the presence of habitat or invasive species.

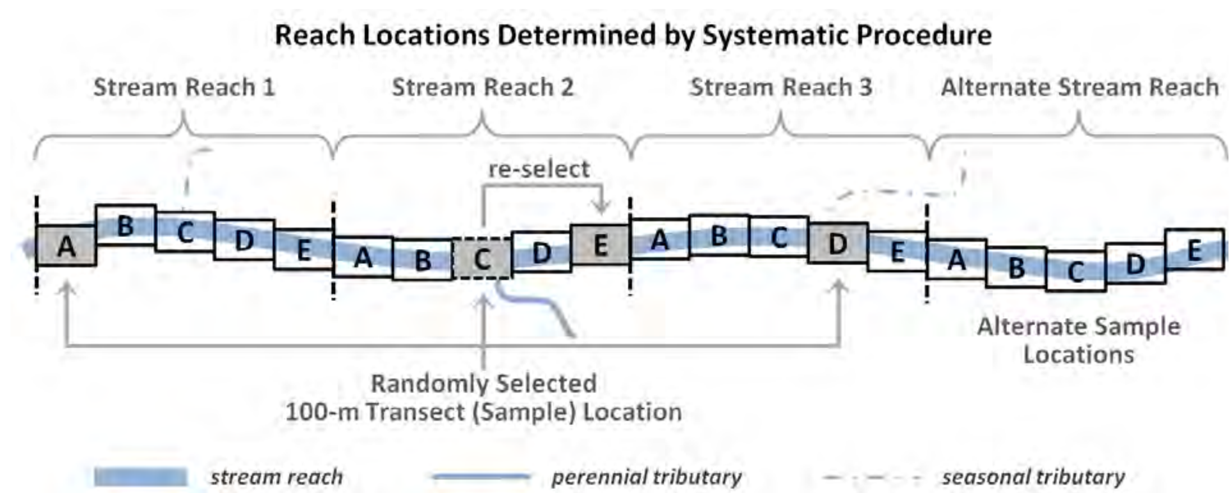
Exhibit 4-7. Example Selection of Alternate Sample Locations

In some cases, field crews may have to identify alternate sample locations as a result of site-conditions. Ideally, field crews will be able to refer to procedural steps that meet the project's sampling objectives without introducing bias.

Example Scenario:

A project sampling design uses a systematic, randomized approach to select three 100-meter lengths of stream reach to estimate average stem density of native willow. Project planners first divide the targeted stream reach into three equal lengths of 500 meters. Subsequently, each 500-meter length is divided into five equal lengths of 100-meters. Finally, a single 100-meter length is randomly selected for each 500-meter segment to position a survey transect along which ten 1-m^2 rectangular quadrats are equally spaced within the bank zone parallel to the stream's wetted edge. The sampling design dictates that transects cannot be adjacent to or include confluences of perennial tributaries.

While establishing transects, the field crew discovers that along one of the randomly selected 100-meter lengths of stream there is an unmapped perennial tributary. Since sampling design rules were established *a priori* in the event of this scenario, the crew knows that an alternate 100-meter length must be randomly selected from the remaining four 100-meter lengths. The sampling design also specifies that this procedure can be iterated as needed until a 100-meter length is selected that meets all sampling design criteria. In the event that none of the five 100-meter lengths satisfy the criteria, the design also specifies that the crew should exclude that 500-meter stretch of stream and proceed to the next 500-meter length. Sampling design criteria indicate that at least three 100-meter transects are needed to meet minimum sample size requirements, and allow for extension of the stream reach by an additional 500-meter length upstream if needed.



Site Permits: All required permits must be identified and secured before initiating field activities. Projects selected to receive federal funding, for example, may be subject to requirements of the National Environmental Policy Act, Endangered Species Act, and/or National Historic Preservation Act. In such cases, documentation of compliance with these regulations must be approved prior to initiating activities that disturb or alter habitat or other features of a site. Likewise, restoration activities that occur in streams and wetlands may require federal permits under Section 404 of the Clean Water Act, and most states require permits for certain activities that require collection of biological specimens (e.g., benthic macroinvertebrate sampling or fish and wildlife sampling). Check with the state environmental or natural resource agency to determine which activities planned for the project may require a permit. In some cases, the delay time for securing permits may be lengthy, so proper project planning should initiate the permitting process well before (e.g., six months to a year) field activities are scheduled to begin.

Coordination with Landowners: In addition to state and federal permits that might be required for ecological restoration activities, permission may need to be obtained from local landowners to access field sites. Ideally, any affected landowners would already be included in project planning. Written agreements are recommended for granting access to field locations on private land; to protect both parties, such agreements should specify the timing and location of activities, the nature of such activities and any special conditions. When sites are located on public land or in remote locations, it is important to notify local officials or other authorities of any scheduled field work. Ideally, authorities should be provided with a document identifying the project manager and their contact information; the location, dates and times of field activities; the purpose of the activities; the number and names of field crew members; and any relevant individual health concerns (e.g., allergies). This information is critical to support effective search and rescue or medical evacuation. It also empowers local authorities to accurately respond to any questions, complaints, or other inquiries by the general public who may encounter field crew members or perceive crew activities as inconsistent with existing land management policies (e.g., the capture of wildlife or the collection of plant specimens in a state or federal park).

Master Schedule: A master schedule that includes when and where QC checks may occur should be provided to project managers and QA crews (see **Chapter 5** regarding various types of QC checks). Maintenance and distribution of such schedules to those who are responsible for implementing them can help ensure these important QA activities are not forgotten or arbitrarily placed, leading to possible inaccuracies in QA results. For instance, a project plan may state that precision checks (see **Section 5.2.3.3**) will be performed for each field crew at a minimum of three plots, or that specimen duplicates will be collected at a frequency of 5%; the master schedule should detail when and where these activities will be performed to meet the stated frequency goals, and which staff are responsible for performing them.

4.3.2 Field Equipment and On-Site Supplies

Proper field gear, equipment and supplies are critical for ensuring that data collection activities are conducted safely, efficiently and in a manner that ensures consistency with project quality objectives. Examples of equipment and on-site supplies supporting ecological restoration projects are shown in **Exhibit 4-8**.

Exhibit 4-8. Example Field Operation Supplies and Materials for Vegetation Plots or Avian Surveys	
• Appropriate clothing • Audio playback and recorder • Batteries • Binoculars/scope • Calibrated quadrat frame • Camera and density board • Cell phone • Data forms, PDRs • Digital camera • Emergency contact information • Extra batteries • Field guides and other keys	• First aid kit • Land access permission forms • Maps, compass (digital data recorder), GPS • SOPs • Species check list • Tape measure (range finder) • Thermometer (digital weather recorder) • Vehicle insurance and registration • Voucher specimen plant press, bags, and labels • Watch • Water • Writing utensils (including extras)
NOTE: *Certain supplies/materials such as a calibrated quadrat frame and voucher specimen plant press, bags and labels are typically only needed for vegetation plots, while supplies such as binoculars/scope are only needed for avian surveys.*	

Field crews need to prepare equipment and assemble their supplies prior to each field event. As part of pre-departure activities, equipment will need to be checked to ensure it is in good working order and has been cleaned to prevent transfer of contamination or invasive species. All instruments need to be checked to ensure they are functional, fully charged and calibrated. If SOPs are not available for equipment preparation, appropriate instructions should be provided. In addition to the equipment used to collect data, equipment checklists should include cell phones, first aid kits, vehicle insurance and registration, GPS, batteries, and water. Checklists are recommended for making sure that all necessary gear, equipment, and supplies are gathered and ready for field use prior to departure.

Site supplies also should include all pertinent SOPs, road maps, topographic maps, field guides, species identification sheets and keys, directions to each data collection site or plot, landowner access permission forms, check lists, and any other information to ensure an efficient and safe day of data collection, including contact information and the location of the nearest medical facilities. Sometimes referred to as "site packets," these supplies also should include blank versions of any required standardized data collection forms (see **Exhibit 4-9** for an example of a completed form for collecting ground cover data), field data sheets, field logs, sample labels, and tracking/chain-of-custody forms, including those needed to cover QC checks and samples.

Exhibit 4-9. Example Completed Data Collection Form

FOREST GROUND COVER 1-M QUADRAT DATA FORM

Site ID/Name: MUD LAKE - 1A

Time Start: 0800 **Time End:** 0822 *(24HR)* **Plot #:** 5

Date: 08-Jun-2017 *(DD-MMM-YYYY)* **Crew Leader ID:** JWC-1 **Assistant Crew Member(s) ID:** KT-1

SubPlot ID: 1A-1 **Quadrat ID:** 10 **Quadrat Photo ID:** 1A-1/10

Weather Condition: Cloud Cover: 45 *(PERCENT)* Wind: 1 *(BEAUFORT SCALE)* Temp: 22 *(CELSIUS)*

Foliage Moisture: Dry X Damp ____ Dripping ____ *(IF DRIPPING – DO NOT SURVEY)*

Name or Group	CC
BARE SOIL	0
DUFF or LITTER	3
MOSS	2
LICHEN	0

Genus, Species Name	Voucher ID	Photo ID	CC / FF
Unknown Herbaceous Seedlings			2
Unknown Woody Seedlings			1
Maianthemum canadense			2 / FR
Aquilegia canadensis			1 / FL
Rubus allegheniensis			2 / A
Fragaria virginiana			3 / FL
Eurybia macrophylla			3 / A
Pinus banksiana			2

Cover Class (CC) Code: **0** = Absent (group) **1** = <1% cover **2** = 1-5% cover **3** = 5-25% cover **4** = 25-50% cover **5** = 50-75% cover **6** = >75% cover

Flowers and/or Fruit (FF) Code: *(for herbaceous species only)* **FL** = flowers only present **FR** = fruit present (or both) *(When at least one individual exhibits flowers and/or fruits)* **A** = FL/FR absent *(No flowers and/or fruits)*

FIELD QC *(CHECK)*

Survey Type:
☑ Routine
☐ QC

Checks:	Yes	No
1. Form Complete	☑	☐
2. Form Legible	☑	☐
3. Data Verified	☑	☐

Comment: Signs of heavy deer browse

Crew Member ID and Signature: KT-1 Date: 08-Jun-2017

OFFICE QC *(CHECK)*

Checks:	Yes	No
1. Data entered into electronic database	☑	☐
2. Form data transcription verified accurate	☑	☐
3. Errors flagged in data form persist in database	☐	☑

Comment: Entry delayed due to holiday

Office QC Check Conducted by: BDT-2 *(NAME AND ID)* Date: 11-Jul-2017

4.3.3 Field Instructions

Although SOPs and sampling plans include specifics regarding the locations, frequencies and procedures for collecting and recording data, these documents typically do not provide some of the information crews need for day-to-day data collection efforts, including pre-departure activities, scheduling and daily wrap-up activities. For example:

- Which data should a field crew member collect first, and where should it be collected?
- Will the effort to measure or observe one variable impact the quality of another variable?
- Are variables stable or transitory? If transitory, are they time-sensitive, or easily influenced by disturbances, the presence of an observer, or other sampling activities?
- What happens if crew members encounter or are exposed to a hazard or other condition impacting data collection and/or quality?
- Who is responsible for ensuring collected specimens are packaged, labeled and transported properly?
- Who is responsible for reviewing completed data collection forms to ensure all relevant data have been collected and reviewed and all recorded information is legible?

Field operation instructions help ensure that data are collected from the appropriate locations, at the correct time, and by the appropriate individuals and provide information on back up plans and contacts if problems arise that might impact data collection or impair data quality. The instructions serve as a daily operations guide for field crews and should be used in conjunction with other project-specific documents, including sampling plans, site packets (**Section 4.3.2**) and health and safety plans. Field operation instructions can be a simple summary or quick reference guide for a single field crew collecting measurement or observer-determined data for a single species at a single location. Alternatively, the instructions can cover detailed activities that impact several crews collecting samples, measurements and observer-determined data for several species at several locations. Regardless, all instructions include the following components.

- The sequence and locations for implementing different SOPs during a given day
- Schedules, roles, and responsibilities for different crew members
- Site-specific safety considerations
- Contact information for individuals to notify when unforeseen circumstances arise that could impact data collection or data quality
- Information regarding required planned QA/QC checks (see Chapter 5)
- Alternate plans and procedures for instances in which data collection is compromised, if for example, sites are inaccessible, inclement weather occurs, or unanticipated hazards are present.

No matter the length of the instructions, we recommend that the following information be included to guide crews during their daily data collection activities:

Schedules: A schedule of field activities is needed to let field crew members know when and where sampling events will occur; which field crews are responsible for each event; and the timing and location of certain QC activities (e.g., see **Chapter 5**). In addition to enhancing data quality, proper scheduling can reduce project costs by more efficiently scheduling hourly labor, reducing vehicle miles, avoiding unnecessary duplication, and ensuring field crews are in place during refresher training or hot checks (**Section 5.3.1**). If possible, guidance for the selection of substitute sites for situations where target sites are not accessible or are unsafe for monitoring activities can also be included.

Site-Specific Considerations: Instructions should include a review of site-specific health and safety considerations. Field data collection presents certain risks and hazards associated with site access; the operation of motor vehicles, boats, and sampling equipment (e.g., electro-shocking); and other dangers such as insect bites (e.g., bees, ticks) and weather effects (e.g., hypothermia, heat exhaustion, sunstroke). Specific safety guidelines for each of the data collection activities should be reviewed and summarized. If not already included in land access permission forms (see **Exhibit 4-8**), information regarding site access considerations (e.g., contacts, landowner expectations) also should be provided.

Overview of Site-Specific Field Activities: Field instructions should provide a summary list of the SOPs to be used and the activities to be conducted at each monitoring site, including confirmation of the site location (e.g., using maps, scaled images and/or GPS data), marking the site (e.g., using flagging, pin flags and/or permanent markings), and documenting the site (e.g., using digital cameras and/or rough sketches made by the crew) to identify the exact locations where samples and data are collected. The overview should also identify the number and types of measurements and observations to be made, samples to be collected, and information about any additional sample volume or samples required for QC purposes.

Post Sample and Data Collection Activities: Instructions should include a listing of the activities to be conducted after leaving the field and returning to the base site or office, as well as a requirement for property owners or responsible local authorities to be notified when all crew members have returned from conducting field activities. Once crews have returned to the base site or office, each of the data collection forms, PDRs and sample labels that have been used or completed throughout the day need to be reviewed again immediately to ensure that they are accurate, complete and legible. All QC check data forms and QC sample labels also need to be reviewed for accuracy, completeness and legibility. Unless these forms and labels are filled out correctly, it will be difficult – if not impossible – to link results to the correct location, time, ancillary information and/or QC results for evaluation of data quality. Any samples or specimens that were collected need to be properly processed, preserved, sealed and labeled in preparation for shipment, which should occur as soon as is practical to ensure holding time limits are not exceeded. Sample shipment and chain-of-custody forms will need to be filled out and included in the packaging; the instructions should provide complete shipping address information, including the name and physical address of the receiving organization as well as a contact name and number at that organization (note that addresses to post office boxes should not be used). During post data collection activities, all equipment should be cleaned and/or disinfected to reduce the risk of interfering substances or organisms, and supplies that were depleted during the day will need to be replenished in preparation for future data collection efforts.

4.4 ARRANGING LABORATORY ANALYSES

Many ecological restoration monitoring programs require field crews to collect and ship samples to one or more laboratories for analyses that will supplement the observations and measurements made directly in the field. Common examples include but are not limited to:

- analysis of environmental samples (e.g., aqueous, soil, sediment, or tissue) for organic, inorganic or biological contaminants or indicators;
- analysis of soil and sediment samples for physical characteristics (e.g., grain size, porosity);
- examination of specimens for ecological health indicators (e.g., abnormalities);
- taxonomic identification and/or counts of organisms within an environmental sample;
- evaluation of specimens to confirm accuracy of species identification by field crews; and
- DNA analysis for species identification.

> **Communication**
>
> **Thorough and extensive communication is key in ensuring appropriate coordination between field teams and laboratories. Means of communication should be established early, and continued throughout the project.**

As with data collected in the field, data generated by laboratories will be used to evaluate project success and inform decisions regarding future actions. In **Section 4.1**, we discussed the importance of using clearly defined SOPs for all project activities –including laboratory analyses. In **Section 4.2,** we discussed the need to verify the competency of field crew personnel in the activities they will perform before they are allowed to gather study data or samples without supervision. In this section, we discuss the need to identify and make arrangements with one or more laboratories that has demonstrated **competency** in using the required techniques and the **capacity** to analyze your project's samples within the required time frames.

4.4.1 Laboratory Capacity

Unless you are working with an in-house laboratory, chances are high that the laboratory will be handling samples from other projects as well as yours. Accordingly, it is wise to verify that the laboratory has sufficient capacity to handle your samples without compromising their integrity, that the processing of your samples will be conducted within required holding times, and that data will be reported using the required format. Depending on project requirements, evaluations of laboratory capacity should consider the following aspects.

The capacity to conduct the analyses within any required holding times: Holding times vary widely, depending on what is being measured or evaluated, the sample type, and the preservation techniques. Some chemical analytes may have multiple holding times, such as a holding time of no more than 7 days before a sample is extracted, and a separate holding time of no more than 14 days between sample extraction and analysis of the extracts. Failing to meet specified holding times will adversely impact data quality so this issue is of particular concern for analytes with short holding times (e.g., 12 hours or less), as these typically require use of a laboratory that is within driving distance of the sampling site and that has the capacity to begin processing samples immediately upon receipt. Sample deliveries should be planned and coordinated to ensure samples will be delivered to laboratories during periods when the laboratory is open (e.g., normal working hours). Project planning teams need to review specified holding times, implement measures for immediate transfer of samples to the laboratory when holding times are short, and ensure the laboratory has the capacity to meet the specified holding times throughout the duration of the project. When contracting for laboratory services, planning teams also must ensure the laboratory is basing holding times on the time of collection in the field, rather than the time of sample receipt at the lab.

The capacity to store and handle your samples: As with holding times, specific requirements for sample processing and storage vary widely depending on the analyte and sample matrix. Some samples/analytes may require preservation or filtration immediately upon laboratory receipt, while others may require only refrigeration to protect sample integrity. Project planning teams need to review these requirements and ensure the laboratory is properly equipped to meet them. For example, if a project will require the laboratory to store large volumes of aqueous samples at ≤4°C, it is important to verify the laboratory has sufficient refrigeration capacity to do so, even during periods of peak demand. At a minimum, the laboratory should have a dedicated sample custodian who is available to immediately inspect and document the condition of samples upon receipt and notify your organization of any problems.

The capacity to report laboratory results in the format and within the timeframes you need: It does little good to have samples analyzed if you cannot receive the results in time to support your decisions and obligations. Thus, project planning teams should determine and define the "data turnaround time" and data format needed from the laboratory. The most common approach is to define turnaround time as the maximum number of calendar days from the time of sample receipt at the laboratory to delivery of the required results. Data turnaround times can vary depending on a number of factors such as the complexity of the analyses, the complexity of the reporting requirements, and the urgency for information. For most "routine" types of analyses, commercial laboratories usually can offer price quotes for their "standard" turnaround time and a premium price for shorter timeframes. Note that the data turnaround time is different than the sample holding times discussed above. For example, samples may have a 7-day holding time, and a 30-day data turnaround time. This means that the laboratory must analyze the samples within seven days of collection, but has up to 30 days to compile and report the results. Project managers should clearly define the data to be reported, including metadata and QC results, along with the reporting format that will be needed to facilitate data evaluation and transfer.

Enforcement Provisions: Even when laboratory capacity has been ascertained, unforeseen situations may arise that can stretch the capacity to its limits, and force the laboratory to prioritize one project over another. To mitigate such circumstances, it may be helpful to establish positive incentives for early delivery, negative incentives for late delivery, and/or damages caused by missed holding times.

4.4.2 Laboratory Competency

The stakes are high when it comes to laboratory results; extensive resources have been invested to collect samples, and the quality of your project data and conclusions will be compromised if the laboratory is not sufficiently competent in using the required instrumentation or techniques, or in applying those techniques to your samples. The need to verify competency is so important that EPA has established three competency policies to better ensure the quality of field and laboratory data generated (EPA 2016). One policy governs internal EPA laboratories, one governs organizations that perform field or laboratory measurements under EPA contract agreements, and one governs organizations that conduct such activities under EPA grants or other assistance agreements. Together, these policies require an assessment of competency before a laboratory is allowed to analyze samples. Concerns about the competency of laboratories analyzing environmental samples are not limited to EPA. For example, many states require the use of certified or accredited laboratories for specific programs (e.g., drinking water analysis) or when using state funding.

Although it may be tempting to rely simply on laboratory accreditation or certification as a sole indicator of competency, we caution against doing so. Among other concerns, the cost of accreditation or certification may be prohibitive for some organizations, and thus may eliminate highly qualified and competent organizations from consideration. Because accreditation requirements sometimes vary by state, highly qualified laboratories may be eliminated if they are participating in a program that does not share reciprocity with the program required by another state. Additionally, accreditation is often specific to a single program, method, or group of analytes, and in many cases, accreditation does not even exist for the types of laboratory analyses you may need (e.g., taxonomic identifications, analysis for emerging contaminants of concern, and use of novel techniques). For example, a laboratory may be certified to analyze samples for the presence of metals in drinking water, but that certification would have little value in demonstrating their competency to analyze benthic organisms in sediment samples or organic compounds in aqueous samples. In such cases, relying on accreditation is primarily of value in confirming that the lab has a quality system in place and undergoes internal and external assessments to verify that it is adhering to its procedures (for the types of analyses covered by the accreditation). Unless all the sample types, analytes and methods in your project fall within an existing accreditation program, we recommend that you view accreditation/certification as one of many tools that can be used. Other tools for demonstrating laboratory competency include, but are not limited to:

- requesting that the laboratory provide results from QC data generated using the techniques required in your project (e.g., can the laboratory demonstrate the ability to produce clean blanks and achieve required detection limits using those techniques?);
- requesting that the laboratory submit descriptions of applicable instrumentation, sampling equipment, method sensitivities, reporting practices, capacity, experience, staffing and past performance;
- examining results from the laboratory's participation in proficiency testing or round-robin programs involving the data collection techniques and sample types being used in your project;

- reviewing reports of audits conducted at the laboratory, or even conducting your own on-site audit before entering an agreement with the laboratory;
- reviewing the laboratory's quality manual, quality management plan or similar documentation;
- requesting references who can attest to the laboratory's past performance history; and
- prior experience working with the laboratory.

In short, we believe that a one-size-fits-all approach to demonstrating organizational competency is neither feasible nor desirable. Instead, a number of options are available, and should be tailored to the specific needs of your project. Finally, it should be noted that assessment of laboratory competency is intended as a preventative measure designed to ensure the laboratory has the staff, equipment, and capability to properly analyze your samples, but it is not a guarantee. The only way to guarantee the quality of the data is to review it, as described in **Chapter 6**.

4.4.3 Soliciting Bids from Qualified Laboratories

In **Section 4.1**, we emphasized the need to customize SOPs to reflect specific project requirements; this advice extends to the analysis of samples using those procedures. Project planning teams should carefully document the technical, QA/QC and reporting requirements that will support their project objectives and data management strategies, and solicit bids from laboratories based on these needs. Although most laboratories provide off-the-shelf analyses through catalog or website listings, many are experienced in adapting their standard analyses to meet specific client-defined requirements. In some cases, laboratories may even employ staff trained to assist clients in defining customized requirements that meet the specific needs of their projects. Detailed strategies for procuring laboratory services are beyond the scope of this guidance, but can be found in a *Guide to Laboratory Contracting* (EPA 1998), which relies on the five-step process shown in **Exhibit 4-10**.

Exhibit 4-10. Steps for a Successful Laboratory Contract*
1. Clearly define your analytical needs. • Number and type of samples • Applicable SOPs or methods • QC requirements • Reporting requirements, including format
2. Develop a clearly defined contract. • Analytical and QC requirements • Data deliverables and data turnaround • Contract enforcement clauses
3. Solicit and award the contract openly and fairly. • Ensure laboratory competency before awarding

Exhibit 4-10. Steps for a Successful Laboratory Contract*
4. Maintain communications with the laboratory after sample receipt.
5. Thoroughly review the resulting data.

** Adapted from the U.S. Environmental Protection Agency a Guide to Laboratory Contracting (July 1998, page 1)*

4.5 PREPARING FOR DATA COLLECTION – CHECKLIST

The checklist below provides a summary list of overarching principles and aspects that should be considered and implemented when preparing for project data collection activities. As with any checklist, the listed items should not be interpreted or applied without comprehension of the supporting information. Users of this checklist are encouraged to read and understand the corresponding details that are provided throughout this chapter, and to implement these details using a graded approach that is commensurate with a project's scope, importance and available resources.

PREPARING FOR DATA COLLECTION – CHECKLIST

- ☐ **Identify, develop or modify standard procedures for data collection and handling.**
  - ☐ Verify the procedures to be used are applicable to the specific needs of your project and are consistent with the goals and objectives.
  - ☐ Verify the procedures are applicable to project site locations, the ecological community and species of concern, and the anticipated ranges of environmental conditions including associated spatial and temporal variability.
  - ☐ Ensure the procedures are documented clearly and appropriately (including revision tracking) and can be easily understood and followed consistently throughout the project.
  - ☐ Verify the procedures are thorough, and include all instructions and details required to collect and/or handle data needs (see Exhibits 4-1 and 4-2). Test the procedures before use to verify they are clear enough to be applied consistently by individuals with varying levels of experience.
  - ☐ Ensure procedures are available to all staff prior to data collection and handling.
- ☐ **Verify that personnel who will be conducting field activities have demonstrated competency.**
  - ☐ Ensure that all individuals who will be collecting and/or handling data have the required expertise and experience, and have been sufficiently trained to safely and accurately perform their assigned tasks.
  - ☐ Ensure training provides an understanding of the purpose of the project, affirms the importance of each crew member's role, provides project-specific instruction and practice in both the field and classroom, emphasizes safety, and includes an evaluation of crew performance.
  - ☐ Plan and implement procedures to certify, document and monitor crew member competency, including plans for re-training or reassigning personnel who fail to demonstrate competency.

PREPARING FOR DATA COLLECTION – CHECKLIST
☐ Plan and implement procedures for conducting periodic assessments to ensure crew competency throughout the project.
☐ **Address site access requirements.**
☐ Obtain required state and/or federal permits and site-access permission from local landowners.
☐ Notify local authorities of planned field activities on public lands; provide them with appropriate contact information and other information needed to support effective public outreach or emergency response.
☐ Verify suitability and accessibility of selected sampling sites and confirm that SOPs are applicable and appropriate for the site conditions.
☐ **Address field logistics before initiating data collection activities.**
☐ Develop and distribute schedules.
☐ Assemble field equipment; ensure equipment is clean, calibrated, and in good working order.
☐ Ensure crew members have all necessary equipment and supplies, including documented procedures, site logistics, maps, data forms, communication devices, equipment instructions, and first aid kits.
☐ **Make arrangements for sample analysis.**
☐ Define and understand your analytical needs, including the number and type of samples, target analytical parameters, procedures to be used and associated QC requirements.
☐ Identify qualified laboratory(ies).
☐ Ensure laboratories are able to analyze your samples in accordance with sample holding time restrictions and project schedules.
☐ Establish clearly defined contract(s)/agreement(s) with the laboratory(ies), including reporting requirements and schedules.

4.6 ADDITIONAL READINGS

- Utah Department of Environmental Quality. 2014. *Utah Comprehensive Assessment of Stream Ecosystems (UCASE) – Field Operations Manual*. Salt Lake City, UT: Division of Water Quality.
- U.S. Environmental Protection Agency. 2009. *National Rivers and Streams Assessment: Field Operations Manual*. Publication No. EPA-841-B-07-009. Washington, D.C.: Office of Environmental Information.

CHAPTER 5 QUALITY CONTROL DURING FIELD ACTIVITIES

The information in this chapter builds on the planning and preparation activities recommended in **Chapters 3** and **4**, respectively. While those activities are essential to the success of an ecological restoration project, they do not guarantee that monitoring activities will go as planned or that all samples and data collected will be accurate and usable. Even well-trained personnel make errors, and situations can arise that were not considered during the planning and preparation stages.

A variety of good field practices and QC checks can be used to identify and mitigate data collection errors and address unforeseen problems to promote continuous improvement, help identify solutions to challenges encountered in the field, and facilitate evaluation of data quality. This chapter provides a QA/QC framework that can be used to (1) demonstrate how well routine field crew members are conforming to requirements specified in the project planning documents and standard operating procedures (SOPs), (2) obtain information that will be needed to evaluate the quality of results reported by the routine field crews, and (3) gather information that can be used to improve data quality over time. It also provides guidance on strategies for reporting, evaluating, and using QC check results to facilitate continuous improvements.

The chapter is organized as follows:

- **Section 5.1** provides a brief review of good field practices that should be implemented in all ecological restoration projects and describes characteristics of effective QA (or expert) crews.
- **Section 5.2** provides in-depth information on five QC checks that can be used to meet the unique needs of ecological restoration.
- **Section 5.3** provides specific strategies for reporting QC check results in a manner that supports timely improvements to data collection procedures and project decision making, and presents a recommended approach for collecting and considering feedback from field crew members to help support continuous process improvements.

5.1 FIELD PRACTICES AND QA CREWS

5.1.1 Good Field Practices

Field crews should be provided with all required SOPs, information, and site-specific equipment, and should be competent in conducting data collection operations systematically and accurately— including the correct use of appropriate and standardized data collection forms, codes, units, terminology and charts. Data collected using these mechanisms should be legible and transferable, and should include field notes, comments and explanations regarding any considerations that might assist with data interpretation. Field crews also should review the collected data and completed data forms for completeness and legibility prior to leaving a sampling site to ensure corrections are made in real time before any changes in site conditions or lapses in memory occur.

Field crew members should rely on their training, experience and available resources to adapt to unanticipated field conditions or events when necessary and document what occurred, how they responded and how the data could be impacted. **Exhibit 5-1** presents a brief summary of good practices that field crews can implement to maximize the quality of data collected in support of ecological restoration projects. These practices assume that field crews have the necessary information and are already competent in data collection operations.

Exhibit 5-1. Good Field Practices during Routine Data Collection

- Adhere to all safety requirements.
- Understand the purpose of data collection.
- Ensure that site packets and equipment are readily available and in good condition (see **Section 4.3**).
- Establish effective communication methods between field crews and the project office or designated project leader to ensure that any questions/concerns or support requests can be readily addressed.
- Use teams of at least two field crew members to collect data (if practical).
- Observe and document any conditions that could impact the data collected.
- Calibrate equipment onsite when practical and ensure proper functioning prior to use.
- Ensure site is marked correctly and markings are stable.
- Have a copy of the SOP in the field and follow SOPs as written. Note any deviations to those procedures that were necessary based on site conditions.
- Prioritize collection of measurements or observations on target variables considered least stable (i.e., transitory) during the presence of the crew, or least resilient to crew disturbance.
- Use verbal repetition to confirm data during data transcription.
- Ensure data collection completeness and legibility prior to leaving the site by completing the following activities: (1) double check all collected data, notes and comments, and (2) ensure all data forms, photographs, recordings, charts, samples and/or specimens are labeled, organized and stored correctly, and (3) ensure samples requiring laboratory analysis are handled in accordance with specified shipping and chain of custody procedures.

5.1.2 Characteristics of Effective QA Crews

Most of the QC checks described in this chapter (with the exception of precision checks) rely heavily on comparisons of data collected by routine field crews to data collected by expert QA crews. Expert QA crews provide a means for estimating accuracy and bias associated with results reported by routine field crews. Because measurements and observations made by QA crews will be used as surrogates for "true values" when assessing the quality of data collected by routine field crews, project managers and others who are responsible for selecting QA crew members must make sure these individuals have the appropriate level of experience, proficiency, and expertise. Ideally, these experts are independent of (and not influenced by) routine field crews or project outcomes. This ensures their findings are objective and unbiased. If independent experts or financial resources are limited, project managers might consider (1) using QA crews to participate in QC checks of a smaller subset of plots, or (2) prioritizing which survey types or target variables should be assessed by these experts. Project managers also might consider using trainers or project principal investigators as QA crews, or accessing available experts for a limited period of time to train routine field crew members to function as QA crews, pairing available experts with routine field crew trainees over a period of time (allowing for simultaneous assessments of selected sample plots). Results of the paired assessments should be evaluated, and the differences discussed and resolved before newly trained QA field crew members are used to perform QC assessments of routine field crew data collection.

5.2 QUALITY CONTROL FIELD CHECKS

This section describes five QC field checks that are similar in function to QC samples that are collected by field teams and analyzed by laboratories. These field QC checks include hot checks, calibration checks, cold checks, blind checks and precision checks. Together, these checks provide a means for (1) verifying the readiness of routine field crews, (2) "calibrating" crew members, (3) evaluating compliance with specified quality acceptance criteria, and (4) assessing variability among crews and individual crew members. QC checks can also be used to identify and mitigate data collection errors, support continuous improvement, help identify solutions to challenges encountered in the field, and increase the confidence in (and understanding of) the quality of data collected.

Section 5.2 is organized as follows:

- **Section 5.2.1** provides detailed information on **hot checks**, including an example review form that would be completed by a QA crew member while conducting a hot check
- **Section 5.2.2** describes **calibration checks**, including some key topics project planners should consider with respect to these checks
- **Section 5.2.3** describes three different checks that can be used to estimate measurement error including:
  - **Cold checks** (**Section 5.2.3.1**)
  - **Blind checks** (**Section 5.2.3.2**)
  - **Precision checks** (**Section 5.2.3.3**)
- **Section 5.2.4** provides a summary of the checks as well as some general considerations when selecting checks and a decision tree for selecting appropriate checks for stable variables

Project planners should consider and select appropriate QC field checks for their project, and include instructions regarding the selected checks in project documentation.

5.2.1 Hot Checks

Hot checks are a type of field QC check used to objectively and systematically determine if data collection activities are being implemented as planned. Hot checks are often referred to as "field audits" or "technical systems audits," (or in laboratory settings, as "laboratory audits") and can be used as part of routine field crew training or during data collection to examine, in real time, the procedures being performed by routine field crew members. This type of check can help determine whether routine field crew members are collecting data correctly and following appropriate SOPs. The QA crew observes the routine crew activities, examines the data collected, and provides immediate feedback on crew/trainee performance, SOP efficacy and/or data quality. The characteristics, purpose and timing of hot checks are summarized in **Exhibit 5-2**.

Exhibit 5-2. Characteristics, Purpose and Timing of Hot Checks

Characteristics	Purpose	Timing	Data Management
• Performed by QA crew • Performed concurrently with routine data collection • Suitable for both stable and transitory variables	• Evaluate accuracy of data collection • Evaluate crew coordination and implementation of SOPs, including establishing and marking plots • Evaluate appropriateness of SOPs • Provide real-time and immediate feedback, training, and problem resolution	• During or at the completion of routine field crew training • Preferably at the beginning of data collection, but also applied, as needed, throughout project data collection	• Field crew data forms are corrected on-site and in real-time as QA crew input is received • Field crew and QA crew data forms are maintained separately

Hot check procedures should be designed to include opportunities for discussion and constructive criticism aimed at improving crew performance and identifying practical solutions to challenges faced by field crews when implementing SOPs in a field setting. Because hot checks are conducted concurrently with field crew data collection, these checks are most effective for evaluating stable variables that are resilient to the presence of additional staff and/or the potential of increased disturbance contributed by the routine and QA crews (or expert). Variables that are transitory in nature (i.e., where their properties change quickly and/or are easily impacted by the sampling effort) can be assessed using hot checks. However, project planners should develop or adopt specialized methods to estimate values that minimize uncontrolled measurement error. Depending on the timing and scope, hot checks can be used to:

- assess crew readiness and progress during training,
- certify crew competence at the end of training,
- calibrate crew members at the beginning of a field season,
- assess accuracy and re-calibration of crew members during the field season, and
- determine the effectiveness of established SOPs.

Hot checks are intended to provide objective and systematic examinations that can be used to determine whether data collection activities conducted throughout the process, from establishment of a sampling plot through site exit, are being implemented as planned and are suitable to achieve the project's sampling objectives and data quality acceptance criteria. These checks can also function as the equivalent of an instrument calibration, in that they provide an early opportunity to ensure that each field crew member is able to use the specified procedures to collect data that meet pre-established data quality acceptance criteria.

During these checks, a QA crew observes routine field crew collecting data in real time, and provides constructive feedback aimed at improving their data collection techniques. Although the primary activity for the QA crew is to observe field crew activities, dialogue between the field and QA crews is also needed to share ideas and provide feedback.

QA crews should:

- convey attitudes that are helpful, constructive, positive and unbiased;
- conduct evaluations in a manner that provides an opportunity for improvements in project data and personnel performance; and
- offer practical solutions to problems and engage in conversation with field crew members to better understand any challenges encountered.

Hot checks also provide an excellent opportunity for field crew members to ask any questions regarding data collection activities that may have arisen since their training and certification, and for less experienced crew members to discuss and resolve unanticipated challenges. These feedback opportunities are inherent to hot checks and are helpful in identifying noteworthy practices that should be shared with other crew members. When applied during a field season, subsequent resolution of important deficiencies may need to be verified quickly through a follow-up hot check of the same field crew or crew member.

As with all QA activities, hot checks benefit from proper planning, including appropriate selection of individuals for the QA crew(s); preparation of checklists, questionnaires, or reports for each protocol being used; and the creation of printed electronic forms for collating assessment results. Project planners should consider the following additional topics when planning to implement hot checks during the field season or sampling period (USDA 2012).

- **Conduct hot checks early in the project cycle.** Although hot checks should be conducted throughout an entire sampling period, they are particularly useful when conducted early to identify issues that could result in errors that might otherwise go undiscovered until late in the data collection cycle.
- **Prioritize inexperienced or problematic members.** Newly certified crew members or members who experienced problems during field training or testing may need to be prioritized for hot checks over more qualified members.
- **Review all variables.** Hot checks should include a review of all measured or observed target and ancillary variables.

- **Address issues promptly.** Data should be corrected onsite as issues are identified, and related problems should be documented and later evaluated to determine the cause.
- **Consider the big picture.** In cases where site conditions have been impacted and data can no longer be collected as specified in the SOP, QA crews can still use the opportunity to ask questions, review and discuss SOPs, and document the results of these discussions.

In addition to assessing whether SOPs are being followed correctly, the QA crew must also determine whether the quality of the data being collected meets established acceptance criteria. Throughout the hot check, the QA crew should compare their observations with what the field crew is recording. Any discrepancies should be noted on reporting forms (e.g., checklists) and discussed with the field crew.

Checklists or questionnaires used by QA crews should be developed and approved for use in advance to ensure all necessary components of the hot check are addressed and the hot check is conducted in an orderly and efficient manner. Ideally, these forms include information such as:

- first and last names of routine and QA crew members,
- location of the hot check,
- date and beginning and ending times of the hot check,
- steps for selecting or locating a transect or sampling site,
- steps of the SOP(s) under review, and
- data quality acceptance criteria.

University of Wisconsin Arboretum staff demonstrate seed collecting technique at Curtis Prairie to students participating in Make a Difference Day at the Society of Ecological Restoration's World Conference in Madison, WI in 2013. Photo credit: Nancy Aten

These documents also should include project- and site-specific questions and allow for comments related to particular activities for each SOP under review. It is important to review each step of the SOPs to determine if protocols are being followed as specified, and provide feedback if and when issues arise. As the routine crew collects data, the QA crew observes the activities and fills out the appropriate checklist. An example checklist for a hot check evaluating data collection in support of a ground cover vegetation survey is provided in **Exhibit 5-3**.

Exhibit 5-3. Example Hot Check Review Sheet

EXAMPLE MONITORING PROGRAM

QA/QC Hot Check: Ground Cover Survey (1-m^2 quadrats)

Date: ______________________ *(DD/MMM/YYYY)* **Start Time:** _________________ *(HH:MM)* **End Time:** __________________ *(HH:MM)*

Weather Conditions: ____ *(TEMPERATURE, WIND, PRECIPITATION)*

Plot ID: ____________________________________ **Quadrat IDs:** ______________________________

Field Crew Members: ____

Field Crew Leader: __________________________ **Signature:** __________________________________

QA Crew Evaluator: _________________________ **Signature:** __________________________________

PROTOCOL EVALUATION	Yes	No
Field crew has all required survey equipment, materials, and a copy of procedures (SOPs)	☐	☐
Survey conducted during full tree/shrub leaf-out	☐	☐
Vegetation is dry	☐	☐
Transect location procedures correctly followed	☐	☐
Quadrats placed along transects in correct locations, parallel to ground in correct orientation	☐	☐
Locations of the quadrats were marked with permanent stakes	☐	☐
Vegetation allowed natural posture after quadrat placement prior to cover assessment	☐	☐
For plants occurring along the boundaries or edges, correctly included or excluded	☐	☐
Referred to the supplemental 5% and 1% cover class, nested mini-quadrat frame for calibration	☐	☐
Assessed cover class from vertical position center 1 meter above quadrat	☐	☐
Photo documentation of quadrat and plant vouchers completed correctly	☐	☐
Field data forms correctly filled in and confirmed accurate and complete	☐	☐

Comments:

DATA QUALITY EVALUATION: Ground Cover Class Determination for 1-m^2 Quadrats by Crew Type

Substrate/Species	Quadrat 1 ID:			Quadrat 2 ID:		
	Field Crew	QA Crew	Difference	Field Crew	QA Crew	Difference
Bare Soil						
Rock						
Tree Stem						
Woody Litter						
Herbaceous Litter						
Moss/Fungi/Lichens						
Species #1 *(RECORD SCIENTIFIC NAME)*						
Species #...n						

Substrate Symbols: **A** = Artificial; **BS** = Bare Soil; **F** = Fungi; **HL** = Herbaceous Litter; **L** = Lichen; **M** = Moss; **R** = Rock; **TS** = Tree Stem; **WL** = Woody Litter

Cover Class (CC) Code: **0** = Absent (group); **1** = <1% cover; **2** = 1-5% cover; **3** = 5-25% cover; **4** = 25-50% cover; **5** = 50-75% cover; **6** = >75% cover

QA REVIEW: *Please circle any missed/misidentified substrate types or plant species and any cover estimates where differences are greater than the ± one class code tolerance quality objective.*

5.2.2 Calibration Checks

One approach to obtaining information needed to assess the quality of ecological restoration project data is to require routine field crew members to measure or observe variables that have been previously determined by an expert. Such **calibration checks** can be performed on one or more variables independent of any sampling unit or plot, staged under controlled conditions, or by using established **calibration plots** within the project area that have been fully characterized by a QA crew. These calibration checks can be viewed as being similar to standard reference materials or performance evaluation materials used in laboratories to assess analytical accuracy and competency. Calibration check results are used to evaluate the data collection abilities of routine field crew members and can support determination of achievable sampling objectives and data quality acceptance criteria. The characteristics, purpose and timing of calibration checks are summarized in **Exhibit 5-4**.

Exhibit 5-4. Characteristics, Purpose and Timing of Calibration Checks

Characteristics	Purpose	Timing	Data Management
• Performed by routine field crew following characterization of calibration plot variables by QA crew • Primarily addresses stable variables	• Provide empirical data for determining sampling objectives and data quality acceptance criteria • Evaluate ability of field crew to collect accurate data • Enhance routine crew performance	• During training • Systematically throughout the project/field season(s) • Shortly after QA crew completes plot characterization	• Field crew and QA crew calibration check data are maintained separately

Calibration Plot Selection Criteria

Calibration plot locations should be:

- **easily accessible,**
- **secure and unlikely to be disturbed,**
- **relatively stable with respect to target variables and ecological change, and**
- **representative of the project site being monitored.**

Typically, QA crews determine the values of the target variables selected for calibration checks just prior to data collection by the routine field crew(s). Locations where specific observations or measurements are to be recorded are marked using semi-permanent methods that may include use of flagging tape or placing stakes/pins in plot centers, transect interval locations and/or quadrat corners. Calibration checks are not used to test the ability of a crew or crew member to establish a sample plot site. These checks are used primarily to (1) evaluate the ability of crew members to consistently collect accurate data in conformance with the SOPs, and (2) provide empirical data that could be useful in determining achievable sampling objectives and data quality acceptance criteria. Evaluation of sample plot establishment is typically addressed during training (see **Section 4.2**) and/or hot checks (see **Section 5.2.1**).

The list below describes topics project planners should consider with respect to calibration checks:

- **Conduct calibration checks prior to routine field crew measurements and observations**. The use of calibration checks requires QA crews to collect data that are independent of the project data prior to field crew measurements and their observations. Calibration check data are collected by routine field crews/crew members after the plots have been characterized by the QA crew, and compared to the results previously reported by the QA crew.

- **Consider using repeated calibration checks**. Field crews/crew members can be asked to repeat measurements or observations of one or more target variables again as part of a regular, repeated calibration check to periodically assess and confirm the precision of their measurements and observations.

- **Assess crew variability**. Between-crew and within-crew variability can be assessed by having different crews/crew members conduct calibration checks within the same time frame. For each parameter assessed, between-crew variability is estimated from a pooled variance from all crews; within-crew variability is assessed by pooling the variance from all visits to the plot by a single crew (Stapanian et al. 2016).

- **Evaluate and enhance field crew capabilities**. Calibration check results can be used to assess the ability of crews/crew members to consistently collect accurate data (when compared to expert results) and provide opportunities for correction or improvement prior to collection of routine data. Calibration checks are also particularly useful for the certification of crew members after training and/or before the start of a new sampling event (see **Section 4.2**), and can be used at the end of a sampling event or field season to document that field crews have maintained their quality standards in data collection.

Project planners should use caution when implementing calibration checks to ensure the integrity of the target variables is maintained over multiple visits by crews or crew members. Repeated visits to calibration plots can easily impact the target variables due to trampling and other disturbances by crew members, particularly those variables associated with the understory vegetation and soil or substrate integrity. In addition, if calibration checks are conducted on a limited set of variables multiple times by the same individual(s), the individual(s) are likely to recall previous results which may bias any assessment of precision and accuracy. This is of most concern for those variables characterized by simplistic results, such as the number of white pine > 5cm diameter at breast height (DBH), estimates of percent cover, vegetation species identification, and percent slope.

5.2.3 QC Checks to Estimate Measurement Error

In this section, we describe three types of QC checks — cold checks, blind checks, and precision checks — that can be used to evaluate how well data comply with the corresponding acceptance criteria to ultimately assess measurement error. **Cold checks** and **blind checks** are conducted by QA crews who are distinct from the routine field crews and whose measurements and observations are considered to be the equivalent of a "true value." In each case, the QA crew visits a plot after data have been collected by the routine field crew and measures or observes the variables and characteristics using the same SOP(s) as the routine field crew.

The original values generated by the routine field crew are then compared to the values collected by the QA crew to determine differences or deviations. The paired values and calculated differences are compared against the applicable acceptance criteria to (1) identify and possibly correct issues related to data collection procedures (including implementation) or personnel training, (2) assess the overall quality of the specific data elements addressed by the checks, and (3) develop more appropriate acceptance criteria. **Precision checks** are typically performed when the use of a QA crew is not feasible, and instead rely on the routine field crews to repeat measurements or observations (USDA 2012). These checks are limited because they lack the expertise needed to provide a theoretical "true" value. While they can provide an assessment of precision, they cannot be used to evaluate bias or overall accuracy.

As with calibration checks (**Section 5.2.2**), these three checks are used to evaluate the ability of crew members to collect the required data using the SOPs; they are not used to test the ability of a crew(s) to establish a plot site. Evaluations of plot establishments are typically addressed during training (see **Section 4.2**) and/or hot checks (see **Section 5.2.1**). As shown in **Exhibit 5-5**, these three types of QC checks differ slightly in how they are conducted, why they are conducted and how they impact the collected data. Each is discussed in detail in subsections **5.2.3.1** through **5.2.3.3**.

The overarching principles listed below should be considered by project managers when planning the type and frequency of these checks as they are built into data collection activities:

- **Conduct QC checks promptly after field data collection.** To minimize the effects of temporal variability that might prevent an accurate assessment of data quality, cold checks, blind checks and precision checks should be conducted as soon as possible following collection of the original data. Although timing will depend on the project, variable and/or characteristic being observed or measured, site conditions, and resources, these checks should be scheduled in a time frame that minimizes the effects of temporal variability between crews. For example, if field crews are conducting monitoring activities during a growing season, the project planners should determine the optimal time for QA crews to revisit the site based on local phenology and other environmental factors germane to the project's location.

- **Address key variables.** These QC checks should address the primary or key set of variables that are being observed or measured, as determined by project quality objectives. Depending on project needs and available resources, these checks also can address supplementary or ancillary data that are associated with the primary variables of interest.

- **Ensure relevance of QC check.** Where cold checks are typically used to both assess and improve the quality of project data that are being collected, blind checks and precision checks are typically only used to provide an overall assessment of the quality of project data once data collection is complete and project data compiled. However, depending on how the results of these checks are used, the results of all three can contribute to both the collection and assessment of project data.

Exhibit 5-5. Comparison of Cold, Blind and Precision Checks

QC Check	Characteristics	Purpose	Timing	Data Management
Cold Checks	• Performed by QA crew • QA crew has access to field crew data • Field crew not told which sampling site(s) will be revisited • Can be used to confirm data quality of problematic site(s) or of randomly selected site(s) • Typically assess a core set of measurements and/or observations • QA crew provides documentation with feedback regarding errors • Used to address stable variables	• Evaluate data accuracy and completeness • Identify and correct problems	• Throughout the project/field season(s) • Shortly after field crew completes activities • Across sampling units and site considered representative of the variability exhibited by the routine field crews	• Field crew and QA crew data forms (hardcopy or electronic) are maintained separately • Field crew and QA crew results are linked by unique identifiers, plot or sample codes for subsequent data quality assessments
Blind Checks	• Performed by QA crew • QA crew does not have access to field crew data • Field crew not told which sampling site(s) will be revisited • Applied to randomly selected sampling sites • Used to assess data quality – immediate feedback not provided • Used to address stable variables	• Evaluate data accuracy and completeness		
Precision Checks	• Performed by separate routine field crews or crew members • Neither crew or crew members have access to the others' data • Used in addition to cold and blind checks, or when it is not feasible to have a QA crew. Also used when observer-determined data have to be collected in real-time to avoid temporal effects • Used to assess data quality – immediate feedback not provided • Used to address stable variables; if performed concurrently, can also address transitory variables	• Evaluate data precision within- and between- field crews or crew members	• Throughout the project/field season(s) • Shortly after or concurrently with data collection by other field crews	• Results are maintained separately • Data collected by separate field crews are linked by unique identifiers, and plot or sample codes for subsequent data quality assessments

5.2.3.1 Cold Checks

Similar to hot checks, cold checks are objective and systematic assessments that are typically used to determine if data collection activities are being implemented as planned and are suitable to achieve data quality acceptance criteria. During a cold check, the QA crew visits a site and measures or observes all or a subset of the variables that have been previously and recently assessed by a routine field crew.

Whereas QA crews conduct hot checks while a field crew is still present, cold checks are performed shortly after the field crew has completed its activities and reported its data. Thus, cold checks provide an opportunity to evaluate routine field crew results and correct errors, but do not provide a means for observing the routine field crew's implementation of the procedures. Cold checks also differ from hot checks in that field crews are not informed of which sites or plots will be revisited. While hot checks provide a potential opportunity for routine field crews to "be on their best behavior," cold checks and blind checks (see **Section 5.2.3.2**) are more likely to provide an unbiased assessment of routine field crew data collection.

We recommend that project planners consider the following principles when establishing requirements for the use of cold checks (USDA 2012):

- **Completion time:** Cold checks should be completed as soon as possible following the initial routine field crew data collection to identify problems and errors.
- **Prioritization:** Cold checks should be prioritized for routine field crews that have incorporated improvements based on results of a previous hot check. This provides an opportunity to confirm the improvements are being implemented correctly.
- **Site selection:** Although it is desirable for QA crews to randomly select plots for cold checks, the desire for randomness may be outweighed by environmental and other logistical challenges or random chance events (e.g., unexpected disturbance or absence of the target ecological phenomenon) that obstruct the possibility to conduct repeat measurements or observations.
- **Data management:** Cold check datasets (including hard copy and electronic data forms) generated by the QA crew should be maintained separately from the routine field crew datasets.

During a cold check, the QA crew often has the routine field crew's data in hand to facilitate comparisons of the field crew results with results collected by the QA crew. This differs from blind checks (see **Section 5.2.3.2**), during which QA crews do not have and have not seen the original field data. In cases where the collected data are comparable, the QA crew can check off the data to indicate agreement; in cases where discrepancies are found, the QA crew should provide notations that include what they believe to be the correct value. Any changes made to the original data should be discussed with additional QA reviewers prior to implementing the change. In cases where resources are limited, project managers might decide to modify cold checks by having the QA crew refer to the routine field crew data only after they have completed and compiled the results of the cold check. This approach also mitigates potential bias that could be introduced due to knowledge of the previously recorded observations and measurements;

although the data are not technically independent, they might be considered along with blind check data (see **Section 5.2.3.2**) for use in evaluating overall project data quality.

The following QA crew procedures are recommended when conducting a cold check:

1. **Identify data collection site:** The first step upon arrival is to locate and confirm the specific site and/or sample unit(s) (e.g., plot, subplot, transect, quadrat, stream reach) for data collection by locating any permanent markers including any necessary reconstruction of sampling lines or areas using flagging or other non-permanent markers.

2. **Collect data:** The QA crew then collects data (following the same SOPs used by the routine field crew), being sure to address all targeted variables initially assessed by the routine field crew.

3. **Compile results:** The QA crew transcribes their results into a data form that already includes the routine field crew data.

4. **Compare data:** While still at the site, the QA crew compares the cold check data to the original data collected by the routine field crew. Data discrepancies are immediately identified and flagged. Note: For QA crew results to be considered unbiased, comparison of results should occur following completion of cold check data collection.

5. **Evaluate differences:** Discrepancies between QA crew and routine field crew data are evaluated and compared to the data quality acceptance criteria for each variable. The achieved compliance rates for the field crew depicted in **Exhibit 5-6**, for example, were 95% (19/20) for identification of genus and 80% (16/20) of species. In certain cases, particularly for transitory variables, quantitative assessment of differences between QA crew and routine field crew results may not be directly comparable, and may require use of reference tables, multiple plots, alternative statistical methods and/or computer software.

6. **Confirm findings:** The findings identified during Step 5 should be confirmed. In the example provided in **Exhibit 5-6**, the QA crew might want to revisit trees 6, 10, 11, and 17 to validate the correctness of their assessments.

7. **Assess causes:** QA crew assesses potential site-related causes for discrepancies and documents findings.

8. **Confirm cold check is complete:** QA crew reviews data form(s) for completion, ensures all notes and flagged results are correctly documented, and confirms that any collected samples are properly labeled and secured for transport.

Exhibit 5-6 provides an example comparison between routine field crew data and cold check data, for tree species identified on a plot. The data quality acceptance criteria are included, with a tolerance for no errors in species identification and a corresponding compliance rate of at least 99% for genus and 95% for species. In conducting their comparison, the QA crew should have noted one genus and species error (tree 11) and three additional species errors (trees 6, 10, and 17).

Exhibit 5-6. Example Cold Check Data Comparison – Tree Species Identification				
Tolerance: No Errors				
Compliance Rate: At least 99% of the time for genus, at least 95% of the time for species				
Tree	**Field Crew**	**QA Crew**	**Genus Error**	**Species Error**
1	Northern Red Oak	Northern Red Oak	No	No
2	White Oak	White Oak	No	No
3	Bigtooth Aspen	Bigtooth Aspen	No	No
4	Black Cherry	Black Cherry	No	No
5	White Oak	White Oak	No	No
6	Red Maple	Sugar Maple	No	**Yes**
7	Black Cherry	Black Cherry	No	No
8	Black Cherry	Black Cherry	No	No
9	Northern Red Oak	Northern Red Oak	No	No
10	Northern Red Oak	Northern Pin Oak	No	**Yes**
11	Balsam Fir	White Spruce	**Yes**	**Yes**
12	Bigtooth Aspen	Bigtooth Aspen	No	No
13	Northern Red Oak	Northern Red Oak	No	No
14	Black Cherry	Black Cherry	No	No
15	White Oak	White Oak	No	No
16	Northern Red Oak	Northern Red Oak	No	No
17	Northern Red Oak	Black Oak	No	**Yes**
18	Black Cherry	Black Cherry	No	No
19	White Oak	White Oak	No	No
20	Northern Red Oak	Northern Red Oak	No	No

5.2.3.2 Blind Checks

The process for conducting blind checks is similar to cold checks except the QA crew has not seen the routine field crew data and does not have the original data in-hand. Thus, blind checks are conducted both separately and independently of the original data collection effort, affording significantly less opportunity for potential unintended bias. Similar to cold checks, routine field crews do not know which of their data collection locations will be revisited. Unlike hot checks and cold checks, blind checks are typically not used to control the quality of project data. Instead, blind check data are collected independently and separately from field crew data to provide information that can be used to assess routine field crew performance and data quality, including the precision and accuracy. Although QA crews are provided with the same project information (e.g., site packet) provided to the field crews, the QA crew does not receive any information regarding the data that have been collected by the field crew except for the date and specific location that correspond to the data collection efforts.

An important step in conducting a blind check is to randomly select a data collection site from the full suite of sampling sites associated with the project. Random selection is valuable because the inferences on data quality derived from blind check results are meant to apply to the entire project dataset. Exceptions would be cases where specific sites are known to have problems or data quality concerns.

We recommend that project planners consider the following principles when establishing requirements for the use of blind checks:

- **Completion time:** As with cold checks, blind checks need to be conducted as soon as feasible after the routine field crew collected the data. Also as with cold checks, timing will depend on the project or variable being measured or observed, site and weather conditions, and resources. As an example, the US Forest Service strives to conduct blind checks within two weeks of the original data collection effort (USDA 2012) so that differences identified between crew results can be attributed to variability in measurement or observation, and not confounded with natural temporal variability.

- **Scope:** Blind check results should provide enough data for each variable (e.g., 10 or greater) being monitored to allow for evaluation of the quality of the overall (i.e., complete) dataset.

- **Data management:** No corrections should be made to the original data based on the results of blind checks. Blind check datasets need to be maintained separately, yet linked to the routine field crew data in the project database. Similar to analytical results of duplicate or replicate samples, blind check data should be treated exactly as the routine field crew data for data entry and subsequent review, including data verification and validation (see **Chapter 6** for a discussion of data review steps).

The following QA crew procedures are recommended when conducting a blind check:

1. **Identify data collection site:** The first step upon arrival is to locate and confirm the specific site and/or sample unit(s) (e.g., plot, subplot, transect, quadrat, stream reach) for data collection by locating any permanent markers including any necessary reconstruction of sampling lines or areas using flagging or other non-permanent markers.

2. **Collect data:** The QA crew then collects data (following the same SOPs used by the routine field crew), including required voucher specimens and/or photos being sure to address all targeted variables initially assessed by the routine field crew.

3. **Compile results:** The QA crew transcribes their results into a data form that is separate from and independent of the routine field crew data.

4. **Confirm blind check is complete:** The QA crew reviews data form(s) for completion, ensures all notes are correctly documented, and confirms that any collected samples and/or specimens are properly labeled and secured for transport.

Once both the routine field crew data and the QA crew's blind check data have been reviewed, they can be compared to assess whether data quality acceptance criteria have been met.

5.2.3.3 Precision Checks

Not all restoration projects have the ability, either due to limited funding or access to available experts, to have separate QA crews conduct hot, cold or blind checks. Nor can many of the target variables associated with ecological restoration projects (e.g., wildlife species counts, vegetation structure, soil moisture) be expected to remain stable even over short time periods. For these situations, we recommend the systematic use of precision checks that are conducted by routine field crew(s) as a necessary component of the sampling design. Observer-determined data must be collected in a reproducible manner in order for it to be reliable and useful in supporting project decisions, and the simplest evaluation of data quality is a precision check.

Precision checks are conducted by having one or more field crews or members conduct re-measurements or observations of the same target variables at the same site. Estimates of within-crew precision can be made if a crew repeats measurement or observation of target variables for any given site where that same crew had previously collected data. Estimates of between-crew precision can be made if two or more crews collect data at the same site. *Because these checks are conducted without the benefit of data collected by experts for comparison, results of these checks cannot be used to estimate the accuracy or bias of the collected data*.

We recommend that project planners consider the following principles when establishing requirements for the use of precision checks:

- **Site selection:** As with other QC checks, sites for conducting precision checks should be selected so that the results are likely to be representative of typical data collection efforts.
- **Timing and variability:** Dates for monitoring will need to be coordinated to meet scheduling requirements and to ensure that crews collect data within a specific window to minimize the impacts of temporal variations on estimates of both within- and between-crew precision. For example, Kercher, Frieswyk, and Zedler (2003) describe a between-crew precision test for two sampling teams of botanists who evaluated species richness and cover estimates on twelve wet meadows in Dane County, Wisconsin, USA. After sampling by the first team, the second team made an independent assessment of ten 1 m^2 quadrats on each meadow. The corners of the quadrats were marked to assist the second team in finding them. Results indicated that species richness and cover estimates were similar, but one of the teams tended to have higher estimates for cover than the other.
- **Data management:** As with blind checks, data collected by the routine field crew or member are not available to the individuals conducting the precision check. Each dataset is treated as if it were the original during the process of data review and checking, and data are reviewed and processed in a manner similar to blind check data, with an emphasis on evaluating precision of the dataset against pre-established quality objectives.

5.2.4 *Summary of QC Field Checks*

For any data collection effort, the more QC checks conducted, the better the ability to assess data quality. Consistent with application of the graded approach to quality management (**Section 2.3**), the type and extent of QC checks applied to collection of observer-determined data will depend on the (1) intended use of the data, (2) anticipated impact of the project, (3) availability of appropriate resources, (4) project schedule and (5) requirements of the funding organization. Comparing and contrasting the five QC checks can be challenging as project managers try to evaluate what checks to consider for their projects. **Exhibit 5-7** provides a summary of the five QC checks discussed in this chapter to facilitate a high-level comparison.

Exhibit 5-7. Summary of QC Checks for Observer-Determined Data

<table>
<tr><th colspan="2" rowspan="2">QC Field Check</th><th rowspan="2">Purpose</th><th rowspan="2">Conducted by</th><th colspan="3">Used to Assess</th></tr>
<tr><th>Precision</th><th>Bias</th><th>Accuracy</th></tr>
<tr><td colspan="2">Hot Check</td><td>Provide Training and Real-time Feedback</td><td>QA Crew</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td colspan="2">Calibration Check</td><td>Provide Training and Calibration</td><td>Field Crew</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td rowspan="3">Checks to estimate measurement error</td><td>Cold Check</td><td>Produce Empirical QC Data</td><td>QA Crew</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>Blind Check</td><td>Produce Empirical QC Data (unbiased)</td><td>QA Crew</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>Precision Check</td><td>Provide Empirical QC Data</td><td>Field Crew</td><td>✓</td><td></td><td></td></tr>
</table>

There are many overarching principles that project planners should consider as they plan the types and frequency of QC checks that will be integrated into data collection activities. These considerations are summarized below and discussed in greater detail throughout the previous sections.

- Prioritize QC checks for routine field crews containing new members or crews with higher levels of quality problems identified during training.
- Use QC checks conducted in real time to address transitory variables (e.g., wildlife species identification and counts) as opposed to relatively stable variables (e.g., % canopy cover).
- Conduct QC checks within an acceptable time frame that sufficiently mimics site conditions at the time of routine field crew data collection.
- Select QC check locations that are sufficiently representative of the sampling sites and variables.
- Report, review and carefully consider results of QC checks within a time frame that allows for sufficient evaluation and, in some cases, data correction.

- Incorporate results of QC checks into real-time decision making as part of feedback to inform improvements in data collection.
- Choose a QC check strategy that provides a reasonable assessment of data collection procedures and/or data (e.g., minimum number of sites, variables at each site, QC checks) to support the credibility of any conclusions based on the results of QC checks.

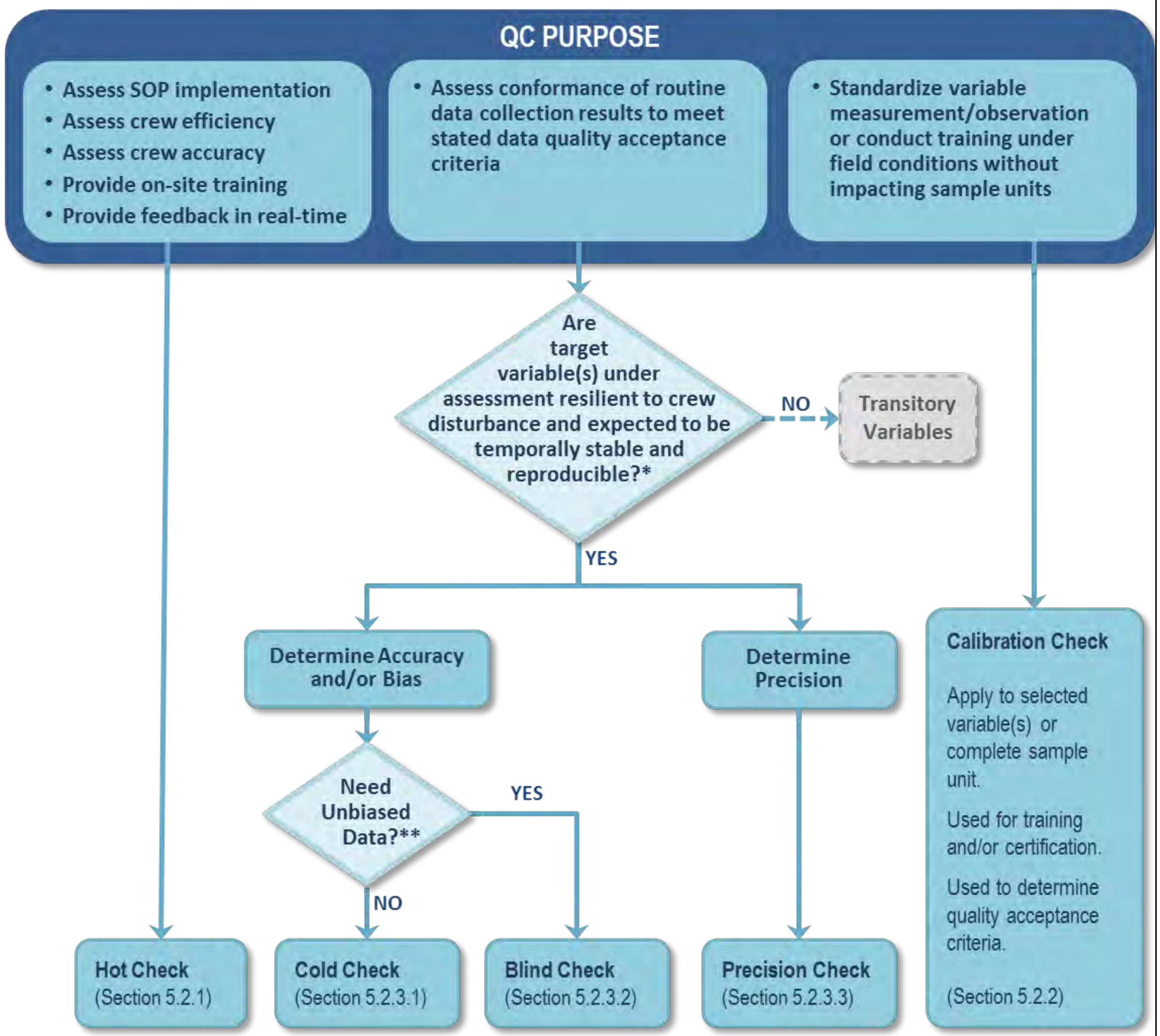
When selecting the appropriate QC checks, project planners also need to consider if the target variables are stable or transitory (as described in **Chapter 3**). With the exception of hot checks (**Section 5.2.1**) and precision checks (**Section 5.2.3.3**), the QC checks discussed in this chapter are applicable to assessing the quality of procedures used to collect data during monitoring of ***stable*** variables. Hot checks are conducted concurrently with routine data collection and are, therefore, an especially useful QC tool when the sampling design requires monitoring of ***transitory*** variables. Precision checks offer similar advantages for ***transitory*** variables, but are limited to providing information about precision, without the added benefit that hot checks offer in terms of assessing accuracy.

The following QA/QC strategies should be considered when projects require monitoring of transitory variables:

- Implement hot checks or concurrent precision checks.
- Conduct classroom or simulated field trials to estimate routine field crew accuracy, bias, and precision (and for potential use in determining data quality acceptance criteria).
- Periodically assess routine field crew ability to meet acceptance criteria.
- Use multiple routine field crew members to produce paired datasets for assessing precision.
- Pair routine field crew members with experts to collect paired datasets that can be used to assess accuracy and bias.
- Collect physical samples that can be split or duplicated to estimate accuracy, bias, and precision.

Exhibit 5-8 below presents considerations to apply when considering strategies to address data collected for stable variables.

Exhibit 5-8. QC Strategies for Stable Variables



* *Includes results from physical and biological samples that can be split, duplicated or vouchered.*

** *Access to previous monitoring results not permitted prior to assessment.*

As just one example of the application of QC strategies described in this chapter, we refer again to the example sampling objectives described in **Chapter 3** (**Exhibit 3-3** and **Exhibit 3-7)** and **Chapter 4** (**Exhibit 4-3**) related to the restoration of native willow. In this project, the monitoring design might include the overall measurement of 30 plots using three routine field crews, with each of the three crews measuring ten of the plots. The project planners could require each crew to be tested prior to the field season by a QA crew made up of field crew trainers, using hot checks. Blind checks could then be performed during the field season to document data quality. Because each routine field crew is measuring ten plots, a minimum of one blind check per crew might be selected as the re-measurement strategy.

5.3 USE AND REPORTING OF QC CHECK RESULTS

This section provides a general overview regarding the use and reporting of results of the QC checks described throughout this chapter. As noted, the results of these QC checks can be used to:

- provide feedback to improve data collection procedures and field crew capabilities;
- inform decisions regarding data collection activities; and
- facilitate assessments of data quality.

All of the QC checks described in this chapter result in some form of documentation of results, including notations, checklists, data forms, or reports. The procedures used to report the results are project-specific and will depend on the type, timing and purpose of the QC checks conducted. To facilitate and expedite use of QC check results, findings and reports should be provided to individuals involved in decision making, including the leaders and managers described below.

- **Field crew leaders** are often responsible for ensuring the correctness and completeness of all data from sampling site(s), and benefit from QC check findings to improve current or future data collection efforts.
- **Project managers** need to know if a field crew or member is failing to meet data quality acceptance criteria so they can make effective and well-informed decisions and take corrective actions as needed.
- **Project data managers** and **QA managers** ensure that corrections identified during the QC checks are reflected in the project database.
- **Project QA managers** are typically responsible for making and/or reviewing data usability assessments (see **Chapter 7**) and rely on QC check information as a critical component in doing so.

The results of these checks should be clearly linked to the corresponding project data, and provided to the appropriate responsible parties in sufficient time to (1) facilitate and improve data collection procedures, assessments and quality; and (2) support project decision making.

5.3.1 Feedback for the Routine Field Crew

Feedback based on the results of hot checks and calibration checks can be provided to field crew members at various stages, including as (1) immediate feedback, or (2) feedback based on results of compiled QC check results. Regardless of when feedback is received by the routine field crew members, the information can result in improvements to training and certification processes, data collection procedures, and the QC check documentation itself.

Both hot checks and calibration checks (**Section 5.2.1** and **Section 5.2.2**, respectively) are often used during training and certification. Immediately reporting these check results to trainers and field crew members can improve crew performance prior to initiating or continuing data collection activities. In cases where results reveal potential problems with SOPs, results should also be provided to project planners or other individuals responsible for ensuring that appropriate procedures are used for the project.

Hot checks are the only QC checks that allow field crew members to receive immediate real-time feedback regarding discrepancies or problems. These checks provide an ideal opportunity to discuss the discrepancies and problems along with any related concerns with experts. Upon completion of hot checks, the QA crew should report their findings to project management in a format that suits the nature of the project and the issues or problems identified. A report can be as basic as providing a verbal summary along with the completed checklists, or as comprehensive as a detailed summary report of key findings and recommendations.

5.3.2 Debriefings

In addition to providing feedback to field crew members, a comprehensive debriefing at the end of a field season or data collection effort is recommended to obtain a qualitative assessment regarding the reliability and appropriateness of the SOPs from the field personnel's point of view. For larger projects that are geographically extensive and involve multiple crews, feedback from routine field crew members should be integrated into both ongoing reporting activities and a detailed debriefing at the end of each field season or data collection effort. For small localized projects, debriefings at the end of each sampling period or data collection effort may be adequate.

Soliciting Feedback from the Field Crew: General Strategies for Project Managers

- **Encourage crew members to contribute ideas.**
- **Establish opportunities for field crews to report questions, concerns or suggestions related to their data collection efforts on a regular basis (during and after the sampling period or field season).**
- **Conduct routine (e.g., weekly) staff briefings, interviews or telephone calls, or request written feedback as part of a routine reporting requirement.**
- **Review feedback promptly if received during the field season.**
- **Respond promptly to all questions and concerns.**
- **Implement suggestions that would help improve operations and data quality.**

Potential debriefing methods include (1) providing field crew personnel with a comprehensive questionnaire, or (2) planning a debriefing meeting (in an office location or at the sampling site) during which one or more field crew members provide project managers with feedback and discuss possible suggestions for improving future data collection efforts. Debriefings and subsequent activities designed to improve data collection processes have been successfully integrated into the Great Lakes Coastal Wetland Monitoring program, which conducts monitoring efforts within coastal wetlands along the Great Lakes. Under this program, a debriefing of regional team leaders is held each winter to review procedures and identify potential improvements. This effort is a key component of their QA program (Uzarski et al. 2017).

On a broader level, an important component of any ecological restoration project is to allow for continuous improvements to data collection processes and data quality. Continuous improvements can be achieved by (1) increasing the effectiveness and efficiency of field SOPs (and resulting data quality) through process improvements that reflect QA crew feedback provided to routine field crew members, and (2) implementing debriefing procedures that help obtain objective and constructive feedback from field crew members.

5.3.3 Use of QC Check Results to Inform Decisions

The extent to which QC checks are used to inform decisions regarding data collection activities and data corrections varies widely, and is highly dependent on the timing, significance, and intended use of the results. Results of all QC checks should be included in the project database along with all original uncorrected field data. This allows for decisions to be made as needed, including during the data review process (see **Chapter 6**) based on all available information. In some cases, depending on numerous factors, data corrections may be needed sooner rather than later. For example, if results of a cold check indicate that a routine field crew member measured tree stem DBH incorrectly, producing an inaccurate estimate of basal area, the result may need to be corrected to reflect the corresponding "true" stem diameter. This information also informs decisions regarding whether additional visits to the site or field team should be made – or more significantly, whether the procedures used should be adjusted or described in more detail. Each project should have documented procedures that are planned ahead and in place for handling such corrections. In general, data errors that are identified during QC checks will need to be corrected in the project database along with a notation to explain the reason for the correction. These errors could include data found to be outside data quality acceptance criteria.

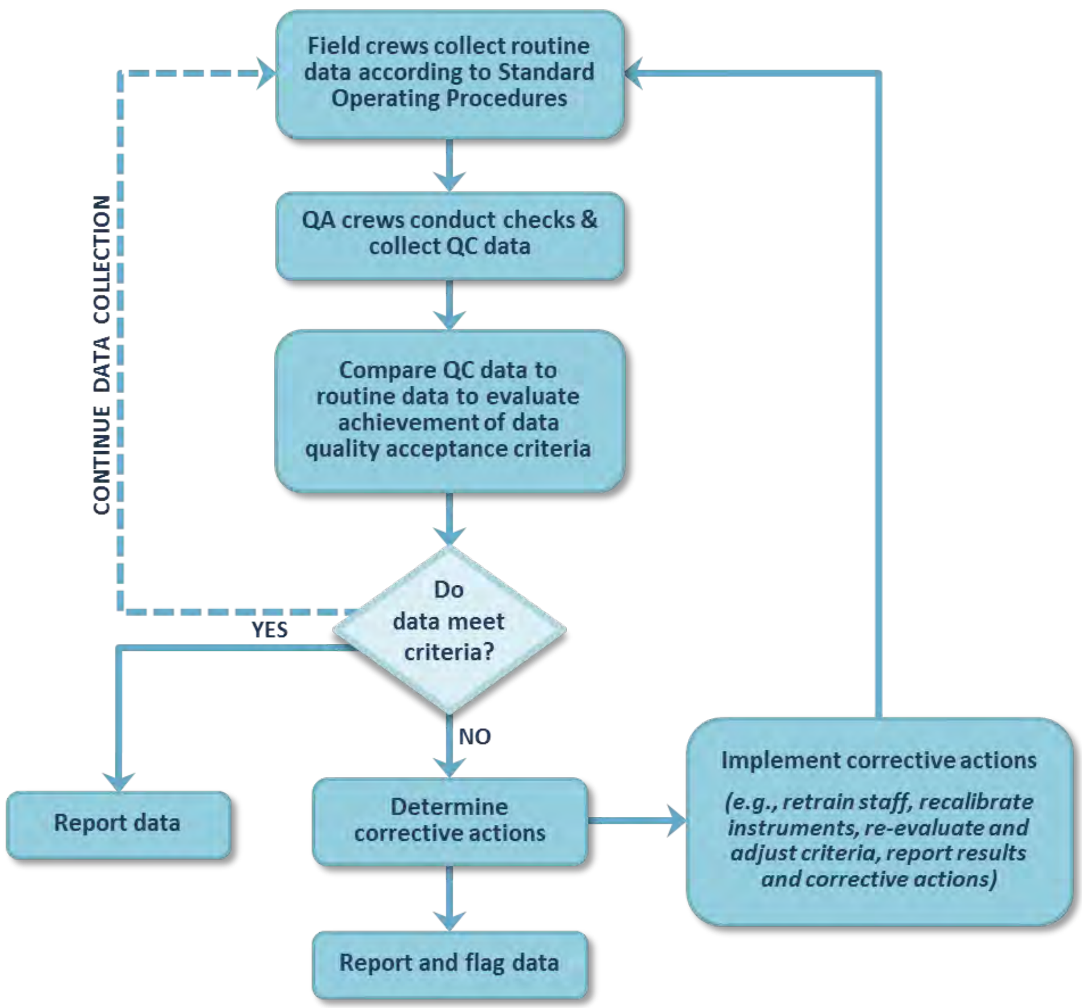
Each non-conformance finding pertaining to documented procedures or data quality acceptance criteria should be reviewed, particularly if the deficiency could result in unacceptable data quality. QA crews can often identify the root causes of a non-conformance finding (e.g., additional training needs, procedural changes) and provide recommendations to project managers that would help address the underlying problem. Resolution of data quality deficiencies may need to be verified by a subsequent hot check (or other type of QC check) within a sufficient period of time to ensure appropriate changes are implemented in a manner that improves data quality.

5.3.4 Assessment of Data Quality

QC check results are crucial for evaluating and documenting data quality. Specifically, these results allow data to be evaluated in terms of data quality indicators (DQIs), such as precision, bias, accuracy, representativeness, comparability, completeness, and detectability, and their related data quality acceptance criteria (see **Section 3.4**). Details regarding data review and assessments including the assessment of QC check results are provided in **Chapters 6** and **7**. In addition, **Appendix B** describes several statistical procedures that support these assessments. Depending on the specific project and purpose of data collection, potential impacts of QC check results include demonstrating that data quality acceptance criteria have been met, ensuring implementation of corrective actions, and improving data quality (see **Exhibit 5-9**).

Results of precision checks (see **Section 5.2.3.3**) provide the simplest means for evaluating whether data collected by field crews meet data quality acceptance criteria for precision. Because there are no QA crew datasets associated with these checks, results are reported separately, and subsequently reviewed and verified using identical procedures and considerations. Results of cold checks and blind checks also can be used to assess precision but because these results are collected by experts, their use is more appropriate for evaluating bias and accuracy. The ability of the data to meet the data quality acceptance criteria for the remaining DQIs also can be assessed using results from the suite of QC checks described in this chapter.

Exhibit 5-9. Iterative Process Incorporating Results of QC Checks



An example of the iterative process shown in **Exhibit 5-9** is a case where precise tree volume data were needed. One variable that fed into the calculation was tree length to a 4-inch top diameter; the specified acceptance criterion for this variable was that the reported length should fall within 1 foot of the true value, 90% of the time. The project manager worked with the database manager on a method for storing the data, and with experts to develop methods for collecting the data. Crews were trained, but the data collected were neither sufficiently accurate nor precise enough to meet the quality requirement. Field crews recognized that it was not possible to meet the acceptance criterion, as the methods being used required a visual estimate of a 4-inch top diameter from more than 100-feet away, through dense canopy and on trees with very little taper. In this example, the field crews informed the project manager of the need to develop alternative sampling methods. The project manager then worked with experts to develop alternative sampling methods, and the desired level of quality was met given the project design.

Results based on the QC checks should be documented in summary reports (or more detailed reports, depending on the intended use) and provided to project managers and decision makers who are evaluating the success of the ecological restoration efforts. These reports also should be provided to individuals involved in the verification and validation of data, as described in **Chapter 6**, and should include an assessment of whether data quality acceptance criteria were met for all targeted variables.

5.4 QUALITY CONTROL DURING FIELD ACTIVITIES – CHECKLIST

The checklist below provides a summary list of overarching considerations regarding the application of QC during field data collection activities. As with any checklist, the listed items should not be interpreted or applied without comprehension of the supporting information. Users of this checklist are encouraged to read and understand the corresponding details that are provided throughout this chapter, and to implement these details using a graded approach that is commensurate with a project's scope, importance and available resources.

QUALITY CONTROL DURING FIELD ACTIVITIES – CHECKLIST
☐ **Establish and maintain good field practices.** ☐ Ensure field crews have all the necessary information, documentation, equipment and materials, training, and data reporting forms needed to perform their assigned field activities. ☐ Establish communication methods between field crews and designated project leader(s). ☐ Ensure field crews have the necessary expertise and materials to record collected data and associated information clearly, legibly and with the level of detail required to address all target variables, including ancillary information. ☐ Establish and implement procedures for field crews to review data during and immediately following collection (e.g., use of multiple crew members, verbal repetition, reviewing transcribed results prior to leaving sampling location). ☐ Establish and implement procedures to ensure all specified data collection activities are completed before leaving sampling sites (e.g., double check all collected data, notes and comments; ensure all data forms, photographs, recordings, charts, samples and/or specimens are correctly labeled, organized, and stored; and ensure samples requiring laboratory analysis are handled in accordance with specified handling, transport and chain-of-custody procedures).

QUALITY CONTROL DURING FIELD ACTIVITIES – CHECKLIST
☐ **Establish qualified QA crews.** ☐ Identify and obtain access to individuals with the appropriate levels of experience, proficiency, and expertise to perform as QA crew members. ☐ Clearly document QA crew activities and responsibilities. ☐ **Determine field QC strategies.** ☐ Determine the type of QC field checks that are appropriate for your project. ☐ Determine the location, timing and number of QC field checks that are appropriate for your project. Chose a strategy that allows a reasonable assessment of sample and data collection procedures, field crews, and the resulting data. Consider prioritizing checks for less experienced crew members and more challenging procedures. Ensure the strategy provides QC check data that are sufficiently representative of site conditions and target variables. ☐ Use QA crews to perform QC field checks where feasible; rely on routine field crews to conduct precision checks in other circumstances or as an additional QA tool. ☐ Conduct all QC field checks within a time frame that sufficiently mimics site conditions at the time of routine field crew data collection. Address transitory variables by conducting QC checks in real time (concurrent with routine data collection). ☐ **Use and reporting of QC field check results.** ☐ Establish and implement procedures to: o Ensure QC field check data are complete and accurately associated with corresponding field crew data. o Compare QC field check data to routine field data, and evaluate the results against data quality acceptance criteria. ☐ Report, review and consider results of QC checks within a time frame that allow for sufficient evaluation and corrective action. ☐ Establish and implement communication between field crews, QA crews, and project decision makers to evaluate and act upon QC field check results and data collection activities.

5.5 ADDITIONAL READINGS

- Bergstedt, Johan, Lars Westerberg and Per Milberg. 2009. *In the eye of the beholder: bias and stochastic variation in cover estimates.* P. Plant Ecol 204:271. doi: 10.1007/s11258-009-9590-7.

- Nadeau, Christopher P. and Courtney J. Conway. 2012. *Field evaluation of distance-estimation error during wetland-dependent bird surveys.* Wildlife Research 39(4):311-320 https://doi.org/10.1071/WR11161.

CHAPTER 6 DATA REVIEW

Data generated and collected during ecological restoration projects form the basis of critical decisions, including whether objectives were achieved and what adaptive management strategies are needed to prevent or correct failures and build on successful efforts. Thorough review of project data is crucial for identifying limitations that might impact its use in making reliable decisions regarding project effectiveness, next steps and potential improvements. For the purposes of this chapter, we refer to the process of evaluating data quality and documenting limitations as a "data review" that consists of data verification, data validation and data certification (see text box).

No single data review process is perfectly suited to the needs of all organizations, projects or data types. Therefore, this chapter provides guidance on process-related options that should be considered. **Section 6.1** discusses concepts to consider when planning data review activities. Data verification and validation processes are described in **Section 6.2**, followed by guidance for handling data discrepancies and errors in **Section 6.3**. Finally, **Section 6.4** provides recommendations concerning data certification. Although the primary focus is on data collected in the field, the review of laboratory data can play a critical role in supporting decisions for ecological restoration projects and is included in some of the examples.

Data Review

Data Review **is a process to confirm data quality, identify any associated limitations, and help managers understand how confident they should be in these data if they are used to support decision-making activities. Components include:**

- **Verification**: ***Confirmation, through provision of objective evidence, that specified requirements have been fulfilled*** **(ISO 2015b, ASQ 2014). For ecological restoration data, this includes verification that specified procedures were followed, results comply with data quality requirements (e.g., established acceptance criteria for data quality indicators were achieved), data entry and calculations were performed correctly, and data integrity has been protected. In other words, data verification asks, *"Did they do it right?"***
- **Validation**: ***Confirmation, through provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled*** **(ISO 2015b, ASQ 2014). For ecological restoration data, this includes ensuring that the data are scientifically valid, and that they support broader project and sampling objectives. In other words, data validation asks, *"Does it make sense?"***
- **Certification**: **Ensuring a secure validated database has been completed, documented and certified (if applicable) and that the data within the database are suitable for final usability assessments in preparation for analysis, reporting, distribution and archiving.**

6.1 PLANNING DATA REVIEW ACTIVITIES

Data review activities should be planned well in advance, preferably along with other aspects of project planning. Qualified data reviewers should be included in planning efforts. These reviewers should be carefully selected and must possess the knowledge, skills and experience needed to accurately assess conformance with required data collection procedures and established project criteria. Early planning of data review allows for the integration of data review components with data collection and documentation processes, which can expedite portions of the review process and facilitate timely support for project decisions. Guidance on the timing, responsibilities and procedures for performing and documenting data review activities are provided in the five subsections that follow.

Important Project Planning Considerations

- **When will data review activities be performed? (Section 6.1.1)**
- **Who will review the data? (Section 6.1.2)**
- **What will be reviewed and what materials are needed? (Section 6.1.3)**
- **How will the data be reviewed and findings conveyed to data users? (Section 6.1.4)**
- **Documenting the results of these decisions in written data review procedures (Section 6.1.5)**

6.1.1 Timing (When to Review the Data)

In general, data review should occur at each stage of data collection or reporting, and each time data are submitted or passed from one level to the next (see **Exhibit 6-1**). Some data review activities, such as those shown in the first row of **Exhibit 6-1**, are performed by field and laboratory staff before crews leave the field or results are submitted by the laboratory. These pre-submission activities should be built into data collection standard operating procedures (SOPs), and provide an opportunity to correct problems or errors in real-time (i.e., during data collection) when conditions best reflect the data collected (see **Section 5.1**). Additional data reviews should be conducted by personnel who were not directly involved with (i.e., were independent of) the generation or collection of data, as discussed in **Section 6.1.2**.

Benefits of Early Data Review

Timely review of data increases opportunities for correcting errors early and preventing similar ones from occurring as the project progresses. In addition, preliminary analysis (e.g., plotting) of key data variables can be useful in identifying unexpected results or trends and determining if modification to the monitoring program is needed. (See Chapters 7 and 8 for guidance on analyzing verified and validated data and adapting the restoration or monitoring programs as needed based on results of those analyses.)

Exhibit 6-1 identifies four potential stages of data review, but these are not absolutes. Project managers should use a graded approach that balances resources against the risks of obtaining and relying on flawed data. This may require deciding to consolidate some of the review activities and accepting the associated risks. For example, limited resources may require combining the activities described in the second and third stages; this action would result in fewer opportunities for (1) correcting procedural problems while the sampling season is still underway, or (2) having labs reanalyze samples that failed to meet specified acceptance criteria. Conversely, use of automated data capture and/or data review tools may streamline activities enough to allow for review of data immediately upon receipt, thus allowing the second and third stages to be combined without compromising opportunities for timely correction of problems.

Exhibit 6-1. Example Strategies for Conducting Data Review Activities at Each Stage of the Data Collection, Reporting, Transcription and Management Process		
When	**Description**	**Examples**
Before results leave the field or lab	Ensure data are complete, legible and correct before reporting results; includes inspection of data by field crew leader before leaving site or internal review of data by lab QA manager	1. Field crew leader confirms the presence of a plant species and ensures the species identification code is documented correctly and legibly before leaving the plot (see **Section 5.1**) 2. Lab QA manager reviews compiled data package and certifies it complies with requirements before submission
Upon receipt of reported results	Ensure field or lab data are reviewed early enough to correct problems and prevent identified problems from recurring	3. During a cold check, the QA crew determines the routine field crew recorded the wrong plant species and identification code, initiates corrective action to prevent future recurrences, and recommends replacing the incorrect routine crew values (see **Section 5.2.3.1**) 4. A data reviewer identifies blank contamination affecting laboratory-reported phosphorus results and requests reanalysis before analytical holding times expire
Before upload to project database	Ensure corrections recommended from previous reviews have been captured before data are uploaded or merged	5. A data reviewer confirms the plant species codes on the original field crew forms have been corrected to reflect the QA crew recommendations made in Example 3 before data entry 6. A data reviewer verifies the reanalyzed phosphorus results requested in Example 4 have been received and are acceptable
After merging with other data	Ensure data manipulation activities were successful without compromising integrity of the database and confirm scientific validity of the dataset	7. After merging data, a data reviewer verifies all required fields are populated correctly (e.g., without data shifts), and units are correctly and consistently reported 8. A data reviewer examines the fully merged dataset (or the newly uploaded material) to determine if reported values are consistent with expected as described in **Section 6.2.3.2**

6.1.2 Internal vs. External Review (Who will Review the Data)

Although staff who generate and record field or laboratory data should review their work carefully before submission, these self-checks are often somewhat subjective. For this reason, data review plans should always include some level of review by individuals who are **independent** of (i.e., not directly involved in) the data collection or generation.

Independent Data Review – Examples

- **Review by experts or QA crews performing QC checks**
- **Laboratory QA Manager review and certification of data packages before release or submission**
- **Review of submitted field or lab data by independent QC staff (data reviewers)**
- **Review of the final, validated dataset by a Senior Scientist or Principal Investigator before submission to the sponsoring Agency**

In some projects, it may be appropriate to plan at least two levels of independent data review that include:

- an **internal review** by the organization that generates the data (e.g., a university, state or other party operating under a federal grant), and
- an **external review** performed by an entirely separate organization (e.g., scientists within the federal agency that is funding the grant or an independent contractor hired by the federal agency to review all grant data submissions).

Questions to consider when making this decision pertain to the likelihood of decision errors, reliability of the organization or individuals collecting the data, available budget, scheduling limitations, and the data review methods/tools that will be used. Examples of relevant questions include the following:

- What is the likelihood that a decision error might be made based on faulty data (or what is the risk of a decision error being made)?
- What is the likelihood the organization generating the data will make mistakes?
- Is it possible to conduct an external review within the project schedule and budget?
- What is the risk of not conducting an external review?
- What tools are available to perform and document the data review activities? For example, in some types of projects (most notably, those involving laboratory analysis of water or soil samples), software that automates data review can be obtained and customized fairly easily.[9]

As discussed in **Chapter 2**, the cost of conforming to quality requirements should be lower than the costs of non-conformance. Therefore, project planning teams making decisions regarding the use of external data reviewers must balance the need to mitigate identified risks against the resources and

[9] The U.S. EPA Superfund Contract Laboratory Program uses data reporting software that automates certain aspects of data review, and similar products can be purchased and customized by entering project-specific details about target variables, data quality indicators, corresponding acceptance criteria, etc.

nature of their project. Decisions do not need to be applied on an all-or-nothing basis. For example, an organization may rely on internal data reviewers who are independent of the data collection activities to verify and validate the data as it is received from the field, and rely on another organization to re-review a representative portion of the data after it is compiled into a project database. Alternatively, if missed deadlines pose a significant risk, an organization may opt to outsource all or most of the review to a firm with expertise in data review.

Risk Mitigation and Decision Making – an Analogy

Deciding whether to incorporate external data review is somewhat analogous to the car buying process. When purchasing a new car, buyers typically rely on internal quality checks performed by the manufacturer and dealer, while used car buyers often hire a mechanic to identify potential problems. An explanation for the difference lies in the degree of risk. New cars usually have a substantial manufacturer's warranty, and manufacturers control quality from start to finish because quality-related problems can have a significant adverse impact on their reputation. Used cars rarely come with warranties that offer the same level of protection and are often purchased from individuals or secondary vendors who cannot guarantee the same level of quality. Project planning teams must similarly consider and balance risks when deciding who should review data and how.

6.1.3 Identifying Data be Reviewed and the Materials Needed (What Data Reviewers Will Examine)

Once decisions have been made about who will conduct the data review activities, project planning teams need to identify the specific types of data that require review and the materials required by reviewers in order to do so. Each of these topics is addressed in the subsections below. Although the emphasis is on data collected by field crews, the concepts presented can also be applied to laboratory results reported from analysis of collected samples.

6.1.3.1 Primary vs. Ancillary Variables

Ecological restoration projects typically involve the collection of (1) data for **primary variables of interest**, such as stem density, species, cover class codes, and tree height, and (2) **ancillary data** such as information about who collected the data and when, weather conditions encountered during collection, vegetative status of target plant species (e.g., flowering, fruiting, senescence), or other information such as voucher and photo IDs or metadata. Both types of data need to be considered when planning data review strategies.

Ancillary Variables – Examples

Examples of variables that can impact reported results, help verify data accuracy and/or influence data interpretation include:

- **wind speed,**
- **flow conditions,**
- **observer ID,**
- **sample location or GPS coordinates,**
- **camera trap metadata,**
- **reproductive status, and**
- **the presence (or absence) of certain plant structures.**

Data concerning primary variables of interest are used to determine if objectives have been achieved and guide adaptive management decisions; careful review is essential to ensure the data are reliable enough to support such decisions. Ancillary data can be used to help evaluate data quality and interpret results as shown in the following examples.

Ancillary Variables Describing…	Can be Used to…
• Where (e.g., stream reaches, transects, plots) and when (e.g., date, time start/end) data were collected	• Verify that reported data were collected from the specified locations and within the required timeframes
• Who collected the data (i.e., identification of field crew teams and members), in conjunction with QA crew data	• Detect bias among results reported by different field crews
• Camera trap placement (e.g., angle and distance of target relative to the camera)	• Explain anomalies when confirming the validity of scientific assumptions (Parsons et al. 2015)
• Environmental conditions (e.g., air temperature, wind, cloud cover, precipitation) at the time of data collection	• Establish whether field activities were conducted in accordance with pre-established criteria and thus can help support (or refute) data collected for a primary variable of interest

For instance, sampling during peak flows can lead to increased variation in the total counts of stream bed invertebrates, and the reliability of bird census data can diminish when wind speed is excessive (Larsen et al. 2004). To address the latter concern, the North American Breeding Bird Survey protocols specify that wind speed must not exceed 12 mph (USGS 2017a). As discussed in **Section 6.2.3.1**, we recommend that project planning teams develop variable-specific procedures that describe how each primary variable, and its corresponding ancillary and QC data will be verified.

Note: In some cases, ancillary data that do not directly support the sampling objectives and monitoring strategy are collected because they are cost effective to obtain while personnel are in the field and may provide useful information for related projects. If such additional variables are collected, project planning teams also need to decide when, if, and how to review the results. At a minimum, we advise allocating enough resources to verify that these additional ancillary data are complete and comply with requirements because (1) concurrent review with other project data is likely to be most cost effective and (2) the ability to investigate and resolve problems tends to diminish over time.

6.1.3.2 Materials Needed for the Review

As shown in **Exhibit 6-2**, data reviewers will need to examine requirements governing the collection or generation of the data they will be reviewing, results of field and laboratory QC checks, and other information (e.g., post-season debriefing results) that may shed light on the data being reviewed. Having access to the requirements and all field and laboratory records during data review is vital.

- Plans, maps, SOPs and other instructions provide a baseline for confirming requirements are met.
- Reporting forms submitted by routine field crews, QA crews and laboratories (digitally or on paper) summarize results for the variables of interest and provide an efficient means for verifying all

required locations were sampled, all required data were gathered, all required QC checks were performed, and results complied with specified QC acceptance criteria.

- Raw field and lab data, including completed forms, logs, video- and audio- recordings, photos, drawings and instrument output provide a means for verifying the procedures and calculations used to generate the data were performed correctly. They also can be used during data validation to investigate questionable results. For example, crossed-out data, inconsistencies between sample collection logs, and other anomalies could be an indicator that certain samples or specimens were mislabeled and may help explain why results collected at two plots during one event appear to be reversed relative to all other recorded observations.

Exhibit 6-2. Example List of Materials and Documents Needed to Review Data

Requirements	Routine Field Crew and Laboratory Data	Field and Laboratory QC Data	QA Information
• Sampling or monitoring plans • Maps of locations to be sampled • Field and laboratory SOPs • Field guides, lists, keys, code definitions • Data review procedures	• Completed data reporting forms capturing primary and ancillary data • Specimen and sample packing forms • Field and laboratory notes and logs (including sample collection logs) • Video, audio/acoustic recordings • Photographs • Chain-of-custody forms	• Instrument calibration records • QC check findings, reports and forms (including QA crew field notes/logs, recordings, recommendations) • Lab QC sample results	Feedback from routine field and QA crews (e.g., debriefing results)

6.1.4 Determining Data Review Strategies (How to Review the Data and Document Results)

6.1.4.1 Level of Review

Project planning teams need to determine the degree of data review that will be required, again balancing resources against risk. At one extreme, this could include nothing more than self-inspection of results before submission. At the other extreme, it could include a complete review of all (1) personnel training records, (2) reported results and (3) supporting information (e.g., calibration records, field or laboratory notes, bench sheets, photographs, recordings), at every stage of the data collection, reporting, transcription and management process. Neither extreme is practical or recommended. The former is highly risky, and any savings in data review resources are likely to be less than the costs associated with making decisions based on data of poor quality. The latter is highly time-consuming, and unlikely to reveal data quality issues that could not be detected using a more cost-effective approach.

In most cases, planning teams should be able to strike a balance that involves:

- reviewing all summary-level results as early and often as practical to
    - maximize opportunities for obtaining missing information and clarifying questionable results, and

- minimize opportunities for propagation of errors throughout the data acquisition and management processes,

- spot-checking supporting data at a pre-determined frequency to confirm that personnel are following procedures correctly, and
- using supporting data as a tool to investigate potential causes of summary-level results found to deviate from requirements or expectations.

Project planning teams also need to determine how and when spot checks will be applied. For example, if a team decides to require spot checks on 10% of the supporting data, data reviewers could be instructed to randomly pick 10% of the values in their data package. Alternatively, spot checks could be pre-assigned in some way that ensures an overall average of 10%, with a higher frequency on primary variables of interest and a lower frequency on ancillary data.

Problems detected may be indicative of other problems within the data. Therefore, reviewers who find problems should be instructed to conduct additional spot checks as needed to determine the potential extent of any errors identified and their impacts on data quality. The amount of additional review required will likely depend on the nature of the errors identified (e.g., whether an error is isolated, part of a pattern, or likely to have a substantial impact on data interpretation).

Spot Check Strategies

Spot checks do not need to be applied consistently. The following are examples of situations where it may be helpful to apply more frequent spot checks:

- **Data reported by new field crew members**
- **Primary variables of interest**
- **Variables that are particularly challenging to quantify**
- **Sites that are known to present more challenging conditions**
- **Data submissions in which initial spot checks revealed problems**

6.1.4.2 Automated vs. Manual Data Review Strategies

Data review can often involve time-consuming manual review of data forms, field and laboratory notes, instrument printouts and other documentation. A number of tools are available to automate some of these processes, ranging from complex data management systems and software to simple, customized spreadsheets and portable data recorders (PDRs) with built-in data capture QC checks.

At the low end of automation, a project team might rely on standardized reporting forms to facilitate manual data entry, coupled with simple automated routines to identify missing values and verify compliance with pre-determined reporting rules (e.g., valid date formats, correct measurement units) or requirements (e.g., reference tables that list valid species names or codes). Errors identified using easily automated checks can be investigated and corrected before remaining data are reviewed manually against requirements that were deemed too difficult to automate given project resources.

At the high end of automation is a fully- or near fully-automated data capture and review process that uses:

- scanners that can read encoded labels such as barcodes or embedded radio frequency identifier tags (e.g., pit-tags);
- digital instruments such as in-line continuous monitoring devices (e.g., a remote data logger monitoring water characteristics and quality);
- laboratory instruments that capture data directly as they are generated; and/or
- laptops, computer tablets, smartphones or more specialized PDRs (e.g., handheld digital weather meters, software enhanced global positioning system (GPS) units) with programs that enable crews to electronically record and check observations and measurements in real time.

These highly automated tools reduce the potential for entry or transcription errors. They also allow data to be automatically checked during capture for conformance to reporting requirements. Data that pass this layer of verification can then be subjected to more thorough review as described in **Section 6.2**.

Data Review Strategies – Finding a Balance

Some data automation efforts can be easily implemented through commercially available software (e.g., review of traditional chemical measurement results). However, some types of data reviews (e.g., for observer-based field data or novel measurement data) are difficult to automate. For ecological restoration projects, an optimal balance of cost and efficiency usually lies somewhere between an entirely manual process and complete automation.

Ideally, decisions about the use of manual and automated approaches are considered early in the planning process and developed, documented and deployed in time for use during staff training and certification.

6.1.4.3 Determining How Data Review Results Will Be Documented and Certified

Data review activities usually result in the identification of at least some questionable data and potential errors.[10] Questionable data are typically caused by:

1. ***field crews, lab personnel and other data handlers*** (e.g., species misidentification, inadequately defined variables or procedures, problems related to data entry or transcription), which is the most common type, or
2. ***factors outside the organization's control*** (e.g., a storm that prevented crews from conducting a field survey during the scheduled time).

Regardless of the cause, it is extremely important that procedures for handling these data be included in project planning decisions and data review procedures. This includes deciding (1) how the data will be

[10] As an example, a semiannual progress report (Uzarski et al. 2015) prepared for the U.S. EPA Great Lakes National Program Office described a comprehensive audit of all water quality data, noting QC flags related to the use of incorrect units (77% of total), incorrect calculations for total alkalinity (17%), questionable pH readings (5%), and values entered in the wrong location (1%).

identified; (2) what and how decisions will be made regarding treatment of the data; (3) what and how corrective actions will be taken; and (4) how the data, decisions and actions will be documented. **Section 6.3** provides guidance on these aspects of data review; **Section 6.4** provides guidance on certifying that the reviewed datasets are complete and of known and documented quality.

6.1.5 Documenting Data Review Strategies

As a final step, project planning teams should clearly document the results of their decisions in writing. Doing so provides a reference and training resource for data reviewers, helps ensure consistency across all data review practices and among different data review personnel, and serves as a tool to ensure data review results are clearly understood and transparent. Whether they are included in a data management plan, the project QA plan, a formal SOP, or some other documentation, these procedures should be (1) in place prior to any data collection; and (2) fully understood by those involved in data review and by those who rely on the quality of the data to support their decisions.

Written Data Review Procedures

- **When will the data be reviewed?**
- **Who will review the data?**
- **What will be reviewed and what documents are needed to support data review activities?**
- **How will this documentation be made available to reviewers?**
- **How will the data be reviewed (including variable-specific strategies and criteria)?**
- **How will results of the data review be documented?**
- **How will issues, such as data discrepancies and potential errors, be documented and handled?**

6.2 DATA VERIFICATION AND VALIDATION

Data verification and validation are related aspects of data review activities performed to provide data users and decisions makers with data of known and documented quality (see text box below and **Chapter 2**). Data **verification** focuses on evaluating whether specified requirements were met, and generally involves determining whether:

- all required data are present,
- approved procedures were followed,
- acceptance criteria were met for specified data quality indicators, and
- data were documented accurately at each stage of data handling.

The U.S. OMB defines quality based on the following overarching principles:

Objectivity: The information and the manner in which it is presented must be accurate, clear, complete and unbiased.

Integrity: The information must not be compromised through inadvertent data corruption, falsification or revisions, and/or unauthorized access.

Utility: The information must be useful for the intended users.

Data **validation** focuses on evaluating whether the data make sense and generally involves determining if reported values are scientifically logical. From a practical perspective, data verification and validation activities often overlap and can occur at all stages of data collection and transfer, beginning with verifying the capabilities of the individuals collecting or generating the data. Specific approaches to data verification and validation may vary by organization, project or data types. Therefore, this section describes general process-related strategies (**Section 6.2.1**), discusses specific activities that are performed during data review (**Section 6.2.2**), and provides examples of techniques that are useful in implementing these activities (**Section 6.2.3**).

6.2.1 General Process-Related Strategies

We believe the three strategies described below are helpful, regardless of project scope, size, and complexity.[11]

1. **Begin by verifying all required data are present and legible.** In essence, this involves conducting a completeness check (described below in **Section 6.2.2.1**) to verify that field and/or laboratory personnel reported results for all data they were supposed to generate or collect. Such checks tend to be less time-consuming than those for other data verification and validation activities, so it is usually most efficient for data reviewers to confirm they have all the required data in hand before immersing themselves in details and discovering they have to stop, request, and wait for missing information.

   If data are illegible or missing, the data reviewer should initiate corrective action activities immediately. For illegible results, this usually involves contacting field or laboratory personnel to request clarification and documenting the corrections as described in **Section 6.3**, "Handling Data Discrepancies and Errors." For missing values, corrective action may include re-sampling if (1) the problem was detected while crews are still in the field, (2) there are sufficient resources to conduct the re-sampling, and (3) the re-sampling efforts are consistent with the study design. If samples requiring laboratory analysis were sent to a laboratory but never analyzed, corrective action should include consideration of whether the analyses can be completed before analytical holding times expire. In some cases, project planning teams may prefer to accept and qualify results generated slightly outside of recommended holding times in lieu of having no results at all.[12]

[11] For the purpose of this discussion, we assume qualifications of field and laboratory personnel have already been established as described in **Chapter 4**, and all results have been reviewed before leaving the field or submitting laboratory results as discussed in **Section 5.1**.

[12] Analytical holding times are typically established by testing the stability of a variable in replicate aliquots over specified intervals of time. If no statistically significant changes are detected, holding times are typically set to the maximum amount of time evaluated. If there is reason to believe the recommended holding times represent the longest period of time evaluated rather than an actual point at which values were determined to significantly change, it may be more helpful to qualify results generated outside of holding times than to have no data at all.

2. **Once data are determined to be complete, focus on summary-level results (e.g., data reporting forms) before examining raw data (e.g., field notes, photos, instrument output).** Summary-level reports are designed to convey information about primary and ancillary variables of interest in an organized, logical format. Accordingly, they are often an efficient mechanism for quickly identifying potential deviations from project requirements and flagging these deviations for further review. For example, when data are reported on hardcopy reporting forms, data reviewers can quickly cross-reference each form against checklists or reference tables that identify acceptable values (e.g., valid site locations, species codes, range limits) for each variable on the form. Such assessments can be streamlined even further if summary data are reported in or have been converted to an electronic format, as discussed below.

   Summary-Level Data – Examples

   - **Results reported on field reporting forms or checklists**
   - **Field data captured with portable device recorders and exported into specified spreadsheet formats**
   - **Data exported from laboratory systems to summary-level printout or spreadsheets**

   Raw data include all other types of records generated by field and laboratory personnel, such as field or laboratory notes, drawings, bench sheets, raw instrument printouts, photographs, specimens, and video and audio recordings. These data as are used to:

   - investigate potential problems identified during review of the summary-level data, and
   - confirm that summary data that passed the initial screen are consistent with the raw data and the required protocols.

3. **Use automated tools as much as possible to quickly identify results that do not conform to requirements (verification) or scientific expectations (validation).** Automated tools can significantly improve the effectiveness and the efficiency of the verification and validation processes, and should be used whenever feasible. Such tools do not have to be expensive. For example, modern spreadsheet software can easily be configured to compare reported results against requirements and expectations by creating or using:

   - look-up tables that capture acceptable values (e.g., lists of all valid site names, species names, species codes) for primary and ancillary variables;
   - formulas or macros to compare reported data against the corresponding values in the look-up tables;
   - conditional formatting or formulas created to quickly identify results that fall outside of acceptable or expected ranges; and
   - frequency checks to help quickly identify missing values or inadvertent data shifts that may have occurred during data merges or other manipulations.

> **Note**: When using spreadsheet software to process data, project teams should document procedures that all staff must follow to minimize the introduction and compounding of error that normally would be avoided when working within a relational database management system that provides advanced version and error control features. Refer to **Appendix A** for a more in-depth discussion of effective data management practices.

6.2.2 Data Verification and Validation Activities

In addition to the general process-related strategies described above, certain activities apply to all data reviews, regardless of the project size, scope and complexity. These activities are described in the following subsections, and include determining if the reported results (1) are complete, (2) reflect correct application of procedures, (3) meet specified data quality acceptance criteria, (4) were documented and reported correctly, and (5) make scientific sense. Many of these activities can be streamlined significantly through the use of electronic data reporting tools that are pre-populated with look-up tables and application of macros, if/then statements, or range checks that can highlight non-compliant or questionable results.

6.2.2.1 Verifying Completeness

In order to confirm all required data were collected, generated, and reported, data reviewers should verify that:

1. data are present from all required sampling locations;
2. data are present for all required variables and corresponding ancillary and QC data;
3. all planned samples and voucher specimens were collected and reported;
4. any required data reporting forms were used and filled out legibly and completely;
5. raw data are present and legible for each variable, as applicable (e.g., field notes, bench sheets, laboratory notebooks, raw instrument outputs, written narratives);
6. all required/supporting QC data are present, including:
    a. samples collected for lab analysis, such as instrument, method and matrix QC (e.g., field or trip blanks, instrument calibration blanks, method blanks, field duplicates), and
    b. samples collected for species identification, such as plant or animal voucher specimens, tissue samples for DNA analysis, audio recordings and digital photographs;
7. field QC checks (e.g., hot checks, cold checks, blind checks, precision checks, calibration checks) were implemented and documented;
8. field crew and laboratory analyst feedback regarding data quality concerns has been documented; and

9. data quality issues identified by field or laboratory QC checks were evaluated, and the affected data have been tagged with corresponding explanations.

Note that the items listed above should reflect the timing and scope of the data being reviewed. For example, when verifying the completeness of routine field crew data reported from a single site assessment on a single day, a data reviewer would address the first five items listed above. In contrast, a reviewer examining a batch of routine field crew data, QA crew data, and laboratory data for a group of sampling events would address the first eight items. The last item is usually applied to data that have already been reviewed and determined to have data quality issues that require correction or annotation of results; the purpose of a completeness check at this stage is to verify that such data review recommendations are captured in the final dataset.

6.2.2.2 Verifying Compliance with Required Procedures

All project results should be carefully reviewed to verify they were collected from the correct location(s), during the correct time(s), using the correct forms and procedures, and that any anomalies, corrections or other issues were properly addressed. This includes verifying that:

- field crews followed the specified protocols;
- environmental samples were properly preserved and handled from collection to laboratory processing;
- laboratories used the specified procedures for sample analysis and analyzed samples within appropriate holding times;
- data were collected at specified frequencies and within specified time frames (e.g., seasons);
- data were collected by individuals having the required experience and training;
- sample locations are consistent with specified locations;
- field and laboratory calculations were performed correctly;
- field notes or laboratory narratives provide explanations of any difficulties encountered, deviations from procedures, or deviations from QC requirements;
- identified errors have been corrected and signed by the person who made the change; and
- data flags that field or laboratory personnel are required to apply to results that deviate from requirements, are present and accurate.

6.2.2.3 Assessing Conformance of Data to Data Quality Acceptance Criteria

> **Commonly used DQIs**
> - **Precision**
> - **Bias**
> - **Accuracy *(includes precision & bias)***
> - **Detectability**
> - **Representativeness**
> - **Comparability**
> - **Completeness**

In addition to verifying that data were generated in accordance with required procedures, reviewers also need to determine if QC data demonstrate conformance with specified acceptance criteria. As discussed in **Section 3.4**, acceptance criteria vary by data quality indicator (DQI) and by the type of data collected.

Determining if precision, bias, accuracy, and detectability requirements were met involves the following activities:

- verifying that equipment used in the field was properly calibrated before use;
- comparing routine field crew results to corresponding results reported by QA crews to determine if the desired level of agreement was achieved; and
- examining results from laboratory analysis of QC standards and samples (e.g., instrument calibration standards and blanks, field blanks, method blanks, field duplicates, spiked samples) to identify any deviations from specified acceptance criteria.

Although strategies for ensuring comparability and representativeness must be built into the sampling design (e.g., through the use of SOPs and a sufficient distribution and number of sample locations to represent the population of interest), data reviewers can use range and consistency checks to help identify inconsistent or unrepresentative values. For example, a consistency check may reveal the reported presence of a plant species outside its previously known range. Such a finding usually warrants examination of photographs or voucher specimens to confirm the identification, and once confirmed, may warrant additional sampling within the study area to more accurately characterize distribution of the species. Similarly, checks for impossible values (e.g., an invalid species name) or illogical values (e.g., a total organic carbon value that is less than a corresponding dissolved organic carbon value) can help identify questionable results, and once investigated and corrected, enhance the comparability and representativeness of the dataset. **Section 6.2.3.2** provides a more in depth discussion of range and consistency check techniques.

Installation of log vanes and a bankfull bench on Elm Creek, Minnesota in the southern glaciated cornbelt region. Photo Credit: Britta Suppes, Joe Magner, Chris Lenhart

6.2.2.4 Verifying the Integrity of Results

Data handling activities introduce ample opportunity for (1) inadvertent corruption of results, or (2) incomplete or inaccurate linkage of related results. For example, errors as small as a single stray value can cause significant data shifts to occur when one set of data is merged with another. Similarly, data transfers between different types of documentation (e.g., from field notes to forms), can introduce mistakes related to transcription and typographic errors, omissions, duplication or erroneous data associations (linkages).

To help identify and correct such problems, we recommend designing data management systems in a manner that documents all modifications by data reviewers, managers or other project staff, such as an audit log that documents the individual who revised the data, the date and time of the revision was made, and the value(s) before and after the revision. (Refer to **Appendix A** for additional recommendations concerning data management.) We also recommend identifying and correcting:

- transcription or typographical errors between field notes and field forms or between field forms and the electronic data system;
- transcription or typographical errors between laboratory bench sheets and laboratory data forms or electronic data deliverables;
- data merge errors, if data have been uploaded from one system to another (at a minimum, this involves randomly checking the entire range of the dataset); and
- any duplicate records inadvertently captured in the dataset.

Verification of data integrity also includes a number of activities that overlap with those discussed in the previous sections, including confirmation that:

- data are legible and reported using correct forms, checklists, PDR devices, etc.;
- reported results are consistent with project requirements (e.g., correct nomenclature, units, location format, use of date/time stamps on digital records, signatures);
- original field forms are available to be examined and are appropriately linked to transcribed data;
- chain-of-custody forms were completed correctly and accurately represent corresponding samples or specimens;
- data have been completely and correctly linked or cross-labeled to supporting or related information;
- QC data are correctly associated with corresponding field data or laboratory results; and
- all revisions or corrections are signed and dated.

6.2.2.5 Evaluating the Scientific Validity of Reported Results

Evaluating the validity of reported data involves:

- evaluating results that appear to be impossible, illogical or outside anticipated range;
- confirming that values reported for one or more related variables are consistent with scientific expectations; and
- confirming project results appear temporally and spatially logical and consistent with scientific understandings (i.e., assumptions) of ecosystems and inherent ecological processes.

Linking Data Elements to Ensure Integrity

Data verification checks for integrity can help confirm the accuracy of links among variables, such as GPS data, digital photographs, digital sound recordings, field instrument data recordings, or laboratory data and the corresponding field data. This linking is often accomplished by adding relevant header descriptors on the field data form that are used in an electronic database to create attributes or entity relationships between related datasets. Data verification activities need to be undertaken to ensure that this linking of data has been accomplished and that data have not been lost or duplicated in the process.

6.2.3 Data Verification and Validation Techniques

The following subsections provide guidance on several techniques that can be used to implement the data verification and validation activities described in **Section 6.2.2**. These include the development and use of variable-specific data review procedures (**Section 6.2.3.1**) and the use of reference tables, compliance checks, range checks and consistency checks (**Section 6.2.3.2**).

6.2.3.1 Variable-Specific Data Review Procedures

One highly effective technique for conducting the activities described **Section 6.2.2** is to develop and use tables that describe specific verification and validation procedures for each variable. Such tables:

- help ensure that each variable is reviewed consistently over time by different staff members;
- facilitate development of automated or manual compliance checks, range checks, consistency checks and look-up tables that can be used to implement data review activities (see **Section 6.2.3.2**); and
- should be incorporated into the project-specific data review procedures (see **Section 6.1.5**).

Exhibit 6-3 illustrates how such a table might be applied to data collected for the ground cover monitoring example used in previous chapters. The example table includes two primary variables of interest (*Plant Species or Ground Cover Group* and *Cover Class Code*), which are highlighted in grey, as well as ancillary variables that provide information about the sampling location and date, field crew members, and equipment used to pinpoint the location of data collection (e.g., *GPS Unit #*). These types of ancillary variables are typically recorded near the header of any field data form (electronic or otherwise) or sample label, and can easily be checked against these forms and labels during data review. The table also includes ancillary variables that can help support or refute questionable results. For example, flowering or fruiting plant structures are key identification features; a "yes" result for the *Flower/Fruit* variable indicates such structures were present at the time of data collection and provides data reviewers with added confidence in the accuracy of the primary variable results. Similarly, verification of the *Plant Voucher Specimen ID* and *Photo ID* variables helps ensure that specimens and/or photos taken by the field crew are correctly linked to the corresponding sample data. Once verified, the specimens and photos can be used to confirm the accuracy of the data reported by the field crew.

Finally, the following observations should be noted:

- **Exhibit 6-3** includes verification procedures for all variables, but validation procedures are included only for the target variables and those ancillary variables that serve as diagnostic tools. Making decisions about what data to review and how those data should be reviewed, are crucial in project planning (see **Section 6.1**).
- The procedures shown in **Exhibit 6-3** are for illustrative purposes only. For example, the verification procedures for digital photographs (see the *Photo ID* variable) focus on confirming photos are properly documented in terms of time, location and unique identifier. Other data (e.g., make, model, shutter speed, exposure settings) may be useful for some projects.
- Although the primary purpose of such variable-specific tables is to clearly identify what needs to be reviewed and how, other information can be included. For example, **Exhibit 6-3** indicates that soil

and foliage moisture help data reviewers verify procedures were followed correctly and includes supplementary notes explaining that these variables also may be useful diagnostic tools during data analysis.

Exhibit 6-3. Example Variable-Specific Data Verification and Validation Procedures		
Data/Sample Verification Strategy: Ground Cover Survey (1-m^2 quadrats)		
Variable	**Description**	**Verification and Validation Procedures**
Site	Name of restoration site	*Verification:* Compare to list of approved names for restoration sites
Transect #	Unique number assigned to each ground cover transect	*Verification:* Compare to all site transects to ensure that each one is uniquely numbered (no duplicate numbers)
Plot #	Unique number assigned to each plot within a transect	*Verification:* Compare to all plots within the transect to ensure they are numbered sequentially and there are no duplicates
Subplot Code	Unique code assigned to each subplot (A1, A2, B1, B2)	*Verification:* Confirm each plot has four subplots using assigned (and no duplicated) codes
Quadrat #	Number of the quadrat examined with a subplot	*Verification:* Confirm there is only one quadrat per subplot and the Quadrat # is within range of acceptable numbers for subplot
Date	Format YYYY-MM-DD	*Verification:* Confirm date is within range of possible dates for survey
Time	Format hh:mm:ss AM/PM	*Verification:* Confirm time is within range of possible times for survey
Observer Name(s)	Full name of crew member(s) collecting data	*Verification:* Compare to list of crew members certified to collect ground cover data
GPS Unit #	Unique number assigned to each GPS unit	*Verification:* (1) Compare to GPS Unit # known to be used by the crew for that date. (2) Confirm this unit's locational accuracy was checked against known locations on a routine basis.
GPS Coordinates	Location automatically generated by GPS unit	*Verification:* Confirm GPS coordinates reflect 3-D and ≤5m accuracy, and are mapped and visually inspected to ensure quadrat locations correspond to correct site, transect, plot and subplot (where relevant)
		Validation: Confirm values are within range of plausible coordinates for latitude, longitude and elevation for the quadrat location
Photo ID	Unique filename of a digital photograph taken of a quadrat or specimen	*Verification:* (1) Confirm digital photograph properties reflect correct date, timestamp and GPS coordinates (if camera is GPS enabled). (2) Confirm Photo ID is cross-referenced to Plant Voucher Specimen ID and Quadrat #.
Soil Moisture	D = dry M = moist S = saturated	*Verification:* Confirm one soil moisture code has been selected for each quadrat where data collection occurred
		NOTE: Can be used to help evaluate potential sources of variation in target variables during analysis of project data
Foliage Moisture	D = dry M = moist W = wet	*Verification:* Confirm one foliage moisture code has been selected for each quadrat where data collection occurred
		NOTE: Can be used to help evaluate potential sources of variation in target variables during analysis of project data

Exhibit 6-3. Example Variable-Specific Data Verification and Validation Procedures

Data/Sample Verification Strategy: Ground Cover Survey (1-m² quadrats)

Variable	Description	Verification and Validation Procedures
Plant Species or Ground Cover Group (***Primary Variable***)	Plant species scientific name or ground cover group name	*Verification:* (1) Confirm that one plant species scientific name, ground cover group, or photo/voucher ID is present and legible for each evaluation of cover. (2) Verify all required species are identified. (3) Verify evidence (from QC checks during field season) that plant species or ground cover groups are correctly identified within data quality acceptance criteria by the field crew member(s) responsible for reported result. (4) Implement verification strategies for "Photo ID" and "Plant Voucher Specimen ID" if physical samples were collected.
		Validation: Confirm the scientific names reported are valid and presence of the species or group is consistent with ecological expectations
Flower/ Fruit	Presence of flower or fruiting structures used to evaluate a plant species name (yes/no)	*Verification:* For each plant species identified, confirm that an assessment of the presence of a flower or fruit was made
		Validation: Use presence/absence at the time of data collection to help support or refute questionable species or cover group results reported by field crews
Cover Class Code (***Primary Variable***)	1 = less than 1% cover 2 = 1–5% cover 3 = 6–25% cover 4 = 26–50% cover 5 = 51–75% cover 6 = >75% cover	*Verification:* (1) Confirm that only valid codes (1 – 6) were reported. (2) Verify evidence (from QC checks during the field season) that cover classes were being estimated within data quality acceptance criteria (e.g., ± one cover class code, 90% of the time)
		Validation: Compare to other values from same location to evaluate consistency with ecological expectations and conditions; investigate further if anomalies are found (e.g., unexpected absence due to senescence or mortality)
Plant Voucher Specimen/ Specimen ID	Physical specimen represented by Voucher and Photo ID	*Verification:* (1) Confirm specimen was collected and archived in accordance with specified protocols and labeled correctly with the correct Quadrat #, and unique Voucher and digital Photo IDs. (2) Corroborate file properties of digital photo (date, time, photo number) by cross-referencing with data form.
		Validation: Use specimen to confirm field crew is correctly identifying the genus, plants species or ground cover group
All variables	After capture in electronic format using a double data entry process	*Verification:* Compare results of double data entry. If discrepancies are found, check hardcopy data to identify and correct errors before merging into project database
All variables	After merging with project database	*Verification:* (1) Run frequency checks for all variables in the existing database (before merging) and for all variables in the file to be uploaded. Then run new frequency checks in the merged dataset to identify potential data shifts that may have occurred. If no problems are identified, spot check results across the dataset to confirm data integrity. (2) Determine total record count in the existing database (before merging) and in the file to be uploaded. Then confirm the total record count of the uploaded file is reflected in the merged dataset. If discrepancies are found, check to identify potential errors in record omission or duplication (a common error as result of appending data to an existing dataset (table) using copy/paste methodology).

6.2.3.2 Reference Tables, Compliance Checks, Range Checks and Consistency Checks

A number of the verification and validation procedures shown in **Exhibit 6-3** involve comparisons of reported values to:

- project-specific lists (e.g., approved names for restoration sites, approved timeframes for sampling activities, names of certified field personnel, valid cover class codes);
- project-specific acceptance criteria (e.g., ≤5m accuracy for GPS coordinates; ± one cover class code, 90% of the time); and
- non-project specific lists (e.g., valid species or genus names).

Each of these comparisons can be expedited by using **reference tables**, coupled with **compliance checks**, **range checks** and **consistency checks**. This aspect of data review is often the easiest to automate, using databases, spreadsheets and valid value checks programmed into electronic data collection forms or devices (e.g., see General Strategy #3 in **Section 6.2.1**).

Reference Tables – Examples

- **Valid site ID codes for the project**
- **List of certified crew members**
- **Dynamic list of species identified in project to date**
- **QC acceptance criteria for each variable and DQI**
- **Typical fish length-weight relationships by species**

Reference Tables: Reference tables (also known as reference lists, look-up tables, or mapping tables) are used as the basis for conducting compliance, range and consistency checks. These tables may be static, dynamic, universal or project-specific, depending on the variable. Depending on the content and use, some reference tables may be easily converted to automated checks, while others may be more suited for use in performing manual checks.

For example, data reviewers may want to compare reported fish measurement data against a reference table such as that shown in **Exhibit 6-4**, which was compiled by the Michigan Department of Natural Resources and documents length and weight relationships typical of large, wild-caught sport fish. This particular type of allometric relationship is highly dependent on water body, year and other variables and should only be used as a tool for identifying questionable values that deserve additional scrutiny as a result of the range and consistency checks discussed below. Although it is possible to automate such comparisons, doing so is likely to require use of a relational database and careful coding. For small projects in which data are stored and reviewed using simple spreadsheet software, it may be easier to manually compare reported results against the desired reference table.

In contrast, when field data are electronically available in spreadsheet format, verification of reported site IDs can be easily expedited by using an “IF” statement to compare reported values to a list of valid site IDs contained in another worksheet within the file.

Exhibit 6-4. Length-Weight Relationships (inches-pounds) for Large Wild Sport Fish[13]									
Length (inches)	Large-mouth Bass	Small-mouth Bass	Walleye	Northern pike	Muskel-lunge	Lake Sturgeon	Channel Catfish	Flathead Catfish	Lake Whitefish
1.5	.0013	.0016	.0010	.0005	.0002	.0005	.0005	.0009	.0006
2.5	.0065	.0077	.0047	.0025	.0013	.0024	.0027	.0045	.0030
3.5	.0186	.0212	.0132	.0072	.0041	.0070	.0082	.0132	.0092
4.5	.0409	.0454	.0282	.0158	.0098	.0154	.0188	.0292	.0211
5.5	.0765	.0834	.0519	.0297	.0197	.0289	.0362	.0551	.0408
6.5	.129	.138	.086	.050	.035	.049	.063	.094	.071
7.5	.202	.213	.133	.079	.057	.077	.100	.147	.113
8.5	.299	.311	.195	.117	.088	.113	.151	.219	.171
9.5	.423	.436	.273	.165	.129	.161	.217	.311	.246
10.5	.578	.590	.369	.226	.182	.220	.302	.427	.343
11.5	.77	.78	.49	.30	.25	.29	.41	.57	.46
12.5	1.00	1.00	.63	.39	.33	.38	.53	.74	.61
13.5	1.27	1.26	.79	.50	.43	.48	.69	.95	.78
14.5	1.59	1.57	.98	.62	.55	.61	.87	1.19	.99
15.5	1.95	1.92	1.21	.77	.70	.75	1.08	1.46	1.23
16.5	2.38	2.32	1.46	.94	.86	.91	1.33	1.78	1.52
17.5	2.86	2.77	1.74	1.13	1.06	1.09	1.61	2.15	1.84
18.5	3.40	3.28	2.06	1.34	1.28	1.30	1.93	2.56	2.21

Compliance Checks: Compliance checks are used to identify data that deviate from study requirements; they include checks to determine if results conform to (1) specified reporting formats and units, and (2) procedural requirements and acceptance criteria for DQIs. As shown in **Exhibit 6-5**, both types of compliance checks are verification techniques that can be applied to all types of monitoring data.

[13] Excerpted from Schneider, Laarman, and Gowing 2000.

Exhibit 6-5. Using Compliance Checks to Verify Ecological Restoration Monitoring Data		
Type	**Description**	**Examples**
Structural Compliance	Data comply with specified reporting formats and units	• Scientific name used when reporting species • Dissolved oxygen results reported in mg/L • GPS locations recorded in decimal degrees • Total phosphorus results reported in µg/L • Sampling time recorded in hh:mm format
Procedural and QC Compliance	Data comply with study parameters and specified QC acceptance criteria	• Routine crew and QA crew cover class codes agree within the specified 90% tolerance limit • Taxonomic re-identification of voucher specimens shows less than 15% difference from field crew taxonomic ID • Recorded GPS location is within project site boundaries • Routine crew data collection and associated cold check assessment were conducted within specified 2-week window • Total phosphorus matrix spike result falls within specified 90-110% acceptance criterion for recovery • Relative percent difference between total nitrogen (N) sample and duplicate is less than the 20% acceptance criterion limit • Site ID is on list of IDs for the project • Field crew name on list of staff certified to collect data • Topographic survey results meet intended levels of precision and accuracy

Structural compliance checks are shown in the first row of **Exhibit 6-5**, and are helpful techniques for verifying the integrity of a dataset. Examples include verifying that units are applied consistently across the dataset and verifying that species and chemicals are reported consistently (e.g., using scientific names, International Union of Pure and Applied Chemistry (IUPAC) numbers, or designated codes). These checks can be performed at any point in the gathering process (e.g., immediately after receipt of field or lab data and/or after the data have been uploaded into the project database). In addition to protecting data integrity, structural compliance checks promote accurate interpretation of whether field protocols were followed correctly. For example, some projects may require that data be collected at certain times of the day; a field reporting form that shows a sampling time of "5:30" (rather than 05:30 or 17:30) could be interpreted to mean data were collected near dawn or early evening.

The second type of compliance check is to confirm the following:

- Project data were generated within required study parameters (e.g., site boundaries, allowed sampling time frames, or acceptable weather conditions). These checks can be performed at any point in the data gathering process, as they do not require comparison of routine crew results to QA crew results.

- Project data meet specified data quality acceptance criteria (e.g., specified limits for precision or bias). These checks can be performed immediately upon data receipt when corresponding QC data are available, as is usually the case for laboratory data (e.g., nitrogen data that include laboratory calibration, blank, spike and duplicate results, or benthic organism counts that include re-counts by lab QA staff). In other cases, reviewers must wait until both the routine field crew and QA crew data are available for comparison (e.g., cover class codes or field-based taxonomic identification of species).

Range Checks: Range checks are used to identify data that are (1) scientifically impossible or illogical, (2) outside the normal range anticipated for the variable, or (3) within an anticipated range, but at such high or low extremes of the range that they warrant additional scrutiny. **Exhibit 6-6** provides examples of how data reviewers can apply such range checks to validate different types of monitoring data.

Exhibit 6-6. Using Range Checks to Validate Ecological Restoration Monitoring Data

Type	Description	Examples
Impossible/ Illogical	Identification of data not scientifically possible	• Values >100% cover for an individual species • Invalid scientific name for a recorded species • Invasive *Phragmites australis* height 30 meters • pH >14 or pH <0 • Total carbon 150% • Time recorded as 28:30
Out-of-Range	Questionable result outside of anticipated range of values for a variable	• Plant or animal species outside of its recorded range • High abundance estimates for a rare species • Water temperature of 35°C • pH of 2 • Chlorophyll a result outside anticipated 0.7 – 11,000 µg/L range (based on historical data)
Extreme Value Within Anticipated Range	Values within anticipated range that may deserve additional scrutiny	• Uncommon or rare taxa for a region • High count for species requiring extensive area • Unusually high or low values for recorded stream temperatures • Very low dissolved oxygen values • Highest or lowest values for biological, chemical, or physical laboratory results within expected range

As shown in **Exhibit 6-6**, range checks can be used to identify impossible values such as a reported pH of 15, a total carbon measurement greater than 100%, a recorded ground cover value greater than 100% for an individual species, or a sampling time recorded as 28:30. This type of range check also can be used to identify illogical values. For example, a recorded height of 30 meters for invasive *Phragmites australis* would likely prompt a reviewer to investigate whether a decimal was omitted (e.g., the originally recorded result was 3.0) or some other error occurred in the field or data processing activities. Although impossible or illogical values can be recorded during actual data collection, they most often arise due to errors during data transcription or processing (e.g., transposed numbers, missing decimal points, misspellings, or faulty equipment readings).

A second type of range check can be used to identify questionable results that might not be impossible but are outside the anticipated range for a given variable. For example, when reviewing data reported in its National Wetland Condition Assessment surveys, EPA compares values reported for conductivity, pH, ammonia, nitrate-nitrite, total nitrogen, total phosphorus and chlorophyll-a to a range of anticipated values developed from historical data generated from samples collected across the U.S. from 1999-2005 (EPA 2012). A range check that reveals the reported presence of an uncommon or rare taxon may prompt a data reviewer to determine if a voucher specimen was taken that can be used to verify the species was identified correctly. Other examples of out-of-range results that require closer scrutiny include the reported presence of a plant species that is not normally found in the area, a recorded stream water temperature that is much higher than the range expected, or a laboratory value for soil pH that is lower than previously recorded for similar soil types in the area.

Finally, range checks can be used to identify and evaluate the highest and lowest values collected for a given variable, even if they are found to be within the anticipated range. There is often a logical reason for these values, but they also might signal an error. For example, unusually high or low values for a stream parameter, such as temperature or turbidity, might be explained by the timing of storm events. If a logical explanation exists for these values, it should be documented in the project records or metadata.

Consistency Checks: Consistency checks are another commonly used data validation technique. Sometimes known by other names, these checks can be grouped according to three general categories that address (1) how well related variables within the dataset compare internally (internal consistency), (2) how well the data for a given variable compares to similar but external data for that variable (external consistency), and (3) how well the data compare to predictions of natural inherent relationships of the measured variables (ecological consistency). Examples of each are provided in **Exhibit 6-7** and discussed below.

Exhibit 6-7. Using Consistency Checks to Validate Ecological Restoration Monitoring Data

Type	Description	Examples
Internal Consistency	Expected relationships between variables within a dataset	• Total cover of all cover classes in a quadrat is at least 100% when all cover types representative of the quadrat are summed • Fish weight/length or tree height/diameter are consistent with known allometric relationships • Total phosphorus (P) is greater than dissolved P • Total nitrogen (N) is greater than nitrate-N • First 6 digits of the Specimen Voucher ID # match the Quadrat # and last 6 digits match the sampling date
External Consistency	Similarity in expected values across space or time for a given variable	• % cover of invasive species is similar to % cover in nearby impacted site • A tree's species ID did not change between two monitoring events • Stream temperature is similar to nearby monitoring location for a specific time period • Macroinvertebrate diversity and abundance are similar to diversity in nearby comparable sites • Culvert reported near site is consistent with previous reports

Exhibit 6-7. Using Consistency Checks to Validate Ecological Restoration Monitoring Data		
Type	**Description**	**Examples**
Ecological Consistency	Compares results with established scientific understanding of ecosystems	• Specific plant species and associations are expected in certain locations • Fish or other species assemblages are consistent with the habitat type or physical habitat characteristics • Field-measured water quality properties (e.g., dissolved oxygen, pH, conductivity, temperature) are consistent with documented biotic assemblages • Soil properties are consistent with published soil maps

Compliance, Range, and Consistency Checks

- **Compliance checks are used to verify data**
- **Range and consistency checks are used to validate data**
- **Range checks focus on examining results for a single variable without requiring comparisons to other variables in the dataset or to other datasets**
- **Consistency checks focus on comparing results for**
  - **One variable to one or more related variables within the same dataset**
  - **A single variable to results for the same variable in a similar dataset (e.g., containing past data from the same location or current data from a nearby location)**
  - **One or more variables for consistency with established scientific understanding of ecosystems or ecological processes**

Internal consistency checks are helpful in identifying data that appear to violate a relationship that naturally exists between one or more variables. For example, the total cover of all plant species recorded for a given quadrat area can exceed 100% as a result of overlapping canopies, but can only range from 0 to 100% for individual species. Therefore, total cover of all cover classes in a quadrat should add up to 100% or greater when including all cover types representative of the quadrat. The previously discussed allometric relationship between the length and weight of certain sport fish species (see **Exhibit 6-4**) and the relationship between the diameter at breast height and expected maximum height of certain tree species are additional examples of relationships that can be examined in the dataset using internal consistency checks. In reviewing laboratory results for internal consistency, one would expect total phosphorus (P) or total nitrogen (N) to be greater than or at least equal to their components (e.g., dissolved P or nitrate-N). These checks can also be helpful in identifying potential problems with ancillary data, such as identification numbers. For example, a project team may decide to facilitate linkages by requiring field crews to identify photos and vouchers with a numbering system that combines the quadrat or transect number with the sampling date, time or other important information. In such cases, internal consistency checks can be used to confirm the components of each photo or voucher ID match their corresponding values.

External consistency checks of values across space or time are another tool that can be used during data validation. Whereas internal consistency checks can only be applied to variables with known relationships, external consistency checks can be applied to any variable of interest. Examples are provided below:

- An evaluation of plant species composition should be similar to that occurring in nearby locations of similar size and with comparable habitat characteristics (consistency in space). These data can also be compared to corresponding data obtained at the same location during a prior monitoring event with comparable conditions (consistency across time) assuming no disturbance has occurred or treatment applied that would have changed conditions since the last monitoring event.

- A tagged animal that is captured repeatedly in live trap surveys should have the same sex recorded each time, although its weight, age and reproductive status might differ.

- Stream temperature data can be evaluated by examining temperatures taken in nearby streams with similar geomorphic and riparian habitat conditions (for spatial consistency) or temperatures taken at the same stream location and same time of year during previous monitoring events (for temporal consistency).

- Laboratory results, such as macroinvertebrate counts or water chemistry measurements, can be evaluated for external consistency by comparing results to the same parameters at similar nearby sites or to results obtained during previous monitoring events at the same site under similar conditions.

Ecological consistency checks are used to evaluate data in relation to established scientific understanding of ecosystems. This type of check is difficult to prescribe and requires specific expertise by those conducting data validation activities. For example, certain plant species or plant associations might be expected to be found in different locations at a site based on soil type and hydrology; a validation check for ecological consistency would evaluate whether or not these species or associations were found as anticipated. If a plant species that is normally only found in dry uplands was reported in a wetland, the result could trigger additional scrutiny of those data, as well as any data associated with them.

Similar approaches to the evaluation of ecological consistency can be applied to data collected from field and laboratory measurements, particularly when combined with results from field observations. For example, certain biotic assemblages are anticipated in stream riffles of fresh-water streams based on certain field and laboratory measurements of water quality. If reported data are not consistent with the anticipated results, they should be evaluated and possibly flagged for potential errors. Recommended procedures for handling such discrepancies or errors (including identifying data with potential discrepancies or errors, deciding how to address those issues, implementing corrective actions, and documenting these processes and decisions) are described below in **Section 6.3**.

6.3 HANDLING DATA DISCREPANCIES AND ERRORS

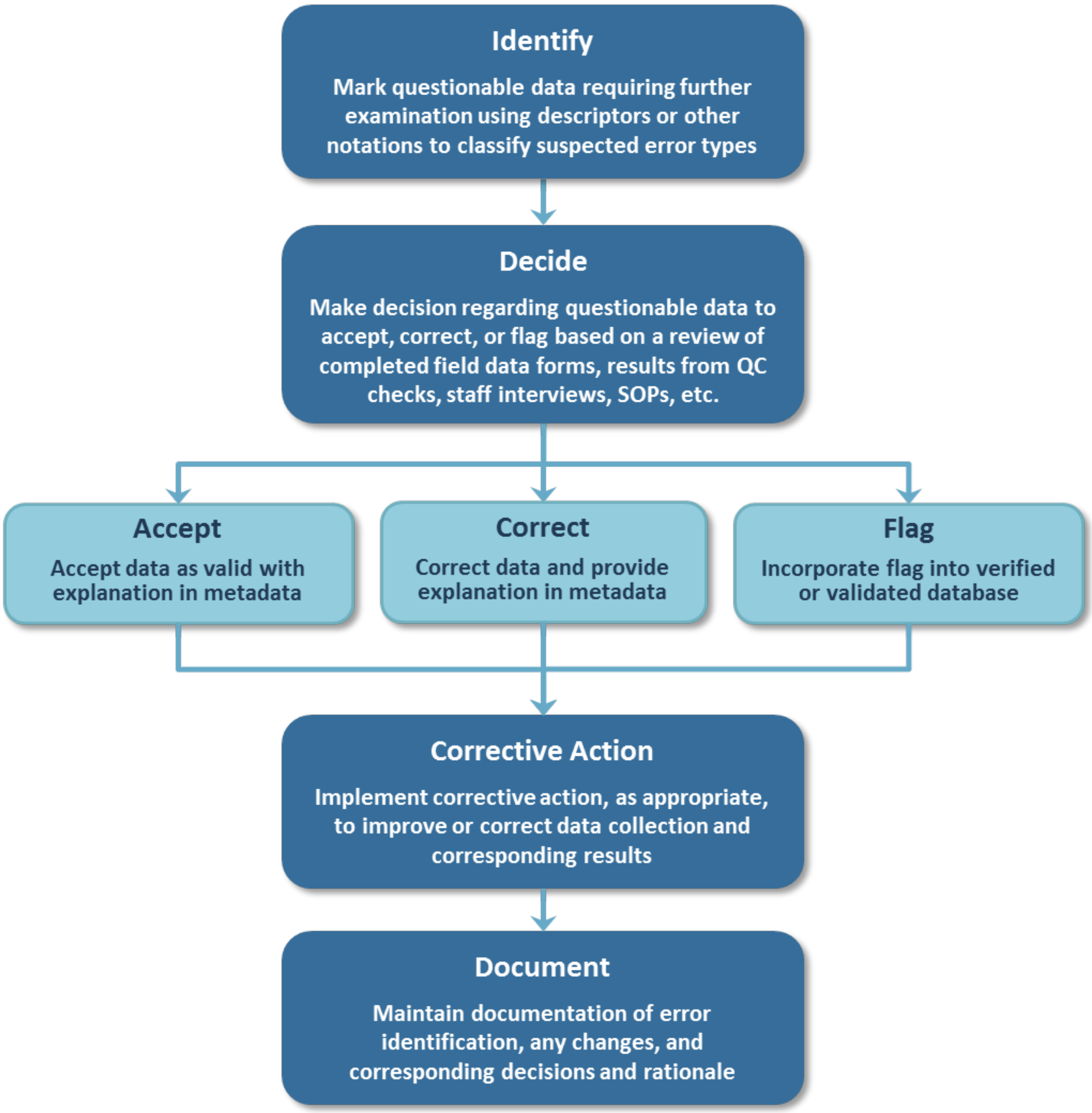
Any results found during the data review process that are inconsistent with specified requirements, acceptance criteria, or scientific expectations should be documented, investigated and, where appropriate, corrected. A summary of the general process is shown in **Exhibit 6-8**, and includes:

- identifying questionable data;

- making decisions regarding how to handle the questionable data identified;

- documenting the identified data, along with any corresponding decisions and actions taken; and
- implementing the corrective action.

Exhibit 6-8. Identifying, Handling and Documenting Questionable Data



The end result should be a transparent, verified and validated database that can be advanced for use in data analysis described in **Chapter 7**. Each component of **Exhibit 6-8** is described in greater detail below.

6.3.1 Identifying Real or Potential Errors

The data verification and validation processes described in **Section 6.2** usually result in the identification of questionable data that require further investigation. Examples include:

- errors introduced during data collection (e.g., missing decimals, transposed numbers, incorrect measurement units) or during transcription of field data sheets to a project database; and
- potential biases that originate from (1) variable measurements or observations, such as improper equipment calibrations or inadequately trained crew members; or (2) site-condition impacts on data quality, such as adverse weather.

Any data identified as questionable should be tagged (e.g., marked or highlighted) for further examination. This tagging should include standardized notations or descriptors that are familiar to all data review personnel and provide a clear reason why the data are considered to be questionable.

Evaluating Questionable Data – Examples

- **A questionable dissolved oxygen reading can be examined by determining whether the equipment used was calibrated or maintained appropriately.**
- **Questionable identification of a rare species can be checked to determine whether voucher samples or photos confirm the identification.**
- **A review of information regarding weather conditions can provide an explanation for questionable results for bird or amphibians.**

6.3.2 Deciding an Appropriate Course of Action

As shown in **Exhibit 6-8**, the next step in the treatment of questionable data is to decide whether to (1) accept the data, (2) correct the data based on available information, or (3) flag the data as questionable. This evaluation typically requires access to ancillary and supporting information, such as SOPs, field notebooks, field QC checks and laboratory results, laboratory bench sheets, discussions with field crew members or laboratory analysts, sample collection logs, chain of custody forms, photographs and audio recordings. The original field data sheets often include notes and additional information entered by field crew members, and may provide an explanation for questionable values.

Questionable data that cannot be accepted as correct and cannot be corrected need to be flagged as suspect using a flag code or other standardized format that explains and documents the reason for this designation. There is no right or wrong way to flag data, but project planners should ensure that a consistent set of codes or identifiers are established early on and used by all personnel involved in the identification, handling, and documentation of questionable data.

Tips for Using Flags to Identify Questionable Data and Standardize Actions

Project planners should develop a list of common and anticipated errors along with corresponding flag codes for use by data reviewers. The use of standardized flags (rather than detailed written descriptions) is more efficient and should be used to ensure that all data are handled appropriately. As they develop the relevant list of codes, project planners should consider that these codes or flags may be used to:

- **Identify actions (such as items for follow-up) or observations (such as QA issues or errors);**
- **Cover a variety of issues, such as missing data, range checks, exceedances (based on established limits), impacts on the sample, non-standard units, etc.;**
- **Identify multiple (potentially concurrent or overlapping) issues and/or action items;**
- **Facilitate global database corrections (requires careful design of flags and accurate tracking); or**
- **Identify patterns in data quality.**

Flags may be numeric or non-numeric values (numeric flags should generally be non-zero values to avoid confusion) and each flag or code is generally linked to a description in a data dictionary. Some project planners will set up a system that allows the reviewer to enter additional comments to explain the flag.

A set of codes or flags should be developed that meets the needs of the project team. When properly designed and implemented, codes or flags can significantly mitigate confusion, facilitate data sorting, and expedite both decision making and the implementation of corrective actions.

Examples of non-numeric flagging codes that have been used by organizations to address anticipated common occurrences are provided in **Exhibit 6-9**. In some cases, multiple data flags can be combined to provide a complete picture of the data quality and/or issues that may require follow-up. Organizations may also use non-zero numeric values, such as "-3" for *rejected data*, "-2" for *missing data*, or "1" for *suspect data*. The use of zero as a flag is not recommended since it can lead to errors (e.g., conversion to a null or blank entry), particularly during data transfer or migration. In all cases, an explanation of any action taken should be provided and included in the database. As questionable data are evaluated and decisions made regarding their treatment, the database should be updated along with any supporting metadata that includes decisions and explanations.

Exhibit 6-9. Example Data Flagging Codes					
Examples from "Estuary Water Quality Monitoring Program – Old Woman Creek"; **National Estuarine Research Reserve System, Ohio Division of Wildlife (National Estuarine Research Reserve System 2015)**		Examples from the Quality Assurance Report for the "National Study of Chemical Residues in Lake Fish Tissue: Analytical Data for Years 1 through 4"; **U.S. EPA, Office of Water (OW)** **(EPA 2014b)**		Examples from the Great Lakes Human Health Fish Tissue Study (GLHHFTS); **U.S. EPA, OW, Office of Science and Technology** **(EPA 2005b)**	
GDM	Data missing	B	Blank contamination	B, RNAF	Blank contamination; Result is not affected
GQD	Rejected due to QC checks	B, RMAX	Blank contamination; result is a maximum value	HRPD	High RPD
GQS	Suspect due to QC checks	HMSR	Potential high bias, high recovery in matrix spike	J	Estimated value
SRD	Replicate values differ	LVER	Low recovery in associated calibration verification	LLCS	Low lab control sample recovery
SIC	Incorrect calibration	MTRX	Chromatogram suggests possible matrix interference	RMAX	Result is a maximum value
CRE	Significant rain event				
CIP	Ice present				
CLE	Collected later/earlier than scheduled				
CSM	See metadata				
CCU	Cause unknown				

6.3.3 Documenting Issues, Decisions and Impacts on Data Quality

It is crucial that data users have access to documentation regarding the results of data review and that these results are incorporated in the project datasets. By making this information readily available, the reasons for rejecting, questioning and/or accepting a data point will be clear and can be used to support project decisions and data usability assessments. Documenting the reasons for accepting questionable data as well as any revisions to the data (including who made the changes and when and why the changes were made) assists in maintaining data integrity and facilitates understanding by both primary and secondary data users. Documenting all revisions also allows you to track recurring or persistent data quality issues that can and should be avoided or corrected during future data collection efforts. Regardless of the problems identified, it is critical that project managers be able to determine the source so that they or other team members may take appropriate corrective actions.

6.3.4 Corrective Actions

As depicted in **Exhibit 6-8**, appropriate corrective action is needed to prevent future problems. Corrective actions are particularly helpful if data review activities are ongoing throughout a project and the quality of data can be improved proactively before additional data are collected. Responses to the results of data review efforts will vary according to your project objectives and to the specific type and intended use of the data. Examples are provided below:

- Corrective action for an erroneous result may require the entire entry be disqualified, in which case the corrective action will be focused on ensuring that data users understand the limitations of the results produced.
- Corrective action for a misidentified sampling location may involve taking steps to (1) confirm the location was incorrectly recorded, (2) correct the error, and (3) document the correct location. In this case, the focus is on fixing and documenting the problem so that the error and the correction are transparent to subsequent data reviewers and users.
- Corrective actions described in **Section 6.2.1** may be taken to resolve illegible or incomplete data.

As noted earlier, questionable data are typically associated with two general types of problems — those associated with field crews, lab personnel and other data handlers, and those associated with factors outside the organization's control. Regardless of the source, the goals of corrective action should be to (1) obtain data that meet the stated project quality requirements, (2) document when that goal has not been met, and (3) determine which problems can be prevented or mitigated in the future through modified practices. The last is part of the continuous improvement phase of the quality management lifecycle and an important component in developing adaptive monitoring strategies described in **Chapter 8**.

Avoid Discarding Data

To the extent possible, project planning teams should avoid corrective actions that result in discarded data, even when data are determined to be unacceptable. Instead, records of the entire data collection and review process — including the criteria against which the data were evaluated, the process for doing so, and the objective DECISIONS made based on those criteria — should be retained and archived in the project files. This information may prove to be critical for subsequent data assessments, resulting project activities, project decisions, and/or future data use.

6.4 DATA CERTIFICATION

The final step in the data review process involves certifying that the datasets are complete for the period of record and have been subject to comprehensive quality inspection. Certification:

- ensures the data review process and any necessary data modifications have been appropriately documented;
- demonstrates good stewardship of data through effective management and oversight practices, resulting in a high degree of confidence that the data can be shared for use; and
- provides confirmation that the data are ready for analysis, reporting, distribution and archiving.

Data certification does not imply that a dataset is completely free of errors, only that rigorous review has been conducted for the period of record to ensure that all data reviewers, project planners and other stakeholders have a solid understanding of the degree of data quality, completeness, structural integrity and consistency. Certification includes documentation of known errors, data gaps and data of questionable quality. It provides a 'seal of approval' by the organization, project manager, or other individual that produced the data, and indicates that the data are in a finalized state, of sufficient quality, and understood well-enough to be assessed for use.

Certifying Datasets – A Seal of Approval

Some agencies, such as organizations within the U.S. Forest Service and National Park Service, certify their datasets following data verification and validation, prior to further assessments. A "seal of approval" is assigned to the dataset, making it available and providing all users with an understanding of the data's quality and potential limitations. Other organizations that collect environmental data, such as the National Climate Data Center, offer data certifications (certification marks) that provide legal assurance of product testing and audits.

Data certification provides an overall assessment of data quality based on existing documentation and the results of the data review. The overall assessment may take the form of a commentary that is appended to the dataset before release. This commentary should:

- disclose the results of data verification and validation;
- provide a description of the data relative to the data quality acceptance criteria;
- review and analyze any significant data problems identified along with their cause, corrective action(s) and follow-up activities;
- assess the relevance or significance of the data elements with respect to the quality of the data and their intended use (e.g., errors associated with important data elements and the potential impacts of those errors);
- include a statement by a data manager certifying that the commentary is true, accurate and complete to the best of their knowledge; and
- provide an audit trail of all changes to the data, including the reasons for any changes, time stamps, and identities of data editors (particularly important for projects with high levels of political impact).

In the event that a correction or update is required following certification, the dataset should be removed from certified status, modified as necessary, reviewed and re-certified. Notification of this process and re-certification should be provided to any previous or current data users.

Depending on the needs of your project and the schedule for data collection, you might certify some of your datasets seasonally, annually or even daily if real-time monitoring is critical to your objectives. Your certification process should encompass:

- specifications for the issuance of certification (e.g., criteria, minimum standards, data quality thresholds, data verification and validation requirements, data maintenance requirements, and prescriptive actions for handling questionable data); and

- requirements for maintaining certification status, renewing certification, and downgrading (or revoking) the certification.

For projects that generate a large amount of data requiring rapid, recurring or point-of-time certification, developing a semi-automated certification process driven by software code that is integrated into the data management system and reporting procedures may be a valuable resource investment. Developing a semi-automated process to review, validate, document and report on data quality provides a means for comprehensive systems analysis with enhanced capacity to analyze, auto-correct, secure and document data quality specific to each component or property for which certification is sought.

Once all data have been verified, validated and certified, the "*check*" phase of the "Plan/Do/Check/Act" quality management cycle and the "*review*" phase of the "Plan/Prepare/Collect/Review/Evaluate" project management cycle are considered to be complete (see **Exhibit 1-1**), and the data are ready for the "*act*" and "*evaluate*" phases discussed in **Chapter 7**. The data analysis activities described in **Chapter 7** include assessments to:

- confirm the data conform to the assumptions used in designing the monitoring program (e.g., the estimated amount of error used to estimate confidence in the resulting data),

- identify any relevant patterns and trends, and

- determine if the project and sampling objectives were achieved.

Where the data verification and validation processes described in this chapter are used to confirm project data were gathered correctly and are scientifically sound, the data analyses described in **Chapter 7** provide important information on the value of the plans and procedures used to prepare, collect and review the data, and help project managers determine if modifications are needed to improve the relevance and quality of the data for future monitoring efforts.

6.5 DATA REVIEW – CHECKLIST

The checklist below provides a summary list of overarching principles and aspects that should be considered and implemented when reviewing project data. As with any checklist, the listed items should not be interpreted or applied without comprehension of the supporting information. Users of this checklist are encouraged to read and understand the corresponding details that are provided throughout this chapter, and to implement these details using a graded approach that is commensurate with a project's scope, importance and available resources.

DATA REVIEW – CHECKLIST

- ☐ **Plan data review activities in advance.**
  - ☐ Determine who will review project data (identify data reviewers with the appropriate knowledge, skills and experience, and objectivity).
  - ☐ Identify which information will be reviewed by which data reviewers.
  - ☐ Identify when data review activities will be performed.
  - ☐ Determine how data will be reviewed and how the results will be reported.
  - ☐ Identify the materials and information data reviewers will need when conducting their reviews.
  - ☐ Determine how the data will be certified for assessment and use.
  - ☐ Document these who, what, when, and how data review decisions in written procedures.
- ☐ **Verify and validate project data.**
  - ☐ Review project data to ensure specified requirements have been met.
    - Are all required data, including QC data, present and legible?
    - Have all revisions or corrections been signed and dated?
    - Have all required samples and voucher specimens been collected and transferred to the appropriate facility within the required holding time?
    - Were the data documented and transcribed accurately?
    - Are units, species names, and chemical names reported correctly and consistently for each variable?
    - Are data completely and correctly linked to supporting or related information?
    - Are QC data correctly associated with corresponding field data?
    - Were approved field and laboratory procedures followed?
    - Have acceptance criteria been met?
    - Has feedback from routine field and QA crews been documented?
  - ☐ Review project data to ensure they are scientifically logical.
    - Have results that appear to be impossible, illogical, or outside the anticipated range been evaluated?
    - Have values reported for one or more related variables been confirmed for consistency with scientific expectation?
    - Have results been confirmed for temporal and spatial consistency with scientific understanding of the ecosystem, its condition at the time of data collection, and its inherent ecological processes?
    - Are data consistent with collected specimens?

DATA REVIEW – CHECKLIST
☐ **Handle data discrepancies and errors.** ☐ Identify questionable data. ☐ Determine how each questionable value is to be handled (i.e., corrected, accepted, and/or flagged). ☐ Document the questionable data, along with corresponding decisions, corrective actions, and supporting rationale. ☐ Implement corrective actions.
☐ **Certify project data.** ☐ Document the data review process and its results, including any necessary data modifications. ☐ Provide a description of any significant data problems, along with associated follow-up actions. ☐ Provide an audit trail of all changes made to the data, including the reasons for the change, time stamps, and identities of data editors. ☐ Provide a description of the data relative to the data quality acceptance criteria. ☐ Provide a data manager's statement to certify that the data and data review documentation are true, accurate, and complete.

6.6 ADDITIONAL READINGS

- Chapman, Arthur D. 2005. *Principles of Data Quality*, version 1.0. Report for the Global Biodiversity Information Facility. Copenhagen, Denmark.
- Chapman, Arthur D. 2005. *Principles and Methods of Data Cleaning – Primary Species and Species-Occurrence Data*, version 1.0. Report for the Global Biodiversity Information Facility. Copenhagen, Denmark.
- National Academies of Sciences, Engineering, and Medicine. 2017. *Effective Monitoring to Evaluate Ecological Restoration in the Gulf of Mexico*. Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/23476.
- Kervin, Karina E., William K. Michener, and Robert B. Cook. 2013. "Common Errors in Ecological Data Sharing." *Journal of eScience Librarianship* 2(2): e1024. http://dx.doi.org/10.7191/jeslib.2013.1024.
- Maletic, Jonathan I., and Andrian Marcus. 2000. "Data Cleansing: Beyond Integrity Analysis" in *Proceedings of the Conference on Information Quality (IQ2000)*. Boston, MA: Massachusetts Institute of Technology.
- Sebastian-Coleman, Laura. 2013. *Measuring Data Quality for Ongoing Improvement, A Data Quality Assessment Framework*. Waltham, MA: Morgan Kaufmann/Elsevier, Inc.
- Sutter, Robert D., Susan B. Wainscott, John R. Boetsch, Craig J. Palmer, David J. Rugg. 2015. "Practical Guidance for Integrating Data Management into Long-term Ecological Monitoring Projects." *The Wildlife Society Bulletin* 39 (3): 451-463. doi: 10.1002/wsb.548.
- U.S. Environmental *Protection Agency.* 2002. *Guidance on Environmental Data Verification and Validation (EPA QA/G-8).* Publication No. EPA/240/R-02/004. Washington, D.C.: Office of Environmental Information.

CHAPTER 7 DATA ASSESSMENT, ANALYSIS AND REPORTING

The preceding chapter discussed procedures for verifying, validating, and certifying the extent to which ecological restoration data were collected as intended and with the appropriate level of quality. This chapter provides guidance on QA/QC strategies associated with data use. As with all other aspects of ecological restoration monitoring, and as discussed in **Section 7.1**, these activities should be planned and documented in advance to ensure the right personnel and procedures are used and promote accurate and scientifically defensible decisions based on project results. The remainder of the chapter provides guidance on data assessment, data analysis and project reporting.

Data Assessment is a continuation of the data review process that involves addressing data quality flags, assessing data quality indicators (DQIs) across measured, observed and calculated variables, and reconciling the data quality with project assumptions and stated sampling objectives. These steps, described in **Section 7.2**, facilitate data analysis and ensure that reported results reflect the appropriate and intended use of the data. For example, during data assessment, project staff might assess how a particular data validation flag on a species identification result might impact the accuracy of a diversity index calculated for the project and ultimately the ability to detect a change in species diversity.

Data Analysis is the mathematical and statistical process of using collected data to describe results, answer questions and support decision making. In essence, the data analysis process quantifies the degree to which restoration project objectives were met. Data analysis can include simple mathematical operations such as the calculations of descriptive statistics or the aggregation of data representing multiple variables into a single indicator or index value. It also can include more complicated and rigorous approaches such as hypothesis testing, regression, trend, or principal components analysis, and modeling. Although it is beyond the scope of this guidance to address all possible approaches to the analysis of monitoring data, **Section 7.3** provides a general overview of options, discusses items that may be of particular interest in ecological restoration projects, and provides guidance on QC steps during the data analysis process.

The results from ecological restoration projects often provide information that is useful in improving data quality in subsequent collection efforts and enhancing the success of future restoration activities. Therefore, **Section 7.4** provides guidance on incorporating lessons learned and other information from:

- data review and assessment into the continual planning process to subsequently improve the quality of data collection, and
- data analysis into the adaptive management process to subsequently improve the success of restoration efforts. Additional information concerning adaptive management is provided in **Chapter 8**.

Finally, **Section 7.5** provides guidance for ensuring that project reports are accurate, appropriate for the intended audience, and properly vetted.

7.1 PLANNING DATA ASSESSMENT, ANALYSIS AND REPORTING ACTIVITIES

When planning data assessment, analysis and reporting activities, project planning teams should determine and document:

- who will be responsible for performing the assessment, analyses and/or reporting;
- when the activity will take place;
- how the assessment or analysis will be performed;
- how the quality of the data assessment, analysis and/or reporting activities will be controlled; and
- how the project data will be used in decision making.

Responsible Project Personnel (Who): Data assessment, analysis and reporting activities should primarily be conducted by senior project personnel (such as the principal investigator(s) or project manager) with the necessary qualifications, background and authority. These tasks require a broad understanding of all aspects of the project, as well as a basic understanding of QA/QC and statistics. The person(s) responsible for these tasks may solicit assistance from other individuals, such a QA manager, field or laboratory technicians, or a statistician, but should retain primary oversight of these activities.

Timing (When): Data assessment, analysis and reporting activities are often conducted near the end of a project, after data review has been completed. However, there may be value in initiating these steps earlier in the project lifecycle. In particular, it may be advantageous to initiate these activities at the end of each data collection season when restoration and monitoring activities span multiple seasons (see text box). Early and periodic initiation of these activities can be a valuable aspect of the continual planning and adaptive management processes (see **Section 7.4**), because it affords opportunities for data to be used in interim decision making to improve the success and speed of restoration outcomes.

Benefits of Early or Seasonal Data Assessment, Data Analysis and Reporting

Data Assessment – Provides an opportunity to identify shortcomings and correct the problems before subsequent sampling

Data Analysis – Yields opportunities to identify data patterns or trends that might suggest alternative restoration approaches

Project Reporting – Provides a means of communicating progress to stakeholders; also may be useful in documenting milestones and providing rationale for interim decisions or changes in project direction or approach

Procedures (How data assessment and data analysis will be performed): Project planning teams should determine and document how the data will be assessed and analyzed prior to initiating the process. Guidance provided in **Sections 7.2** and **7.3** can be useful in planning these procedures based on the types of data collected and the project objectives. For data assessment or analysis steps that might be performed repeatedly, standard operating procedures (SOPs) should be established to ensure the methodology is consistent throughout the project and well documented. For example, data analysis for ecological restoration projects may rely upon the calculation of specific metrics of ecological diversity (e.g., species-composition, -richness and -evenness) or composite indices such as an index of biotic integrity (IBI), floristic quality index (FQI) or index of macro-invertebrate biotic integrity (M-IBI). Project staff should establish SOPs for calculating such variables and indices just as they do for collecting the data used in the calculations.

Quality (How the quality of the data assessment, analysis, and/or reporting activities will be controlled): High quality data are of little value if they are analyzed and reported inappropriately. Therefore, project teams should establish QA/QC strategies for the data assessment, analysis and reporting phases of the project, just as they do for the data collection and data review phases. In most cases, this involves reviews and spot checks. The data assessment step is itself a QC process to determine data usability, but steps in this process should be reviewed internally – and possibly externally – to ensure the correct procedures and assumptions were used. For data analysis, QC steps should include spot checks of analyzed data to ensure the correct procedures were followed and results were accurately calculated. For reporting, internal and external peer reviews may be used to ensure quality (**Section 7.4**). Planning at each phase of the project should include identification of the individuals who will perform reviews and/or spot checks and the nature and extent of the reviews.

Use (How the project data will be used in decision making): One of the most important aspects of overall project planning is to establish a level of quality control that is commensurate with the intended use of the data (i.e., the Graded Approach). This concept also applies to aspects of data assessment and analysis. Data assessment and analysis procedures should be planned with the intended use and decision-making process in mind. Project planners should ask the following questions:

- What decisions will be made with the data?
- How does the data analysis inform those decisions?

For example, data analysis that is used to inform the adaptive management process and adjust seasonal sampling strategies may not require the level of rigor demanded by data analysis that supports ultimate decisions to terminate a restoration project or initiate a new restoration project.

7.2 ASSESSING IMPACTS OF DATA QUALITY ON USE

This section provides guidance on data assessment, a continuation of the data review process described in **Chapter 6**. Data assessment involves evaluating how the quality of the validated dataset impacts its intended use, and the process answers a number of questions, including the following:

- Should I use data that were flagged in the data review process? If so, how?
- How do data quality flags influence my ability to make decisions based on the data?
- Were project assumptions and sampling objectives met?
- Do DQIs meet minimum levels of performance necessary to assess project objectives?

- What is the level of uncertainty in the project decisions that I make?

To answer these questions, this section provides guidance on quantitative and qualitative procedures and subsequent evaluations needed to determine the reliability of monitoring data, their limitations, and their application to inform decision making within an adaptive management framework. Guidance is provided on addressing data quality flags, revisiting project assumptions and sampling objectives, and evaluating DQIs. Specific guidance is offered on statistical approaches to assess whether DQIs achieve the specified acceptance criteria to test null hypotheses given the expected effect-size and corresponding Type 1 and Type 2 decision errors.

7.2.1 Addressing Data Validation Concerns

Once the data review steps described in **Chapter 6** are complete, an additional step is needed to evaluate the potential impact of flagged data and determine any limitations on the use of the data. Specific objectives of this process include the following:

1. Identify different types of data issues and/or instances of flagged data.
2. Determine the possible effects of these data issues for the evaluation of project objectives .
3. Decide how to address data issues such that the impact on data analysis is minimized.
4. Communicate corrective actions taken and data usability limitations to data users.

7.2.1.1 Types of Data Quality Flags and Impacts on Data Quality Indicators

The data review activities described in **Chapter 6** may identify a variety of flagged data including, but not limited to, the examples shown in **Exhibit 7-1**.

Exhibit 7-1. Examples of Potential Limitations on Data Use as Identified During Data Review Efforts that Affect All DQIs[1]

<table>
<tr><th>Type of Flagged Data</th><th>Possible Causes</th><th>Possible Effects on Data Usability</th></tr>
<tr><td>Missing data values</td><td>• Weather conditions or other factors prevented collection
• Data values overlooked or not recorded</td><td rowspan="4">• Reduction in sample size affecting Type 1 and Type 2 error rates
• Potential reduction in ability to compare key variables over time or space
• Potential reduction in usable data for decision making
• False positives, false negatives, incorrect classifications or other data errors affecting data interpretation
• Incorrect calibration of equipment resulting in reduction of usable data</td></tr>
<tr><td>Data collected outside of data quality acceptance criteria</td><td>• Imprecision or bias for continuous variables
• Species identification error</td></tr>
<tr><td>Violations of SOPs</td><td>• Incomplete training and crew certification
• Procedures for collecting data not followed</td></tr>
<tr><td>Other data flagged as suspect from verification or validation checks</td><td>• Data collection errors
• Data entry errors
• Spelling errors</td></tr>
</table>

[1] *Table was adapted from US Army Corps of Engineers, Environmental Quality Assurance for HTRW Projects, Engineer Manual. October 10, 1997, EM 200 1-6, table 3-1. Accessed at https://triadcentral.clu-in.org/tech/documents/entire.pdf on 2/2/2016.*

Each of these issues has the potential to impact different DQIs, thereby influencing data analysis and ultimately the evaluation of project objectives. For this reason, care should be taken in evaluating the usability of flagged data. As a first step, data analysts should determine the magnitude and direction of impact that flagged data may have on DQIs and on data analysis by addressing the key questions discussed below.

Does the flag affect primary or ancillary data? As discussed in **Chapter 6**, data review strategies may differ for primary versus ancillary variables; the same is true when assessing impacts of non-conformances on data use. Primary variables are those that will be used in data analysis to evaluate project objectives. Ancillary data may support the evaluation of project objectives, but generally are not used to determine the ultimate success of a restoration project. As such, data quality flags on primary variables are much more serious and have greater potential to influence project outcomes. For instance, using the willow restoration example discussed throughout this guidance, a data flag indicating a deviation from the SOP for measuring soil moisture (an ancillary variable) may have the potential to impact decisions regarding future watering needs for restoration plantings, but the flagged data should not impact the ability to determine whether the restoration project objective of restoring native willow to an average density of at least 2.5 stems per square meter was met. Conversely, a data flag indicating a deviation from the stem count SOP (a primary variable) could substantially impact the ability to determine whether restoration project objectives were met.

What are the specifics of the data quality flag? As mentioned above, different types of data quality flags may impact one or more DQIs. Evaluation of potential impact requires an understanding of the details concerning the data quality flag. For example, a data quality flag may identify violations of sampling SOPs, but it is important to understand the nature of the SOP deviation to evaluate its impact. Placement of monitoring transects at 20-m intervals rather than the SOP-prescribed 10-m intervals may significantly impact the representativeness of collected data, but not significantly impact their accuracy. In the same way, a violation of data quality acceptance criteria could result from a low recovery of matrix spike samples for pesticide analysis or low precision in field duplicate samples. The former would impact data bias and accuracy, while the latter would impact precision.

Key Questions When Examining Flagged Data

- **What type of data does the flag affect?**
- **What are the specifics of the flagged data?**
- **What is the extent of the flagged data?**
- **How are data quality indicators affected?**
- **How will the data be used in data analysis?**
- **What are the direction and magnitude of the error?**

What is the extent of the flagged data? Some data flags may signal issues with a single result or group of results, while others may identify a consistent and recurring issue throughout the collection of a given data type. In general, the more widespread the issue, the greater the potential impact on data quality and data analysis. However, potential systematic biases also can be introduced through issues that may be experienced in some but not all data collections. For example, violations of data collection SOPs at only one particular site may introduce a systematic bias that could lead to improperly determining a true difference exists between sites. Similarly, in restoration projects with before and after monitoring, any changes in sampling or analysis protocols between sampling events may introduce bias and impact evaluations of restoration project objectives. The same can be said for laboratory data where data flags associated with a certain batch of samples align with a pre- and post-assessment of a single site or in a site-to-site assessment. When data analysis involves statistical comparison of sites or temporal collections, the impact is lower when the occurrences are randomly spread across the sites or temporal collections than when lumped within a given site or collection.

How are data quality indicators affected? Flagged data can impact multiple aspects of data quality, and the analyst should seek to understand the impact on each DQI. Additional guidance for evaluating DQIs is provided in **Section 7.2.2**. Though the guidance provided in this section is focused on evaluating these indicators across the full data collection effort, the approaches provided also may assist in evaluating the impacts of specific flagged data.

How will the data be used in data analysis? The impact of flagged data also depends on the type of data analysis planned. Some calculations and statistical methods are more robust and less influenced by variations in the data. For example, species identification and enumeration data may be aggregated into a multi-metric calculation, such as an IBI. In this case, data flags for the accuracy of enumeration counts may have less impact on the aggregated multi-metric parameter than on straight abundance values. In the same way, non-parametric statistical approaches may be less sensitive to data flags than parametric approaches.

What is the direction of the error? For flagged data that result in bias, the direction of the bias should be considered. Depending on the direction of the bias, the flagged data may or may not influence the overall determinations of data analysis. For example, blank QC samples can indicate contamination in water samples. If the level of contamination exceeds the QC criterion, data associated with this collection effort may be flagged with possible positive bias due to contamination. If, however, the preliminary conclusion of data analysis is that contaminant concentrations in the associated field samples were below biological effect thresholds (even considering the possible bias associated with sample contamination), the data flag may be considered inconsequential. On the other hand, if the preliminary conclusion of data analysis is that contaminant concentrations were just above biological effect thresholds, the data analyst should apply more caution in interpreting the flagged data. In this case, the concentrations reported slightly above the effect thresholds may be a result of the same contamination present in blank QC samples.

7.2.1.2 Corrective Action and Usability of Flagged Data

Section 6.3.4 discusses corrective action taken as a part of data review. These steps primarily involve correcting data collection and reporting errors and preventing the errors from recurring in future data collection efforts. After data have been reviewed and compiled in a certified system, the data assessment phase provides another opportunity for corrective action. In this phase, project personnel should evaluate the usability of the reviewed data for inclusion in the data analysis and, for each data quality flag, must decide whether to:

1. retain the flagged data,
2. discard the flagged data from data analysis, or
3. use some corrective action to limit the impact of the issue on data analysis and decision making.

Project personnel should consider the impacts of each of the above options on data analysis and decision making. While it seems that discarding flagged data may be the most conservative approach, this option is not without impact on the data analysis process. By reducing the quantity of data, Type 1 and Type 2 errors are impacted, and the ability to detect statistical differences within the dataset is reduced. Project personnel should weigh the impacts of each of the above options and choose the option with the smallest impact. Examples of corrective actions that can be taken to limit the impact include **data consolidation**, **data correction** and **confirmatory analysis**. Each of these is discussed below.

Data consolidation: In some circumstances, data can be aggregated or consolidated to reduce the impact of a given data quality flag on data analysis. For example, if a large amount of data reported by one laboratory technician was flagged during data review because QC spot checks and archived voucher specimens confirmed the technician was confusing two different benthic macroinvertebrate species (species A and B) and incorrectly identifying both as the same species, the data analyst could choose one of the following options:

- Retain the flagged data even though all samples analyzed by this individual would be biased low in species richness and species diversity.

- Exclude the flagged data from data analysis even though the amount of data with which to evaluate project objectives would drop significantly and thus compromise the ability to detect actual differences resulting from the restoration (Type 2 error).

- Apply a corrective action that involves modifying the results such that identifications for both species in question are consolidated. Enumerations of all individuals for species A and species B would be combined into a single enumeration for species A and B. This corrective action would reduce species richness and diversity systematically across all samples, but may be the most appropriate action because it would eliminate a bias that might unevenly impact one treatment more than another and lead to a potentially erroneous conclusion.

Data correction: In situations where the impact of a given data flag is unknown, an investigation can be initiated to assess the potential impact and correct data appropriately. For example, if one water quality probe used for dissolved oxygen measurements failed calibration and was shown to be inaccurately biased low, post-restoration monitoring could be conducted to determine the impact of this discrepancy on data analysis (e.g., calibration records and post-restoration measurements could be used to determine the average deviation between this probe and actual dissolved oxygen conditions). If the post-restoration monitoring revealed that the probe was biased low by an average of 0.8 mg/L oxygen, then data from this probe could be corrected by + 0.8 mg/L.

Confirmatory analysis: In situations where the impact of a given data flag is unknown, a statistical investigation could be initiated to estimate the potential impact. If this analysis confirms the impact is small and does not directionally bias the data analysis or decision-making outcome, the data can be retained. Using the dissolved oxygen example above, a statistical power analysis could be performed to show that, based on the variability of dissolved oxygen data and the number of samples, a 3.6 mg/L difference is the minimum that could be detected as statistically significant. If the observed difference was only 1.7 mg/L, deviations of ±0.8 mg/L resulting from the probe error would not have impacted the decision that there was no difference. (If results were biased low by 0.8 mg/L, there would still be no observed statistical difference, and if results were biased high by 0.8 mg/L, results would still not reach the threshold of determining a statistical difference.) In this case, the analysis could be used as confirmation that the data can be retained without changing the decision-making outcome. In this case, the flagged data may have impacted the bias, accuracy and precision of estimates of selected variables, but did not affect the resulting conclusion.

7.2.1.3 Example Assessments of Data Limitations and Impacts on Data Use

This section provides example scenarios designed to illustrate how the data assessment process can be used to evaluate the impact of flagged data on data analysis. Because both scenarios are based on the example willow restoration project that has been carried throughout this guidance, **Exhibit 7-2** is provided as a summary the objectives, required data and acceptance criteria associated with the example project.

Exhibit 7-2. Project Specifications for Example Scenarios 1 and 2[1]	
Project Goal:	Restore optimal willow density along stream riparian shoreline impacted by historical grazing to reduce bank erosion and to provide habitat for riparian wildlife species
Project Objective:	Restore native willow to an average stem density of 2.5 stems/m^2 along 1,000 linear meters of stream riparian shoreline within the toe and transition zones after 2 years
Sampling Objective:	Demonstrate achievement of a mean density of 2.5 stems/m^2 (with 90% certainty or statistical power when the true density is at least 20% greater than the targeted 2.5 stems/m^2) along 1,000 linear meters of stream riparian shoreline within the toe and transition zones after 2 years, with a 5% chance (α) of incorrectly concluding that the 2.5 stems/m^2 objective was reached when it in fact was not.
Null Hypothesis:	Stem density in restoration area will be $\leq$2.5 stems/m^2 after 2 years
Required Data:	Stem density will be determined by counting willow basal stems on thirty (30) 1-meter x 3-meter rectangular plots, with plot markers geo-referenced using sub-meter accuracy global positioning system (GPS) equipment
DQIs	**Acceptance Criteria for Primary Variables of Interest**
Precision Bias Accuracy (Error Tolerance and Frequency of Compliance)	*Willow Shrub ID (Genus and species criteria):* • Genus (Salix) Level: 100% correct (error tolerance), 95% of the time (frequency of compliance) • Species level: 100% correct (error tolerance), 90% of the time (frequency of compliance) *Willow Shrub Stem Count*: ±10% (error tolerance), 95% of the time (frequency of compliance) *WGS84 GPS Position:* Latitude/Longitude Horizontal Accuracy within ±0.5 meter (error tolerance), 95% of the time (frequency of compliance)
Representativeness	Data are obtained in accordance with a statistically sound sampling design, are complete and meet minimum data quality acceptance criteria for precision, bias, accuracy and detectability.
Comparability	Data are determined to be representative and have been collected using equivalent procedures.
Completeness	A minimum of 95% of plots provide valid data for each target variable.
Detectability	*Willow Shrub ID:* Species level ID correctly identified 90% of the time when willow is truly present or not identified when truly absent. *Willow Shrub Stem Count:* A basal stem is counted 95% of the time when it is truly present, regardless of abundance, or is not counted when truly absent.

[1] *Table reflects information extracted from Exhibits 3-3, 3-7 and 4-3.*

As shown in **Exhibit 7-2**, the monitoring plan called for determination of willow stem density on thirty 1-meter by 3-meter rectangular plots. For the purpose of both example scenarios, the average plot density determined by the field crew was 3.8 stems per square meter.

Scenario 1: Missing Data

Description of Flagged Data: The field crew was able to sample only 25 of the 30 plots on the restoration site due to unsafe conditions resulting from weather.

Data Assessment Process and Considerations: In this situation, field crews would have likely notified the QA officer and project manager of the issue prior to data review, and the project manager would have made a decision about resampling the site when conditions were safe. For the sake of this example, we will assume that the decision was made to not immediately resample (due to budget, personnel or timing constraints), and the data proceeded through the data review step, receiving a data flag for missing data. During data assessment, the data analyst assessed the impact as described below.

- **Type, specifics, and extent of the flagged data:** The flagged data affected both primary variables (willow basal stem density) and ancillary variables (invasive species counts, soil texture and soil moisture). The impact associated with the primary variable is more severe, and has the potential to directly affect achievement of the project and sampling objectives. The impact on ancillary variables is less critical. However, the analyst should consider these impacts in the analysis and reporting of those variables, particularly if any are later determined to be important in explaining variance of one or more primary variables. The extent of the flagged data affects 5 out of 30 plots. The impact of this extent will be determined based on assessment of the various DQIs.

- **Impact of the flagged data on DQIs:** The data analyst investigated the impact of the flagged data on each DQI.

    - *Completeness.* The analyst determined the missing data reduced completeness to 83%, which is below the minimum completeness criterion of 95% established in the project QA plan. Although the sampling plan was designed to accommodate a 5% loss of data, the 17% loss has the potential to negatively impact the achievement of sampling objectives.

    - *Representativeness.* The analyst viewed the spatial locations of the sampled and missing plots on a Geographic Information System (GIS) and determined the sampled plots still maintained good representative coverage of the site. The missing plots were not biased towards a given region or environmental gradient. The location of plots and the order of sampling were selected randomly. Therefore, even with fewer plots, representativeness was maintained.

    - *Precision, Bias and Accuracy.* Using existing data, the analyst compared within-plot and between-plot variability. This investigation revealed there was no difference in within-plot and between-plot variability, meaning plots were large enough to encompass the natural variability associated with environmental patchiness. This indicated that, as long as existing plots were representative of the site, additional plots would not have likely altered the precision, bias and accuracy of the resulting stem count mean.

    - *Comparability and Detectability.* The data analyst determined the flagged data did not significantly impact comparability and detectability.

- **Impact on the sampling objective**: The sampling objective and design of 30 plots was selected to provide the ability to demonstrate whether the project objective to restore native willow to a mean density of at least 2.5 stems/m^2 was achieved. The sampling objective also was designed to provide decision makers with 90% certainty in correctly concluding the restoration objective was achieved if the actual stem density was at least 3 stems/m^2 (i.e., at least 20% greater than the desired density). The sampling objectives and design, however, were based on assumptions of variability for the stem density results. Now that data have been collected, the analyst was able to recalculate the statistical power analysis using actual variability to determine the impact of the reduced sample size. The results of this analysis revealed the reduction in sample size from 30 to 25 would reduce the probability with which the targeted 2.5 stems/m^2 stem density (when exceeded by 20%) can be detected from 90% to 78%. If the acceptable level of certainty is held constant at 90%, the actual stem density would have to be at least 35% greater (instead of 20%) than the targeted stem density. Based on this analysis, the analyst concluded the sampling objective was not met. After considering both options, the analyst decided to maintain the original levels of certainty (90%) and Type 1 error rate (5%), and accept a decreased ability to detect increases in the mean stem density. As a result, the project data will only support the ability to detect change if the change is at least 35% instead of the originally planned 20%.
- **Impact on the restoration project objective:** Finally, the analyst tested and rejected the null hypothesis that the mean willow stem density would be $\leq$ 2.5 stems/m^2. In this case, the estimated mean density was 3.8 stems/m^2 (i.e., 52% greater than the 2.5 stem/m^2 target) and, even with reduced detection power, the restoration project objective was met. In summary, the flagged data caused a failure to achieve stated sampling objectives, but that failure did not prevent achievement of the project objective.

Scenario 2: Precision and Accuracy Problems

Description of Non-conformance: The field crew was able to sample all 30 plots but a blind check of two of the plots by a QA crew found that one of the three routine crews had problems meeting the acceptance criteria for precision and accuracy of their stem counts. As shown in **Exhibit 7-1**, the criteria required crews to report stem count data that were within 10% of actual total count, 95% of the time. The QA crew determined the routine field crew was counting lateral stems (developed from lateral buds) on the same plant as representing basal stems. As a result, the routine crew was overestimating the willow density by an estimated 1.2 stems/m^2 on average.

Data Assessment Process and Considerations: In this situation, the project manager or QA crew should have alerted the routine field crew of the QC failure and conducted additional training to correct the problem for future monitoring. The QA officer and project manager would have then made a decision about resampling the plots that had been incorrectly monitored. For the sake of this example, we will assume that the decision was made to not immediately resample (due to budget, personnel or timing constraints), and the data proceeded through the data review step, receiving a data flag for failure to meet the acceptance criteria established for precision and accuracy. During data assessment, the data analyst assessed the impact of this issue described below.

- **Type, specifics, extent and direction of the flagged data:** The flagged data affected a primary variable (willow stem density) and have the potential to directly affect the achievement of project and sampling objectives. The extent of the flagged data includes 1 out of 3 routine field crews, therefore, 10 of the 30 plots may have been affected. QC and training logs indicate that refresher training corrected the problem, but not until after this crew had monitored 7 plots. QC logs also indicate that the errors resulted in an average overestimation of stem density by 1.2 stems/m^2. In summary, the issue biased the primary variable by 1.2 stems/m^2 in 7 of the 30 plots. The data analyst has the options of retaining these data as is with the associated data flags, rejecting the flagged data, or correcting the data.

- **Impact of the non-conformity on DQIs:** The data analyst investigated the impact of this issue on each DQI.

  - **Completeness.** If the data are retained or corrected, there is no impact on the completeness criterion. If, however, the flagged data are rejected, completeness will be reduced to 77%, which is below the minimum completeness criterion of 95% established in the project QA plan. While the sampling plan was designed to accommodate a 5% loss of data, a 23% loss has the potential to negatively impact the achievement of sampling objectives.

  - **Precision, Bias and Accuracy.** As previously stated, this issue established a positive bias of 1.2 stems/m^2 in 7 of the 30 plots; this bias affects the overall accuracy of the stem count mean. If the affected plots were corrected by the average -1.2 stems/m^2, the stem count mean (across all 30 plots) is reduced from 3.8 to 3.2 stems/m^2. The analyst also compared the estimates in precision among the 7 plots with flagged data to the precision estimated among the remaining plots, and determined the issue produced a decrease in precision. Specifically, the analyst concluded that the coefficient of variation (CV, also known as the relative standard deviation or RSD) among the 23 plots with unflagged data was 12%, while the CV among the 7 plots with flagged data was 26%. Including the 7 plots into the site mean decreased precision from a CV of 12% to a CV of 18%. If the flagged data were corrected by the average -1.2 stems/m^2, the impact on precision would be negligible (CV of 18%). This is because the error was not likely consistent across the 7 plots, but the average correction factor was applied consistently. In other words, the correction would adjust for the bias in the stem count and, as result, produce only a minor change in precision.

  - **Representativeness, Comparability and Detectability.** The data analyst determined the issue did not have a substantive impact on representativeness. In contrast, he concluded the impact on comparability can be stated qualitatively as significant, since results from this field crew are biased and not comparable to the other 2 field crews. This issue also limits the comparability of the results to results from other similar studies or projects. Detectability could be impacted depending upon the methodology used when counting stems. For example, if the SOP defined valid stems (for counting), as native live willow stems ≥30 cm in total length emerging directly from a root base, then detectability would be reduced by miscounting the true number of stems that meet that criteria (sensitivity) or, alternatively, by miscounting as result of error in correctly determining if a stem was valid or not (specificity).

- **Impact on the Sampling Objective:** The original sampling design of 30 plots was selected to meet the sampling objective of demonstrating that a mean density of 2.5 stems/m^2 had been achieved (with 90% certainty when actual stem density is at least 20% greater). However, and as discussed in Scenario 1, the original design was based on assumptions of variability for the stem density measurement. Now that data have been collected, the analyst was able to recalculate the statistical power analysis using actual variability to determine the impact of excluding (censoring), including or correcting the flagged data.

    - If the flagged data are excluded, the sample size would be reduced from 30 to 23. A power analysis based on actual sample variability revealed this reduction would reduce the probability of concluding the targeted of 2.5 stems/m^2 density had been achieved (when actually exceeded by 20%) from 90% to 62%. If the acceptable level of certainty is held constant at 90%, the actual stem density would need to be 47% higher (instead of 20%) than the 2.5 stems/m^2 target. Based on this analysis, the analyst concluded the sampling objective would not be met if the flagged data are excluded.

    - If the flagged data are included, there would be no change in the sample size, but the variability would increase due to the reduced precision. In this case, the data analyst's power analysis revealed the increase in variability would reduce the certainty with which the desired stem density can be correctly detected (when actually exceeded by 20%) from 90% to 83%. If the acceptable level of certainty is held constant at 90%, the actual stem density would need to be 32% higher (instead of 20%) than the 2.5 stems/m^2 target. Based on this analysis, the sampling objective would not be met if the flagged data are included. In addition, the mean would remain biased.

    - If the flagged data are corrected, there would be no change in the sample size, but the variability would increase due to the reduced precision. In this case, power analysis results would be similar to the results discussed above for the option of including the uncorrected data.

    In summary, all three options fail to meet sampling objectives, and the data analyst should use caution in assessing restoration project objectives.

- **Impact on the restoration project objective**: Lastly, the data analyst considered how each of the three options discussed above would impact the restoration project objective.

    - If the flagged data are excluded, the mean willow stem density would be 3.2 stems/m^2 (28% greater than the target 2.5 stems/m^2). However, reductions in the sample size increase the minimum detectable difference from 20% to 47%, and excluding the flagged data, hypothetically, may not support rejection of the null hypothesis. In this case, project staff would be unable to confirm that restoration project objectives were met; they also would be unable to definitively state whether this was due to failures in the restoration approach or failure to meet the sampling objectives.

  - If the flagged data are included, the mean willow stem density would be 3.8 stems/m^2 (52% greater than the target 2.5 stems/m^2). In this case, the null hypothesis would be rejected, and project staff would conclude the restoration project objective was met. In doing so, however, project staff would likely be accepting the identified bias and ignoring evidence that the bias significantly impacted the data quality.
  - If the flagged data were corrected, the mean willow stem density would be 3.2 stems/m^2 (28% greater than the target 2.5 stems/m^2). However, increases in variability increase the minimum detectable difference from 20% to 32%, and correction of the flagged data would not support rejection of the null hypothesis. In this case, project staff would be unable to confirm that restoration project objectives were met. As result, they would be unable to definitively state whether this was due to failures in the restoration approach or failure to meet the sampling objectives.
- Based on the data assessment, the data analyst decided to exclude the flagged data and report that results could not confirm that restoration project objectives were met. The data analyst then met with the project team to develop a supplementary quality document for additional sampling in year 3 that would attempt to confirm whether restoration project objectives were met a year after project completion. In making this decision, the data analyst was rightfully concerned with retaining flagged data that were biased, shown to impact multiple DQIs, and would bias the project conclusions. Correcting the bias in the data ultimately led to the same conclusion to exclude the data, and the analyst decided that the most defensible decision was to exclude the data and develop plans for supplementing the data collection effort. While collecting additional data has a cost, accepting a Type 1 error based on biased results also has significant costs. If the restoration approach is truly not effective, investing in additional restoration efforts using the same flawed approach could be much more costly.

7.2.2 Statistical Techniques for Evaluating Data Quality Indicators

Restoration data typically include results obtained in field settings by one or more trained crew members, as well as results obtained from chemical, biological and physical analyses conducted in a controlled laboratory environment. When combined, restoration data encompass a variety of data types, including discrete, continuous, categorical (qualitative), or binary data. The unique properties of each variable type should be considered when selecting the appropriate statistical procedures to assess data quality.

As examples, consider the following:

- Observer-determined results that are based on best professional judgment tend to be coarse in resolution. They generally consist of discrete continuous, numeric data reflecting actual counts or proportions (e.g., 1, 15, 100); discrete classes or groups of estimated values (e.g., 0, 1-10, 11-100, 101-1000) that are reflective of a continuum; or categorical, non-numeric data (e.g., species identification, land cover type). Statistically, the distributions of such data are typically different from data collected by calibrated instruments.

- A scientific instrument or measurement device can enable field or laboratory staff to record results for a given variable with an implied precision (regardless of whether it is appropriate to do so). Common examples in environmental monitoring projects include: relative humidity reported as "90.05%"; locational data reported as "WGS84: -86.75309"; or pH reported as "6.55." These types of results represent continuous data and, though it is possible to record reported values with a large number of significant figures, the appropriate number of significant figures (i.e., level of precision) should reflect requirements specified in the SOPs or other QA documents.

The statistical procedures involved in evaluating the degree to which a dataset achieves sampling objectives can vary depending on a number of factors, including the type of data (e.g., discrete, continuous, categorical), measurement scale (e.g., nominal, ordinal, interval, ratio), number of results, and distribution. **Appendix B** provides information about statistical procedures that are often suitable for the unique types of data produced in ecological restoration projects. The material provided in **Appendix B**, however, is not intended to supplant the need for data analysts to work with a statistician who is familiar with analysis of environmental and ecological data. Instead, it is intended to provide data analysts with information that may be helpful in discussing and understanding strategies recommended by a qualified statistician.

7.2.3 Revisiting Project Assumptions

During the data assessment process, the analyst should revisit assumptions that were made during project planning. These may be explicit assumptions that drove the restoration activities and sampling design or implicit assumptions inherent to chosen options. Reevaluating these assumptions can be critical for ensuring a proper understanding of data quality and usability, correctly interpreting results, and informing the adaptive management process. Several common categories of assumptions are listed below, but many others may be applicable to individual restoration projects.

Assumptions about controlling variables: At the outset of the project, the planning team determines which variables to measure or observe based on an understanding of the ecological system and assumptions regarding which variables will be important in controlling and responding to the restoration actions. Throughout the course of the project, however, it may become evident that additional variables are essential in controlling or describing restoration progress. These variables can be added to the monitoring regime as a critical component to the adaptive management process (see **Chapter 8**). Likewise, some planned variables may turn out to provide information of little or questionable value and may be removed from long-term monitoring as a decision outcome of adaptive management.

Assumptions about data variability: When developing sampling designs, project planners typically make assumptions about the magnitude of variability in data because these assumptions are necessary to develop power curves that inform sample size selection. When data from the project become available, the analyst should reevaluate stated or implied assumptions of data variability (similar to that discussed in the example scenarios presented above). If variability is higher than expected, the chosen sample size may not be adequate to meet sampling objectives. If variability is lower than expected, project resources may be invested in sample sizes that are unnecessary. In either case, sample size targets may be revised through the adaptive management process. However, data analysts must be aware of the impacts such decisions may have on data quality and consistency. In particular, comparability, representativeness and precision may be affected. Data analysis may also be impacted if certain statistical methods require equal sample sizes.

Assumptions about data ranges: Assumptions regarding the natural range of target variables may have guided decisions on analytical methods and procedures used in data collection. If actual data are outside the range of original assumptions, the selected methods and procedures may no longer be the most appropriate option. These decisions can be reevaluated through the adaptive management process; however, the data analyst should consider the impact of any change on data quality.

Assumptions about project timing: Many assumptions are made during project planning regarding the project timeline, and delays in the project can potentially impact restoration success. Project activities can be interrupted by funding delays, permitting challenges, weather, poor planning or other unforeseen circumstances. Planning teams should allow for seasonal flexibility by defining target and alternate periods acceptable for specific restoration activities. If the planned buffer periods prove to be insufficient (i.e., due to more frequent or longer delays), the project team should assess the impact of the delays and may need to modify restoration activities, objectives or goals. Project delays may also require modifications to the monitoring design or extension of the monitoring period to ensure restoration will be effectively monitored during ecological recovery.

Project timing can also significantly impact DQIs such as representativeness, comparability, and detectability. In order to adequately detect some ecological measures, it is important that project timing overlap critical seasonal cycles such as migration, nesting, reproduction, flooding regimes, growing seasons, etc. If project delays push sampling past critical seasonal windows, sampling may not adequately detect or represent the true ecological condition of the site. Inconsistent timing of sampling events from year-to-year may also impact the comparability of data between those years and misrepresent trends in the progress of ecological restoration.

Assumptions about the implementation of restoration actions: Most ecological restoration projects assume that restoration activities will be conducted as planned. However, implementation of those activities can be impacted by a number of unforeseen circumstances (e.g., severe weather or floods, inability to sufficiently remove invasive species, uncontrolled wildlife foraging, or contamination of seed mixtures). In such cases, the data analyst should consider the impact of incomplete or improper restoration implementation on project and sampling objectives. If these objectives cannot be met without fully implementing the restoration activities, the project team should use the adaptive management process to consider whether the objectives need to be revised or whether supplemental restoration activities are needed.

Assumptions about the speed and trajectory of recovery: Short-term and long-term monitoring plans are typically developed based on assumptions regarding the speed and trajectory of ecological recovery following restoration activities. If these assumptions are not met, monitoring plans may need to be modified to accommodate the actual pace and direction of recovery. This could mean extending the long-term monitoring period if recovery is slower than planned or adding monitoring variables if the direction of recovery is different than anticipated.

7.2.4 Evaluating Sampling Objectives

The preceding portions of **Section 7.2** discussed the elements of data assessment necessary for evaluating the impact of data quality issues on the intended use of the data. These elements are not distinct from the evaluation of sampling objectives; instead, they are integral components of an adaptive management process. Although it is not necessarily a separate step, evaluation of sampling objectives represents a culmination of the data assessment process that ties the data assessment to criteria stated in the project planning documents. The sampling objectives were specifically developed to ensure that project objectives can be adequately evaluated; failure to achieve the sampling objectives can jeopardize the project's ability to determine with certainty whether project objectives have been met.

Evaluation of whether sampling objectives have been achieved involves (1) assessing the impact of data quality concerns, (2) providing a definitive yes or no statement as to whether each objective was met, and (3) documenting the degree to which the objective was or was not achieved – including a description of any explanatory factors. Each of these is discussed below.

Assess the impact of data quality concerns as described in the preceding sections: Data assessment may identify a wide range of concerns and impacts and, along with reporting those concerns, the data analyst should focus on how those concerns specifically impact the sampling objective. For instance, the data analyst may report that missing data resulted in a 10% decrease in statistical power, or measurement error caused a decrease in precision and resulted in an increase of the minimum detectable difference from 20% to 30%.

Provide a definitive yes/no statement as to whether each sampling objective was met: Using the same willow example discussed throughout this chapter, the analyst should statistically determine whether the variability of the usable data would demonstrate achievement of a mean density of 2.5 native willow stems per square meter, with:

- 90% certainty when the true density is at least 20% greater than the targeted 2.5 stems/m^2 and
- a 5% chance (α) of incorrectly concluding that the 2.5 stems/m^2 objective was reached when it in fact was not.

Describe the degree of achievement: If the sampling objective was not met, the analyst should describe quantitatively how close the data came to meeting the objective. For instance, this could be expressed as: "*given the desired power and alpha level*, *the data were only capable of demonstrating if a minimum detectable difference of 30%, rather than the targeted 20%, was achieved*" or "*at the targeted minimum detectable difference level of 20%, the data could only achieve 82% power, rather than the targeted 90% power*." If the sampling objective was achieved, the analyst should describe the degree to which data quality exceeded the objective.

7.3 ANALYZING AND INTERPRETING DATA

This section provides guidance specific to data analysis and interpretation with the assumption that data review and data assessment steps have been completed. This section is not intended to describe all possible approaches that can be used to analyze ecological restoration data. Rather, this section provides guidance on the common series of data analysis steps (EPA 2006a), QC considerations throughout the process, and specific conditions that may be unique to ecological restoration projects.

7.3.1 Review Project Objectives

The overall purpose of data analysis is to determine whether project objectives have been met. A review of these objectives at the initiation of data analysis is useful in focusing the data analysis process. Within ecological restoration projects, there is often a plethora of data and numerous potentially interesting trends and relationships within the data. Although these relationships may be useful in informing ongoing and future restoration activities through the adaptive management process (**Chapter 8**), the primary focus of data analysis should be on the *current* stated project objectives. These objectives may have remained unchanged throughout the project, or they may have been revised through the adaptive management process based on previous data analysis and lessons learned.

7.3.2 Conduct Statistical and Graphical Data Review

A subsequent step is to calculate basic summary statistics based on the data. These might include, for example, determining the mean, median, percentiles, interquartile ranges, standard deviations and coefficients of variation for each variable, as well as correlations between primary or calculated variables. It is often helpful to prepare graphical representations, such as histograms, frequency plots, box and whisker plots, or plots of spatial data. These statistics and graphs help data analysts gain a mental picture of central tendencies, variability, potential temporal or spatial trends, and possible relationships between variables. Statistical and graphical reviews can also highlight outliers or anomalies within the data that were not identified in the data review or data assessment steps.

7.3.2.1 Treatment of Outliers

Graphical representations and statistical summaries of data can reveal potential outliers. When potential outliers are identified, the data analyst should take the following steps:

- **Confirm the validity of the result:** The data analyst should consult the data reviewers to determine if the potential outlier represents an error that was not identified during data review. Because the outlier could represent a transcription or data entry error, data reviewers should consult original field data sheets to confirm the result in question matches the result originally recorded by the field crew or laboratory analyst (see **Chapter 6**).

- **Investigate the cause:** If the potential outlier represents an accurately recorded result, the data analyst should investigate whether there is some explanation for the potential outlier by consulting the field or lab personnel that recorded the result and reviewing other data obtained in close proximity and near the same time as the potential outlier. Such investigations may reveal an explanation for the potential outlier, such as animal activity, vandalism, weather, urban structures, natural disturbances or other causes. If a cause is identified, and the cause is an anomaly that is not representative of the site, the data analyst can consider flagging the result as an outlier.

- **Evaluate variability:** The data analyst should evaluate the range of variability observed across the site and statistically compare the potential outlier to the distribution of the variability. Standard statistical methods are available for analyzing variability and formally identifying outliers. Commonly used statistical outlier tests include Grubbs' test and Dixon's test (Grubbs 1969; Dean and Dixon 1951). Beyond the formal statistical evaluation, however, the data analyst should consider whether the potential outlier falls within natural ranges for the variable and is representative of the diversity of the restoration site. A value that falls within natural ranges and represents the diversity of a site should not be discarded, even if it is identified as a statistical outlier. A determining factor should be whether the estimated value is representative of the conditions at the site.

- **Make a determination and document the decision**: Based on the above steps, the data analyst should make a decision to retain or discard potential outliers. This decision and the rationale for this decision should be formally documented in project files and data analysis reports.

7.3.2.2 Treatment of Censored Values

In addition to outliers, another data analysis consideration that deserves attention is the treatment of censored values. By censored values, we mean data that are reported as less than (<) a certain value or greater than (>) a certain value. Censored values can represent results that are below a sensitivity threshold (detection limit) or above a range. Examples of censored data would include nitrate concentrations reported as <0.1 mg/L (the detection limit) or most probable number bacterial counts of >1184 cfu/100mL (the maximum measurement range for a given dilution).

When variables containing censored values are used in mathematical or statistical calculations, the data analyst must decide how to numerically represent the censored values. This choice can potentially bias the resulting calculation. For instance, in calculating an average for a variable with *censored values at the lower end (< values)*, there are several options, but each carries certain biases:

- **Ignore the censored values**: This approach is not recommended, because it severely overestimates the variable mean. In this case, only low values are excluded, so the mean is biased in the positive direction.

- **Set the censored value at the limit**: In this approach, a censored value of <0.1 would be numerically set to 0.1 for the purpose of calculations. This approach also biases the value in the positive direction and overestimates the mean. This approach may be appropriate in some situations; however, the data analyst should be aware of the presence and direction of the bias.

- **Set the censored value at zero**: In this approach, a censored value of <0.1 would be numerically represented as 0 for the purpose of calculations. In contrast to the previous approaches, this approach biases the value in the negative direction and causes an underestimate of the variable mean. As with the previous approach, this approach may be appropriate in some situations; however, the data analyst should be aware of the presence and direction of the bias.

- **Set the censored value at half the limit**: In this approach, a censored value of <0.1 would be numerically set to 0.05 for the purpose of calculations. Although this approach is likely to produce the least bias in the mean, the mean may still be biased and the data analyst will not know the direction of the bias. This approach may be appropriate in some situations but, depending upon the decisions that may be made from the data, the analyst may elect to choose another option with greater bias just to have the certainty of knowing the direction of that bias.

Options for the treatment of *censored values at the upper end (> values)* are more limited, since the upper end is unbounded. While zero bounds the lower end, > values can theoretically approach infinity. For this reason, typically the only viable option is to set the value at the upper limit (e.g., > 1184 would be set to 1184). In this case, the data analyst should be aware that the value is biased in the negative direction and the variable mean is underestimated.

Recommended steps for determining the best option for handling censored values are provided below.

- **Consider whether the data gathering technique is adequate:** The data analyst should first consider whether the method or data collection technique selected to quantify the variable provides an adequate level of sensitivity. This decision should have been considered during the project planning phase, but if actual data ranges vary significantly from those anticipated in the planning phase, this decision may need to be reconsidered. The decision depends upon the range and availability of alternative methods or data collection techniques, the natural range of the variable at the site, and the decisions that will be made from the data. Often, the decision in question is whether the variable exceeds some biological threshold. In this case, the selected technique should have a detection limit below the threshold that defines the decision point.

- **Consider the inherent biases:** The data analyst should consider the inherent biases that result from the different options and determine which bias is acceptable. This determination depends upon the use of the data and the willingness to accept Type 1 or Type 2 errors. As an example, consider an analyst who is using phosphate data to test a null hypothesis that the mean phosphate concentration is ≤ a biological threshold for impairment. If the data analyst is more concerned about the consequences of a Type 1 error (false positive), they may choose a treatment option for censored values that underestimates the mean. If the data analyst is more concerned about the consequences of a Type 2 error (false negative), they may choose a treatment option for censored values that overestimates the mean.

- **Make a determination and document the decision:** Based on the above steps, the data analyst should make a decision on how to treat censored values. This decision and the rationale for this decision should be formally documented in project files and data analysis reports.

7.3.3 Select Procedures for Analyzing Project Data

Based on the project objectives and on the preliminary statistical and graphical data review, data analysts can select appropriate procedures for analyzing the data. A wide variety of approaches and statistical tools are available for analyzing ecological restoration data; **Exhibit 7-3** describes three broad categories of approaches, but it is beyond the scope of this document to list all possible approaches or provide specific guidance on any. Data analysts should consider the project objectives, recognize the quality and usability of the data, and consult a qualified statistician to ensure the most appropriate data analysis approach and statistical tests are selected.

Exhibit 7-3. Potential Data Analysis Approaches for Ecological Restoration Projects

Data Analysis Approach	Description	Example Use
Comparisons of Means or Medians	Statistical tests used to test whether the means or medians of two or more sets of data differ significantly. A comparison of means for two sets of data would be done with a simple two-sample t-test, while the more general Analysis of Variance (ANOVA) can compare a greater number of means and/or control for additional variables. Non-parametric versions tend to focus on comparing medians and include the Wilcoxon-Mann-Whitney test (two medians) and Kruskal-Wallis (more than two).	Testing whether the relative cover of native species differs significantly between plots sampled at a restored site vs. plots samples at a control site
Regression/ Trend Analysis	Models used to assess the relationship between one or more (usually continuous) variables (e.g., time) and the continuous primary variable of interest (e.g., stem density). Models may assume linear or non-linear relationships between variables and may be parametric or non-parametric (e.g., Thiel-Sen regression).	Testing whether the rate of change per year in the density of a target species exceeds a target rate or effect-size
Approaches for Categorical Outcomes	Tests for outcomes that can have two (e.g., alive or dead) or a few possible values rather than continuous numeric values. The proportions falling into the different groups can be compared across datasets using Chi-Square tests, and models testing the effect of continuous variables on the proportions can be fit using logistic regression and other log-linear models.	Testing whether the proportion of a target species surviving over a period of time varies between sites

7.3.4 Verify Assumptions Associated with Selected Procedures

Before conducting the selected statistical tests, it is important to understand the underlying assumptions of those tests and to check to see if these assumptions can be verified. For example, certain statistical tests require that data be normally distributed, variance components are additive, and there is no inherent bias. A number of statistical procedures are available to test these assumptions. If they are violated, it is possible to identify if a corrective action, such as a data transformation, can correct the problem or if other more robust statistical procedures or non-parametric approaches might be needed.

7.3.5 Implement Data Analysis Procedures

After completing the above steps, the data analyst can perform the selected statistical tests and interpret project results. All of the previous steps contribute to ensuring that the calculations and associated conclusions address the project objectives in a scientifically defensible manner.

7.3.6 Assess Restoration Project Objectives and Goals

The focus and the culmination of data analysis should be an assessment of restoration project objectives and overall project goals. As described in **Chapter 3**, ecological restoration projects should set narrative project goals that describe the change in ecological condition that is desired as a result of the project. These goals are then operationalized into more specific restoration project objectives that (1) support the overall restoration goals, (2) serve as the foundation for planning restoration and monitoring activities, and (3) provide the basis for measuring progress. If developed appropriately, using the SMART (specific, measureable, achievable, results-oriented, and time-sensitive) approach (Doran 1981), assessing the achievement of restoration project objectives should be a relatively straightforward aspect of data analysis and interpretation. For example, **Exhibit 3-3** presents specific statistical interpretations of project objectives for defined case studies. If similarly prepared, these statistical interpretations should be easily evaluated and project objectives clearly assessed.

In practice, the evaluation of overall restoration goals is somewhat more complicated and inexact. Although project objectives are developed as the most specific expression of restoration goals, it is likely that qualitative aspects of the project team's conception of restoration success are not adequately captured in specific project objectives. In addition, restoration outcomes cannot always be predicted and are often influenced by factors other than the action itself (e.g., unexpected disturbances, such as extreme weather events, malfunctioning equipment or contaminated seed/ planting stock, ineffective herbicide, reduced sample sizes, violated assumptions). Consequently, there often remains a level of data analysis and interpretation beyond the straightforward evaluation of project objectives. At this level, results are evaluated in an ecological and temporal context where project planners apply best professional judgment and a weight-of-evidence approach to interpret the overall effectiveness of the restoration actions. In short, qualitative evaluations of project success should be considered alongside quantitative assessments of formal project objectives. Results from this analysis are often important inputs to the adaptive management process and can inform future actions and restoration objectives.

To demonstrate the difference in evaluating project objectives and overall restoration goals, we will use the case study example of restoring native wet prairie that has been carried throughout this guidance document (**Exhibit 3-3**). The restoration goal for this project is to "restore native wet prairie plant species cover to improve floristic quality on a 15-acre wet prairie degraded by historic drainage and introduction of invasive reed canarygrass, *Phalaris arundinacea*." One of the project objectives set to implement this goal was to "reduce total cover of reed canarygrass (RC) to less than 10% across the 15-acre wet prairie after eight years." After a formal assessment of this project objective, it may be determined that data quality was insufficient to determine whether the site dropped below the 10% threshold in reed canarygrass cover. However, monitoring may have confirmed the natural recruitment and establishment of two native endangered wetland species as a result of restoration activities. In this case, project staff may determine that, while it was not possible to conclude the project objective was successfully achieved, evidence indicated that the overall restoration goal of restoring native wet prairie plant species was achieved.

7.3.7 QA/QC for the Data Analysis Activities

Like all aspects of an ecological restoration project, data analysis activities should be subject to quality management strategies to ensure appropriate approaches are used and accurately performed. Recommended QA/QC strategies include the following:

- **Proper experience and training:** Project personnel responsible for data analysis should have the proper experience and training to adequately conduct the analysis. Although it is not possible to list the exact qualifications for this position, the data analyst should have a senior position among the project team, have training and experience in statistics, be familiar with all aspects of the restoration project, and thoroughly understand ecological principles and processes associated with the restoration project.

- **Development and use of SOPs:** For aspects of data analysis that may be performed repeatedly, the data analyst should develop and follow SOPs that are appropriate for specific calculations (such as for an IBI) or for specific statistical tests (such as use of SAS software for analysis of variance). The development and use of SOPs for these tasks provides documentation and adds transparency to the data analysis process, provides an opportunity for review of procedures, and ensures consistency in the implementation of data analysis procedures.

- **Spot checks of calculations and statistical results:** Project personnel other than the data analyst (such as a data reviewer) should conduct spot checks of calculations and statistical results to ensure that errors have not occurred in the data analysis process. These spot checks should be independent corroborations of calculations made during data analysis.

- **Confirmation of statistical assumptions:** All assumptions embedded within the use of a particular statistical method should be confirmed. These may include assumptions regarding distributions of the data, independence of variables, randomness of samples, homogeneity of variance, or equality of sample sizes. The confirmation of statistical assumptions should be formally documented in project files and data analysis reports.

- **QA review:** The overall data analysis packet (report and supporting documentation) should be thoroughly reviewed by a trained statistician. The statistician should review the selection and use of statistical methods for data analysis, the explicit and implicit assumptions made regarding the data, the interpretation of statistical results, and the presentation of project findings.

7.4 USE OF ANALYZED DATA WITHIN THE CONTINUAL PLANNING PROCESS AND ADAPTIVE MANAGEMENT PROCESS CYCLES

Assessments of project data (**Section 7.2**), data analysis (**Section 7.3**), and the preparation of project reports (**Section 7.5**) provide a venue through which project managers can summarize results, suggest opportunities to improve the quality and reliability of data collection, and improve the execution and success of the restoration project. This valuable information can feed into two potential planning cycles: (1) the continual QA planning process and (2) the adaptive management process.

The **continual planning process** is at the core of any quality system. It ensures that information gained in collecting and reviewing data feeds back into deliberate steps to improve the quality of ongoing data collection efforts. Information gained from the data assessment and data analysis steps discussed in this chapter is ripe for inclusion in the continual planning process. For example, spot checks that reveal improper identification of species can be used to plan additional species identification training sessions.

The **adaptive management process** is a project management approach that continually uses collected data and lessons learned to inform decision making and adjust the project direction, if needed. The data analysis and reporting steps covered in this chapter provide such an opportunity. For example, if data analysis reveals that soil moisture is positively correlated with willow establishment success, project implementation plans might be adjusted to include placement of a moisture barrier that will reduce evaporative loss from the soil during the planting season.

Both planning cycles attempt to improve management of the project. The continual QA planning process is focused more specifically on improving the quality of the project data, whereas the adaptive management process focuses more broadly on improving the success of the overall ecological restoration project. The remainder of this section discusses the continual QA planning process; additional details on the adaptive management process are provided in **Chapter 8**.

7.4.1 Identifying Opportunities for Continual Improvement

As illustrated in **Exhibit 7-4** below, each data collection step during a project lifecycle provides an opportunity for improvement. Examples of potential improvements include:

- suggesting more specific quantitative project objectives or adjustments to data quality acceptance criteria for specific variables during the planning step;
- improving SOPs or crew training when preparing for new field activities;
- recommending a different sequence or frequency of QC checks during the field season;
- suggesting that certain verification or validation checks be integrated into field data recorders to minimize errors coming in from the field; or
- providing recommendations for reducing or adding variables being monitored as a result of data analysis efforts.

Exhibit 7-4. Example Project Lifecycle with Key QA Components

The main point is that opportunities for quality improvement exist and should be noted in project reports to benefit future data collection efforts.

7.4.2 Establishing Quality Improvement Processes – Basic Concepts

In addition to pursuing opportunities for improvement as they arise, project teams should consider the following basic quality improvement concepts.

- **Plan to revise QA planning documents as needed:** The development of QA planning documents such as quality assurance project plans (QAPPs) are an important part of the continual planning process. Managers are forced to consider all aspects of project development before the project begins. Such planning documents establish sample collection and data review procedures that are appropriate for the intended use of the data. However, these documents also should be viewed as dynamic documents that can and should be revised when needed to address opportunities for improvement.

- **Strive to identify and then meet or exceed expectations:** Focus on the needs, performance expectations and opinions of all interested stakeholders or parties. A critical starting point is setting restoration project goals and objectives as described in **Chapter 3**.

- **Prevent problems from occurring:** As the saying goes “an ounce of prevention is worth a pound of cure.” Examples of preventive measures to ensure quality include the development of comprehensive SOPs, as well as adequate training of field crews in the use of these SOPs (see **Chapter 4**); the implementation of QC checks early in the field season (see **Chapter 5**); and the development of written procedures for data review, assessment and analysis, and assignment of qualified individuals to perform them (Chapters 6 and 7).

- **Identify root causes:** The root causes of significant problems need to be identified and corrected as soon as possible during a field season. If field crews are consistently unable to achieve data quality acceptance criteria for a particular variable, the root cause of this deficiency needs to be identified. For example, a root cause analysis may indicate that the SOP needs to be improved, training is inadequate, or more highly qualified staff should be recruited. Once a root cause or causes have been identified, corrective actions should be implemented to resolve and prevent the problems from recurring.

- **Encourage a no-fault attitude:** A no-fault attitude encourages staff to identify problems, solutions to problems, and other process improvement opportunities. At the beginning of a field season, staff should be encouraged to look for and report opportunities for improvements to data collection activities, including those related to the procedures themselves or the associated logistics (e.g., ideas for improving safety or reducing staff fatigue). Management should perform timely evaluations of staff recommendations and provide feedback, which can foster team building and an overall quality improvement attitude. Public acknowledgement of staff contributions to quality where planned outcomes were achieved or exceeded is encouraged. The “acknowledgement” section of reports is an opportunity to provide this credit to staff.

- **Maintain timely data review, assessment and analysis:** In order to constructively contribute to the adaptive management cycle, assessment and analysis of ongoing data collection efforts should be conducted with a timeliness and frequency that allows for lessons learned to inform and adjust upcoming sampling efforts. Delaying data assessment and analysis steps to the end of a project eliminates the advantages of the adaptive management process and may limit the ultimate success of a project.

- **Adjust:** Periodic reviews or assessments often identify opportunities for improvement. As data are reviewed, common errors by field crews or laboratory staff can be identified, particularly those affecting data quality. These needed changes in data collection should be identified to answer current and emerging monitoring questions. Likewise, project teams should consider ways to reduce data collection and associated QC costs and adjust accordingly. For example, it may be possible to update data collection techniques to take advantage of new technologies yet maintain the integrity of previous core variables.

7.5 PREPARING AND REVIEWING PROJECT REPORTS

The eventual release and sharing of data and corresponding reports is a critical component of every ecological restoration project, and should be considered throughout all aspects of data collection, review and assessment. Just as the data are used to support decisions regarding a project's ongoing activities as well as its success, project reports are used to present and explain those data, along with the resulting conclusions, decisions and rationale.

In 2013, the U.S. government published two memoranda specifically related to the dissemination of data generated under federally funded projects.

Project Reporting

Project reports are intended to communicate results and other information to stakeholders or external parties, including:

- **Final project outcomes**
- **Ongoing progress**
- **Achievement of milestones**
- **Rationale for interim decisions**
- **Changes in project direction or approach**

- On February 22, 2013, the U.S. Office of Science and Technology Policy (OSTP) established a policy on "Increasing Access to the Results of Federally Funded Scientific Research" that requires public access to datasets resulting from federally funded research, including datasets used to support scholarly publications.
- On May 9, 2013, the U.S. Office of Management and Budget (OMB) issued Memorandum M-13-13, "Open Data Policy-Managing Information as an Asset," which requires agencies to collect or create information in a way that supports downstream information processing and dissemination.

Although the policies stated in these memoranda are intended for agency-wide application by government agencies spending a certain amount of funding on projects that generate data, their intent should be considered across all projects in which data are generated, particularly those that are sponsored by publicly funded agencies. With the release of project data, the importance of corresponding technically sound, transparent, clearly written, and professional reports cannot be overstated. This section briefly describes the purpose of these reports, provides some recommendations regarding their content, and discusses approaches to ensuring their quality prior to release.

7.5.1 Project Report Types and Objectives

Project reports can be generated to meet a variety of objectives. Reports can be used to document internal project decisions, provide periodic updates on project progress, summarize project conclusions for a partner or funding agency, disseminate results to the scientific community, or present information about the project to the general public. Each of these reports may have different objectives, be targeted to a different audience, include different content, and require a different level of quality assurance and review in the development. Examples of the types of reports that may be generated throughout the course of an ecological restoration project are discussed below.

Internal reports: Internal reports may be useful for documenting the rationale and supporting data for internal decisions regarding a change in the restoration approach, experimental design, sampling methodology, data review strategies, or any other aspect of the project. Internal reports can also be useful in documenting project milestones. For instance, project personnel may prepare a data review report documenting their assessment of data quality before embarking on data analysis and reporting of final results. Although internal reports are generated for a limited audience, such as project personnel, project partners, or the funding agency, they may be or may become publicly available. Internal reports need a level of review and QC to document accuracy and readability, but they do not typically need the level of external peer review that might be recommended for culminating project reports.

Periodic or annual reports: Annual reports are often useful for periodically documenting progress and interim results of larger multi-year projects to a variety of audiences (e.g., the funding agency, project partners, general public), and the writing style and level of detail in such reports should reflect the intended readers. Because data collection efforts are still underway, annual reports usually do not include significant data analysis. When data analysis is included, it is more likely to represent preliminary trends rather than definitive conclusions. For this reason, annual reports may require a higher level of review than internal reports, but probably not the level of review necessary for final reports.

Scientific publications: If the intent of a report is to disseminate the project's findings to the broader scientific community, the project staff should consider preparing and submitting an article for publication in the peer-reviewed scientific literature. By targeting the article to a particular scientific journal, the authors will ensure that the content is disseminated to the appropriate audience. Delivering publications through the scientific literature also ensures that the typical standards for scientific peer review are met. Before submitting manuscripts, however, project staff should seek internal and project partner reviews of draft documents.

Final reports: Almost all ecological restoration projects will require a final report that documents the methods and procedures used, data analysis approaches, project results, and conclusions. Most government agencies have a responsibility to make the results of their scientific studies and projects available to the public in a timely, clearly presented, and easily accessible manner. In general, data that are generated under government-funded projects should at some point be made available to other groups within the sponsoring agency, other government agencies, and tax payers. As noted in the U.S. Geological Survey (USGS) data management website (USGS 2017b), "*Data sharing benefits the researcher, research sponsors, data repositories, the scientific community, and the public. It encourages more connection and collaboration between scientists, and better science leads to better decision making*."

The remaining guidance in **Section 7.5** primarily applies to the preparation of final reports. Other types of reports can benefit from this guidance, but the content and QC strategies required will vary depending on the report type and the intended audience.

7.5.2 Content of Project Reports

By the time a report is generated, the supporting data should have been thoroughly reviewed (**Chapter 6**), and all data limitations should be transparent and fully understood. Data assessments as described throughout this chapter should be complete, and project reports should contain sufficient information to explain and defend the conclusions reached, using information that is accurate, clearly presented, and consistent with the report's discussion. For example, if a report is intended to present conclusions regarding the success of an ecological restoration project, it should (1) describe the project objectives along with the methods used to monitor the impacts of the restoration activities, and (2) present data in a manner that clearly relates the data to these objectives and conclusions. Any deviations from the original plans should be included with an explanation of why the deviations were required and their impact on any results. Most importantly, reports should include a discussion of the quality and reliability of the data in the context of project decisions and conclusions.

Recommendations for the general content of project data reports include, but are not limited to the following:

- Acknowledgements – Including reviewers
- Definitions (Glossary) – Specialized information/vocabulary, formulas, standard values, units of measure
- Executive summary
- Project goals and objectives
- Data collection strategies– Discussion of the project design and methods used
- Results – Discussion and presentation of data, including results of data review, data limitations, and data analysis
- Conclusions – Discussion based results of the data analysis, including assumptions
- Graphics, figures, tables
- References
- Appendices – Supplemental information, original data, or quoted matter that is too long for the body of the report

The data must be clearly explained, regardless of whether access is provided to complete datasets or data are summarized in tables throughout the report. This discussion should describe how the data were generated, include all noted limitations, and provide a sufficient amount of data to support any conclusions. Although standardized scientific notation is generally applied to represent units of measurement, it may not apply to much of the data typically collected for ecological restoration projects. Regardless of the format, units of measurement should be applied consistently and explicitly stated to avoid ambiguity and confusion. Equations, calculations, extrapolations, acceptance criteria and alternate interpretations also should be provided to proactively address questions from those interested in (or planning to use) the information.

Whatever the content of the report, authors should assume that the contents will need to be scientifically and legally defensible for individuals involved in project decisions, funding the data collection effort, and using or leveraging the data for other projects or related decisions, particularly if policy decisions could be impacted. Report preparation should include the following activities.

- **Determine the audience:** Consider the type of information and the level of detail and technical complexity that is appropriate for the intended audience of the report and tailor the writing accordingly.
- **Determine report format:** Organizations either conducting a restoration effort or funding that effort may have a manuscript format that is preferred or required. These formats customarily include how the manuscript text, text citations, footnotes, equations, tables, graphics, photographs and citations are to be formatted. Where applicable, report authors should follow these formatting rules and seek editorial review to confirm they have been followed correctly.
- **Determine organizational policy:** Learn and follow the policy of your organization regarding manuscript submission such as authorship, technical review, editorial review, statistical review, policy review and final management review.

7.5.3 Assuring the Quality of Project Reports

Project reports should be considered draft or preliminary until they have been reviewed and approved for release to ensure the presentation of results is accurate, clear and understandable, and that the interpretations and conclusions are scientifically sound and technically defensible. Until these documents have been sufficiently reviewed and are deemed final for release, their status should be clearly indicated as draft, with notations restricting their release. The accompanying text box includes some helpful suggestions for authors as a final check of their reports to ensure the presentation of exhibits, numbering, references and other formatting issues are complete and consistent throughout the document.

Three different levels of review may be applicable to ecological restoration project reports: internal review, project partner review and external peer review. Similar to the review and certification of project data, as discussed in **Chapter 6**, the level of review required for project reports is dependent on the size and impact of the project, the extent to which and how the results will be used, the intended audience, and the agency that is responsible for the product. Guidance is provided on each of these review levels.

Report Checks

- ✓ Check titles, affiliations, and addresses of authors to be sure they are correct
- ✓ Run a spell-check
- ✓ Provide the scientific name for each organism (include all authorities if used)
- ✓ Revisit referenced Web sites to check the accuracy of the URL and availability
- ✓ Check the numbering of footnotes and any text references to earlier footnotes
- ✓ Acknowledge others who contributed
- ✓ Make sure there is a citation for every reference in the text and a text reference for every citation
- ✓ Number tables and figures consecutively throughout in the order they are mentioned in text
- ✓ Provide all tables and figures in their native format to those responsible for final document production and formatting
- ✓ Include logos for other agencies if they are needed for a formal title page

Source: (U.S. Forest Service 2009)

Internal review: All final reports should undergo internal review prior to release. Internal review should include technical review, editorial review, statistical review and policy review. The technical review should be conducted by technically qualified individuals who have at least supervisory-level involvement in the project and can verify the reported information is consistent with the activities that were planned and implemented. A trained statistician should conduct the statistical review. Personnel with sufficient skills in communication, language and professional formatting should conduct the editorial review, and the policy review should be conducted by upper-level management to ensure that the procedures and findings are consistent with organizational practices. These reviews do not necessarily have to be conducted by different personnel; in some cases a single reviewer may have the qualifications to perform a technical review, editorial review and statistical review simultaneously.

Project partner review: Ecological restoration project reports may benefit from reviews by project partners. Many projects are conducted in close association with multiple partners including non-governmental organizations, consultants, local governments or state or federal agencies. At a minimum, these partners have some familiarity with the project and may have participated in the planning or implementation activities. While these partners are not completely independent, they can provide a fresh look at data and their input may be extremely useful. Soliciting and obtaining reviews from these partners also may be much easier than managing an external review process.

External peer review: Depending upon the requirements of your organization, requirements of the funding agency, the size and impact of the project, and the potential implications of the project results, an external peer review may or may not be required. For example, *OMB's Final Information Quality Bulletin for Peer Review*:

- requires each federal agency to obtain peer review of "influential scientific information" and "highly influential scientific assessments" prior to dissemination;
- establishes minimum standards concerning the need for peer review and the types of peer reviews that agencies should consider in different circumstances;
- provides guidance concerning peer review practices;
- grants agencies broad discretion in determining the type of peer review that is appropriate for influential scientific information and the procedures used to select qualified reviewers; and
- establishes more rigorous requirements for highly influential scientific assessments (OMB 2004).

Qualified Peer Reviewers

- **Subject matter experts with specific technical expertise in the subject matter of the report undergoing review**
- **Unbiased and have no stake in the outcome of the review of publication**
- **Not directly associated with the particular work performed**

The bulletin is applicable to all U.S. government departments and agencies, and many agencies have established internal policies, procedures or guidance for complying with the OMB requirements. Project managers should determine whether their project reports are subject to the OMB or Agency-specific peer review requirements before release. For example, EPA has a *Peer Review Handbook* that supports the Agency's peer review policy and provides detailed guidance for planning and implementing peer reviews (EPA 2015). Although this handbook is tailored to EPA employees, it recommends a number of practices that are useful to all organizations, including the following.

- **Complete internal and partner reviews:** Before submitting a report for peer review, conduct the necessary internal reviews and partner reviews (if desired). This should improve the quality of the document before it released and help limit the number and extent of comments that project teams will need to address.
- **Determine the need for a peer review:** Is peer review required by your organization or the funding agency? Would the report benefit from a peer review? If so, it is helpful to document the rationale for this decision.
- **Plan the peer review:** Begin by selecting a peer review approach. Assuming the peer review is not being conducted through refereed scientific journal, the planning process should consider:
    - the type of review (e.g., reviews by one or more individuals versus reviews by an advisory board or other qualified panel);
    - whether peer reviewers will be blind (i.e., unknown to the project team);
    - timelines for the peer review process, including timing for the selection of peer reviewers, start of the review, length of the comment period, and deadlines for reconciling and responding to comments and completing a final version of the report; and

- the necessary qualifications of the reviewers (e.g., relevant scientific and technical expertise as well as independence).

  As a final planning step, project staff should prepare peer review materials, including a charge that describes the objective of the review and any specific advice sought, miscellaneous instructions, the draft report, and any supporting materials, such as a certified project database with associated database descriptors (i.e., metadata).

- **Conduct the peer review:** At a minimum, this includes sending the peer review materials to peer reviewers and receiving their comments. It also may include intermediate checkpoints to determine if reviewers have any questions that might require clarification.

- **Complete the peer review:** Evaluate and address each of the peer review comments, and submit the revised document for final review in accordance with your organizations' requirements. For formal peer reviews conducted in accordance with OMB or other Agency-specific procedures, this step also may require preparation of a reconciliation memo or response to comments document that explains how each comment is addressed.

Even if peer review is not required, project managers may wish to consider whether an external peer review would benefit their project. External peer reviews can provide (1) useful insight that may have been overlooked by project personnel, and (2) an unbiased assessment of the project that affords an additional level of transparency and scientific validity to the project.

7.6 DATA ASSESSMENT, ANALYSIS, AND REPORTING – CHECKLIST

The checklist below provides a summary list of overarching principles and aspects that should be considered and implemented when assessing, analyzing and reporting project data. As with any checklist, the listed items should not be interpreted or applied without comprehension of the supporting information. Users of this checklist are encouraged to read and understand the corresponding details that are provided throughout this chapter, and to implement these details using a graded approach that is commensurate with a project's scope, importance and available resources.

DATA ASSESSMENT, ANALYSIS, AND REPORTING – CHECKLIST
☐ **Plan data assessment, analysis and reporting activities.** ☐ Consider the purpose and intended use of the project data. ☐ Determine who will be responsible for data assessment, analysis and reporting (identify individuals with the necessary qualifications, background and authority), including those who will be responsible for QC spot checks. ☐ Determine when assessment, analysis and reporting activities will take place. ☐ Determine which data will be assessed, analyzed and reported.

DATA ASSESSMENT, ANALYSIS, AND REPORTING – CHECKLIST

- ☐ Determine how the assessment and/or analysis will be performed and how the results will be documented.
- ☐ Determine how the data will be used in decision making.
- ☐ Document these who, what, when and how decisions in written procedures.

☐ **Assess the impacts of data quality on the intended use of the data.** (Determine how the validated dataset(s) might impact the intended use of the data.)

- ☐ Identify types of data issues and instances of data flags.
- ☐ Determine the extent of the issues and data flags.
- ☐ Determine the impacts of these issues and data flags on data quality indicators (DQIs) and data use (e.g., reduction in available data, reduction in ability to evaluate key variables).
- ☐ Determine the impacts of these issues and data flags on the evaluation of whether project objectives have been met (e.g., potential risk of false positives or false negatives on decision making).
- ☐ Decide how the data affected by issues or data flags should be handled.

☐ **Analyze and interpret the data.** (Determine whether project objectives have been met.)

- ☐ Calculate summary statistics (e.g., to determine mean, median, percentiles, ranges standard deviation, coefficients of variation, and uncertainties) and prepare graphical representations to aid in understanding the dataset.
- ☐ Identify, evaluate and determine how to handle censored values (e.g., values reported as less than detectable) and outliers.
- ☐ Consider and determine how to handle potential biases in the data.
- ☐ Select and implement data analysis approach (e.g., comparisons of means or medians, regression/trend analysis, categorical outcome).
- ☐ Verify assumptions for the selected statistical tests are met.
- ☐ Document results of data analyses, including calculations, data used, and corresponding decisions and their rationale.
- ☐ Complete a QC assessment of data analysis activities and results (e.g., were data analysis procedures followed, are calculations and statistical results accurate, are statistical assumptions correct, are results accurately and thoroughly documented).
- ☐ Determine whether project goals and objectives have been met.

DATA ASSESSMENT, ANALYSIS, AND REPORTING – CHECKLIST

☐ **Evaluate results of data analysis and assessment for possible use in continual planning and adaptive management.**
 	
☐ **Prepare project report(s).**
  ☐ Determine the type of report(s) that will be needed (e.g., internal, periodic, final and/or scientific publication).
  ☐ Determine and outline the contents of the report(s) (e.g., project objectives, monitoring methods used, results, data analysis and assessment procedures, and resulting conclusions and actions).
  ☐ Determine who will be responsible for preparing and reviewing the reports, including who will be responsible for addressing reviewers' comments and questions.
  ☐ Prepare report(s).
    o Are data presented and explained clearly and consistently, including their limitations?
    o Are the procedures used to collect the data clearly explained?
    o Are results, conclusions and decisions clearly explained and supported by the presented data?
    o Are the contents scientifically and legally defensible?
  ☐ Facilitate and complete internal and external reviews.
    o Identify qualified and objective internal and partner reviewers with knowledge of the project.
    o Determine the need for an external review and, if needed, identify qualified and objective external reviewers.
    o Prepare review questions and materials, and provide them to reviewers along with the draft report and supporting materials.
    o Evaluate and address reviewer comments, and revise the report as needed.

7.7 ADDITIONAL READINGS

- Milberg, Per, Johan Bergstedt, Jonas Fridman, Gunnar Odell, and Lars Westerberg. 2008. "Systematic and Random Variation Vegetation Monitoring Data." Journal of Vegetation Science 19: 633-644. doi: 10.3170/2008-8-18423.

- Stribling James B., Kristen L. Pavlik, Susan M. Holdsworth, and Erik W. Leppo. 2008. "Data Quality, Performance, and Uncertainty in Taxonomic Identification for Biological Assessments." Journal of the North American Benthological Society 27 (4): 906-919. doi: 10.1899/07-175.1.

- Tufte, Edward R. 2001. "The visual display of quantitative information." Cheshire, Conn: Graphics Press.

- U.S. Geological Survey. 2017. “502.4 - Fundamental Science Practices: Review, Approval, and Release of Information Products.” U.S. Geological Survey Manual. Last modified February 17. https://www2.usgs.gov/usgs-manual/500/502-4.html.
- U.S. Geological Survey. 2017. “Data Management: Data Release, Sharing, and Publication.” USGS (Supporting and Enabling USGS Data Management). Last modified March 23. https://www2.usgs.gov/datamanagement/share.php.

CHAPTER 8 THE RELATIONSHIP BETWEEN QUALITY MANAGEMENT AND ADAPTIVE MANAGEMENT STRATEGIES

The QA/QC principles presented in the previous chapters lay the foundation for sound decision making regarding the effectiveness of ecological restoration projects.[14] However, application of these principles and meticulous collection of quality control (QC) data during the effectiveness monitoring phase are of little value if the fully validated data are not used in a way that allows restoration ecologists to (1) conclude project success or draw on lessons learned; (2) determine if adjustments to the restoration or monitoring design are needed; and (3) implement those adjustments to improve overall project or program outcomes. Adaptive management provides a flexible framework for decision making that provides an information-driven approach to adjusting restoration actions where and when needed (Williams, Szaro, and Shapiro 2009; Williams and Brown 2012).

Adaptive management is not a final step; it is a framework of continual improvement actions conducted throughout a project lifecycle. Restoration often takes time, sometimes decades, requiring continuous collection, management, and assessment of data to ensure progress toward desired outcomes. Conversely, some ecosystem manipulations can cause a rapid change in system states and require immediate response to unexpected outcomes. The ability to effectively apply adaptive actions depends on the quality of **all** the steps preceding it, including the:

- clarity of project objectives,
- design of the monitoring plan,
- quality of collected data, and
- analysis and interpretation of the data.

Hilderbrand, Watts, and Randle (2005) present some reality checks regarding ecological restoration. Many fail to recognize that restoration is attempting to create ecological change in a few years that typically takes tens or hundreds of years to evolve under natural succession by itself. Restoration efforts are often built upon oversimplified concepts, ignoring uncertainties that will inevitably result in unexpected outcomes and failures. This often leads to the creation of a restored ecosystem that may be incapable of adapting to current or adjusting to any new stressors or other occurrences in the future. Once these realities are firmly grasped then one can clearly see that ecological restoration is not a one-time event. It requires continuous monitoring and feedback inside the context of an adaptive management strategy that will increase the probability of executing a responsive, sustainable, and successful project. Arguably, an Adaptive Management Plan (AMP) could then be thought of as an experiment requiring a well-crafted experimental design (Fischenich and Vogt 2012). In an ideal world,

[14] Briefly, these principles include (1) carefully defining and documenting the project goals, project objectives, and sampling objectives, (2) designing and implementing a monitoring program that will provide data needed to determine if the objectives have been met, (3) identifying and implementing QA practices and QC checks during the monitoring program to ensure the plan is properly followed and data quality targets are being achieved, and (4) reviewing the quality of data generated to confirm it is of sufficient quality for its intended use.

adaptive management should be utilized only after disputing parties have settled on a set of questions (hypotheses) to be tested and resolved using an adaptive methodology (Lee 1999) as would normally be accomplished with any experimental effort.

This chapter offers guidance to ecological restoration practitioners on ways to apply adaptive management principles to their ecological restoration projects. The most effective place to build quality assurance measures into the entire project is with an adaptive management strategy.

8.1 DEFINITION

There are numerous definitions of adaptive management in the literature (Holling 1978; Walters 1986; Lee 1999; Anderson et al. 2003; Roux and Foxcroft 2011). One major source of uncertainty in any scientific or engineering field is linguistic uncertainty. Terminology and jargon tend to inhibit communication across disciplines and within the same discipline. To that end, for the purpose of this guidance document, we define adaptive management as: a structured and sequential learning process (decision-support) that increases knowledge and reduces uncertainty, iteratively leading to more effective ecological restoration (Clark County 2016; Sutter 2018). We do not advocate any one particular definition over another, but rely on each reader to adopt a definition that best meets the needs of their project and institutional requirements. Suffice it to say a shared aspect of all definitions is the recognition that natural resources are ever changing and management decisions must often be made without all the necessary information about these systems (Peters et al. 2014). An adaptive management definition generally includes the following key components (Williams, Szaro, and Shapiro 2009; Williams and Brown 2012; Runge and Knutson 2012; Williams and Boomer 2012):

- provides a framework for restoration,
- addresses both short- and long-term issues,
- recognizes the uncertainty of restoration results and the need to improve restoration actions,
- allows for an iterative decision-making process,
- provides an opportunity to learn throughout the process of restoration,
- improves restoration activities based on continuous feedback (both within a single project and from one project to the next), and
- clarifies that restoration is based more on evidence than hypotheses.

An AMP lays out the path to follow and the corrective actions that need to be taken when there is high uncertainty in whether a project is on a trajectory to achieve the desired outcomes. If poor quality monitoring design or data indicates the project is on a successful trajectory when in fact it is not (Type 1 error, i.e., a false positive), ecological harm will continue. Alternatively, if poor quality monitoring design or data indicates the project is not on a successful trajectory when in fact it is (Type 2 error, i.e., a false negative), costly and unnecessary operational or structural changes may be undertaken. It is imperative that quality management be built into every ecological restoration project to avoid costly financial mistakes and irreversible ecological disasters.

An AMP requires monitoring data as input on how well a project met (or is meeting) its intended outcome. Monitoring is an integral part of the AMP, but must also be adaptable to changing needs and findings. Sometimes the wrong indicators have been monitored; they have not been responsive to the restoration actions. Monitoring may go on for a decade or longer after project completion. New cost-effective methods may become available during that time that can reduce the cost of long-term monitoring. A method may need to be changed because it is not able to achieve the desired data quality objectives necessary to determine project success within a desired range of uncertainty. To quote Pirsig's classic novel on quality, *Zen and the Art of Motorcycle Maintenance*, "the pencil is mightier than the pen" (1974). It should be realized that an AMP is not chiseled in stone, but must be flexible (hence the name, "adaptive") enough to address ever changing conditions and lessons learned.

8.2 ROLE OF ADAPTIVE MANAGEMENT FOR ECOLOGICAL RESTORATION PROJECTS

As defined in **Section 8.1**, adaptive management is an approach that improves management and enhances learning. It provides a framework for:

- implementing ecological restoration actions within the context of uncertainty (**Section 8.2.1**);
- Using available knowledge and verified validated results of monitoring efforts to adapt actions (**Section 8.2.2**); and
- increasing the effectiveness, efficiency and enduring value of projects (**Section 8.2.3**).

8.2.1 Framework for Implementing Ecological Restoration Actions within the Context of Uncertainty

Ecological restoration projects are long-term endeavors with substantial uncertainty. Time is a primary variable when restoring natural communities and restoration is done within the context of a changing environment resulting from a suite of interacting anthropogenic disturbances, including, but not limited to:

- invasive species,
- disruption of predator-prey relationships,
- altered hydrogeomorphic and fluvialgeomorphic regimes,
- altered fire regimes,
- deposition of atmospheric nitrogen and other contaminants, and
- climate change.

These changes drive the need for ecological restoration, but magnify the uncertainty of ecological restoration success. Added complications arise when selecting a restoration goal such as a "natural" state that existed before the need for restoration or recognizing that systems are dynamic and may have multiple possible responses to restoration actions (Hilderbrand, Watts, and Randle 2005). Monitoring is essential to confirm that the ecosystem is progressing as anticipated on a preferred trajectory.

Trend detection is perhaps the most important ecosystem response that a monitoring effort should be designed to capture. At some time "zero" at point "X," a restoration action was imposed on the system to be monitored and we want to assess whether a response can be observed above the background noise or separate it from the natural variability in the system. There are many sources of uncertainty that tend to blur the ability to observe trends in both time and space. Lyons *et al.* (2008) present four key causes of uncertainty that shape natural resource assessments and related management choices.

1. Inherent spatiotemporal variability frequently propels ecosystems in directions that may or may not be in agreement with prescribed restoration treatments.
2. The patterns identified in ecosystems are often based on a poor understanding of the biological processes that led to these patterns.
3. Direct measurement of numerous important ecosystem variables is not always possible.
4. Results or restoration measures frequently diverge in the magnitude and spatial coverage from prescribed management treatments.

The fact that many system variables are not measured directly is the primary focus of this guidance document (i.e., uncertainty in the measurement system). By incorporating monitoring into planning, adaptive management plainly deals with these causes of uncertainty and permits decision makers to create additional understanding regarding just how systems act in response to restoration efforts while accomplishing restoration goals and objectives (Lyons et al. 2008).

As an example, a problem may be encountered during the restoration of a wetland where vegetation does not establish well in all areas. This may be due to the fact that different plants have different salinity tolerances and certain areas of the wetland have salt seeps. Monitoring information can help to accurately identify these areas so that additional salt tolerant species can be planted there.

8.2.2 Framework for Adapting Ecological Restoration Policies and Actions based on Lessons Learned

> **Structured Decision-Making Framework**
> **"A formal application of common sense for situations too complex for the informal use of common sense."**
> **(Keeney 1982)**

Adaptive management promotes learning by requiring the collection of information and the monitoring of outcomes to adjust policy and procedures. Therefore, at the core of any adaptive management program is a dedicated monitoring program to provide the information that is necessary for these adjustments (Peters et al. 2014). No AMP is complete without a placeholder for incorporating monitoring data, as it is not feasible to fully gauge the success of an ecological restoration undertaking without collecting information on the response of the system to the restoration measures. By "placeholder," we mean that monitoring has been institutionalized and there is a group of decision makers that are actually expecting the monitoring data with specific intentions for its use. **Chapters 3 – 7** provide guidance on applying effective quality management strategies to the collection of monitoring data. However, monitoring is not a standalone activity — it must be integrated into a much larger, structured decision-making framework.

Adaptive management provides a structured decision-making environment in which monitoring data can reside, and a foundation upon which to communicate and incorporate the values and expert reasoning of decision makers and specialists (Keeney 1982) using high-quality, real-time monitoring data to examine the overall implications of restoration actions. A stand-alone monitoring program with no clear linkages (i.e., a placeholder) to a structured decision-making framework will, over time, experience loss of interest and hence reductions in funding. Preferably, monitoring should discover problems relatively early in the project lifecycle so that remedial efforts can be implemented quickly as required (Atkinson et al. 2004).

It is important to note that given all the uncertainties and complexities associated with restoration projects, monitoring data need not be the only input into the adaptive management decision-making process. For example, in complex systems there can be widely varying conditions with a variety of both positive and negative feedback loops. Even the best monitoring data may not provide "the answer" unless these data can be supplemented by other information sources, including the scientific literature. The findings from other similar restoration efforts may also help explain current results identified during the analysis of monitoring data.

8.2.3 Framework for Increasing the Effectiveness, Efficiency, and Enduring Value of Ecological Restoration Projects

Evaluating the quality of restoration project construction is part of what is commonly referred to as implementation monitoring, and most often lies within the purview of the contract management specialist. While the primary focus of this guidance is on effectiveness monitoring used to document status and trends in resource conditions resulting from restoration activities (Mulder et al. 1999), implementation monitoring should be an essential component of the adaptive management framework. Failure to properly implement the restoration design may have profound impacts on the efficacy of the restoration efforts and the effectiveness monitoring results. Key questions include whether there are any QA/QC guidelines in place for implementation monitoring, whether the project was completed in accordance with specifications, and whether implementation and effectiveness monitoring efforts are linked together somehow. This linkage is perhaps the essence of adaptive management. If the restoration effort was not fully executed (or was not completed in accordance with specifications or in the correct location), users of the effectiveness monitoring data may be looking for a response to something that was either not completed, partially or incorrectly completed, or completed in the wrong place. While this may not directly influence the data quality attributes of effectiveness monitoring indicators collected in the field, it does suggest that QA/QC may need to be implemented during the project design phase.

As discussed in **Section 3.5**, secondary data are valuable resources for establishing baseline conditions and augmenting new monitoring efforts. Often times, a different standard operating procedure (SOP) or field method is enlisted to gather new data compared to these historical datasets. It may be more advantageous to adopt the SOP that was used in the secondary data to avoid data comparability issues. That is, provided the older SOP or alternate secondary data SOP is not flawed in some manner (e.g., unacceptable data quality, too destructive). See **Section 4.1.3** for additional guidance on the evaluation and comparison of SOPs.

8.3 PRACTICALITIES OF ADAPTIVE MANAGEMENT IN ECOLOGICAL RESTORATION PROJECTS

The success of adaptive management strategies can be improved if projects are well planned, implemented and monitored. Monitoring data is the foundation upon which adaptive management is built. Without monitoring data, there can be no assessment of whether or not a project has achieved its objectives. The types of monitoring and the limitations associated with each are explored in the following subsections.

8.3.1 Need for Accurate Monitoring Baselines

An effective AMP should be based on monitoring data that reflects the "typical" state of the ecosystem being restored; it is unwise to allocate monitoring resources in response to broad-scale deviations owing to natural biological or human influences that are not being managed (Walters 1986). For instance, a frequent emergency response action is for organizations to establish new monitoring programs after broad-scale changes in the system have been observed. The purpose of these new monitoring programs is not only to demonstrate to the public a discernable sign of apprehension for the issue, but also to determine the reasons for these changes. Unfortunately, it is not always easy to deduce the causes of the changes afterwards. Environmental disturbances sufficient to be useful for variable assessment are probably linked to changes in ecosystem properties (e.g., introduction of new organisms, demise of species substocks, new resource extraction strategies). Although adaptive management requires adaptive monitoring, strategies that move monitoring objectives to the most recent crises as they appear will preclude the collection of compelling and stable data over time that lend themselves to rigorous statistical evaluations and trend detection. The result is that new estimates for measured variables are generated that are not characteristic of typical plots that could have been monitored to detect change in response to restoration measures (Walters 1986).

8.3.2 Limitations of Surveillance Monitoring

When developing an AMP, project managers should avoid surveillance monitoring in lieu of effectiveness monitoring. Surveillance monitoring (i.e., broadly monitoring many elements without deciding what is most relevant to the project) is not driven by any sort of testable hypothesis (Nichols and Williams 2006). It is a retrospective look at observations collected in overabundance. As Platt (1964) states, "*Biology, with its vast informational detail and complexity, is a "high-information" field, where years and decades can easily be wasted on the usual type of "low-information" observations and* *experiments if one does not think carefully in advance about what the most important and conclusive experiments would be*." Regardless of the motivation behind surveillance monitoring, it provides little useful information for interpreting or recognizing any kind of signal from a restored ecosystem. Chapters 2 and 3 of this document describe strategies for developing hypothesis-based sampling objectives that can be used as the basis for designing an effectiveness monitoring program that will allow project managers to determine if their restoration activities are yielding the desired results and make adjustments where needed.

8.3.3 Modeling Ecosystem Responses

Models may have a valuable role in adaptive management strategies. Conceptual ecological models are useful in identifying relationships between ecosystem components and in interpreting monitoring results (Fischenich and Vogt 2012). Predictive models are used to simulate ecosystem responses to restoration actions and monitoring efforts can provide important information for these models. For example, scientists engaged in rebuilding sandbars in the Grand Canyon portion of the Colorado River fine-tune model assessments and decrease the level of uncertainty in those estimates by quantifying the concentration of sand present in water samples as well as their associated particle sizes (Grams et al. 2015). They utilize this joint modeling-monitoring method since sand concentrations in the Paria River tributary are outside of acceptable ranges for other procedures (e.g., acoustics) to perform dependably. The information and programs to apply the model to calculate contributions of sand from the Paria River are accessible to all interested parties including water administrators, stakeholders and other participants in the community.

8.3.4 Space-for-Time Substitution

Searching for similar ecological restoration projects that have been completed at comparable locations in the past can be a valuable assessment tool in adaptive management, particularly if high-quality monitoring data have been collected and are available. Space-for-time substitution is a meta-analytic method that can be used to look for temporal trends using projects that have been implemented at various times across space. The replacement of space for time is frequently applied during model projections when there are no available time-series datasets that have been collected over the long term (Blois et al. 2012; Banet and Trexler 2013). Detractors of this approach submit that other influences besides what is considered to be the primary driver may shape ecosystem responses and, as these may differ spatially, false conclusions could result. To assess if temporal data could be replaced by spatial data in predictive models, Banet and Trexler (2013) used information collected during Florida Everglades monitoring. They found that after a drying event, the populations of bluefin killifish (*Lucania goodei*) predicted from spatial models were comparable and at times superior to those predicted from temporal models. Model performance was found to be acceptable, provided the model did not make inferences outside of the extent of variation found in the initial dataset. Banet and Trexler (2013) assessed the feasibility of a space-for-time substitution approach for evaluating ecosystem restoration effectiveness by comparing their results to other studies. The comparison indicated that space-for-time substitution performs well in ecosystems possessing certain properties such as low beta-diversity (ratio between regional and local species diversity), short-time intervals in the reaction of organisms to primary drivers and high connectivity linking locations.

8.3.5 Recordkeeping

A key component of adaptive management over the long term is recordkeeping. Project or program documentation should include records regarding how decisions have been made, including any findings that triggered management actions (Medema, McIntosh, and Jeffrey 2008). These records are of most value when they provide a clear and understandable explanation of the whole process leading to particular management decisions. This grants future managers with the ability to identify those restoration methods that have been successful in the past and provides them with an understanding of how particular choices that led to current management approaches were made. Within this context, recordkeeping is an even more critical element of adaptive management (Lindenmayer and Likens 2010; Sutter 2018) and no other approach is clearly superior (Westgate, Likens, and Lindenmayer 2013). The collection and preservation of quality data is a key component to the continued improvement of adaptive management principles for ecological restoration projects.

8.4 INCORPORATING QA/QC DATA INTO ADAPTIVE MANAGEMENT

Chapters 3 – **6** provide guidance on incorporating QA/QC strategies throughout effectiveness monitoring. The QA/QC data that result from implementation of these strategies should be viewed as an integral part of adaptive management and institutionalized in the adaptive management framework. No decisions should be made based on findings presented in the AMP without a thorough assessment of data quality and its impact on trend detection and decision making. **Chapter 7** provides guidance on the analysis of validated project data to determine the degree to which project objectives are being met.

Management of **all** routine and QA/QC data gathered during the effectiveness monitoring program is important for identifying the results of restoration activities and related decision made under an adaptive management context. This undertaking is very challenging considering the reality that diverse agencies including federal, state, or tribal entities collect data independently (Peters et al. 2014). **Appendix A** discusses data management strategies that project planning teams can employ when designing and implementing an effectiveness monitoring program; these strategies also apply to the overall adaptive management framework.

As mentioned in **Section 8.2.3**, implementation monitoring should be linked to effectiveness monitoring within the framework of adaptive management decision making. QA/QC data associated with implementation monitoring should be utilized in decisions regarding whether project specifications were adhered to and to what extent there were departures from those specifications. Depending on the organizations responsible for funding, managing and implementing the project, QA/QC criteria may be found in Quality Assurance Project Plans (QAPPs), Quality Assurance Manuals, or other similar types of documents (see **Section 2.4**). QA/QC activities should also be emphasized in the planning and implementation of follow-up operations and maintenance (O&M), such as in O&M manuals for restoration sites. Findings from QA inspections prior to, during and after project construction should be presented in the AMP. Ramifications of not meeting project specifications should be discussed, along with how these shortcomings may manifest themselves in the ecological response of the system as observed in the effectiveness monitoring component.

8.5 ADDITIONAL READINGS

- Buchsbaum, Robert N., and Cathleen Wigland. 2012. "Adaptive Management and Monitoring as Fundamental Tools to Effective Salt Marsh Restoration." In *Tidal Marsh Restoration: A Synthesis of Science and Management*, edited by Charles T. Roman and David M. Burdick. Series: The Science and Practice of Ecological Restoration. Washington, D.C.: Island Press.

- Conservation Measures Partnership. 2013. Open Standards for the Practice of Conservation. http://cmp-openstandards.org/wp-content/uploads/2017/06/CMP-OS-V3.0-Final-minor-update-May-2107.pdf

- Convertino, Matteo, Christy M. Foran, Jeffrey M. Keisler, Lynn Scarlett, Andy LoSchiavo, Gregory A. Kiker and Igor Linkov. 2013. Enhanced Adaptive Management: Integrating Decision Analysis, Scenario Analysis and Environmental Modeling for the Everglades. Scientific Reports 3, Article number: 2922. doi: 10.1038/srep02922.

- The National Academies of Sciences, Engineering, and Medicine. 2017. Effective Monitoring to Evaluate Ecological Restoration in the Gulf of Mexico. Washington, DC: The National Academies Press. doi: 10.17226/23476.

- Mazur, Nicki, Andy Bodsworth, Allan Curtis and Ted Lefroy. 2013. Applying the principles of adaptive management to the application, selection and monitoring of environmental projects, University of Tasmania, Hobart, Tasmania.

- Murphy, Dennis D. and Paul S. Weiland. 2014. Science and structured decision making: fulfilling the promise of adaptive management for imperiled species. Environmental Studies and Science 4:200–207. doi: 10.1007/s13412-014-0165-0.

- O'Donnell, T. Kevin and David L. Galat. 2007. Evaluating Success Criteria and Project Monitoring in River Enhancement Within an Adaptive Management Framework. Environmental Management 41:90–105. doi: 10.1007/s00267-007-9010-5.

- Rist, Lucy, Adam Felton, Lars Samuelsson, Camilla Sandström, and Ola Rosvall. 2013. A New Paradigm for Adaptive Management. Ecology and Society 18(4): 63. http://dx.doi.org/10.5751/ES-06183-180463.

- Ruiz-Jaen, Maria C. and T. Mitchell Aide. 2005. Restoration Success: How Is It Being Measured? Restoration Ecology Vol. 13, No. 3, pp. 569–577.

REFERENCES

Adamcik, Robert S., Elizabeth S. Bellantoni, Don C. DeLong, John H. Schomaker, David B. Hamilton, Murray K. Laubhan, and Richard L. Schroeder. 2004. *Writing Refuge Management Goals and Objectives: A Handbook*. Washington, DC: U.S. Fish and Wildlife Service.

Amacher, Michael C., William A. Bechtold, David Gartner, Mark H. Hansen, Olaf Kuegler, Paul L. Patterson, Charles H. Perry, KaDonna C. Randolph, Bethany Schulz, Marie T. Trest, James A. Westfall, Susan Will-Wolf, and Christopher W. Woodall. 2009. *FIA National Assessment of Data Quality for Forest Health Indicators*, edited by James A. Westfall. General Technical Report NRS-53. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station.

American Society for Quality. 2014. *ASQ/ANSI E4:2014: Quality Management Systems for Environmental Information and Technology Programs*. Milwaukee, WI: ASQ Quality Press.

American Society for Quality. 2017. "Cost of Quality." ASQ.org. Accessed May 2. http://asq.org/learn-about-quality/cost-of-quality/overview/overview.html.

American Society for Quality. 2018. "Plan-Do-Check-Act (PDCA) Cycle." ASQ.org. Accessed January 8. http://asq.org/learn-about-quality/project-planning-tools/overview/pdca-cycle.html.

Anderson, J.L., R.W. Hilborn, R.T. Lackey, and D. Ludwig. 2003. "Watershed Restoration—Adaptive Decision Making in the Face of Uncertainty." In *Strategies for Restoring River Ecosystems: Sources of Variability and Uncertainty in Natural and Managed Systems*, edited by R.C. Wissmar and P.A. Bisson. Bethesda, MD: American Fisheries Society.

Atkinson, Andrea J., Peter C. Trenham, Robert N. Fisher, Stacie A. Hathaway, Brenda S. Johnson, Steven G. Torres, Yvonne C. Moore. 2004. *Designing monitoring programs in an adaptive management context for regional multiple species conservation plans.* U.S. Geological Survey, Western Ecological Research Center. Sacramento, CA.

Baker, Richard J., and John R. Sauer. 1995. "Statistical Aspects of Point Count Sampling." In *Monitoring Bird Populations by Point Counts*, edited by C. John Ralph, John R. Sauer, and Sam Droege. General Technical Report PSW– GTR–149. Albany, CA: Department of Agriculture, Forest Service, Pacific Southwest Research Station.

Banet, Amanda, and Joel C. Trexler. 2013. "Space-for-Time Substitution Works in Everglades Ecological Forecasting Models." *PLoS ONE* 8 (11): e81025. doi: 10.1371/journal.pone.0081025.

Bird Studies Canada. 2000. *The Marsh Monitoring Program Quality Assurance Project Plan*. Accessed May 25, 2017. http://www.bsc-eoc.org/download/mmpqualplan.pdf.

Block, William M., Alan B. Franklin, James P. Ward, Joseph L. Ganey, and George C. White. 2001. "Design and Implementation of Monitoring Studies to Evaluate the Success of Ecological Restoration on Wildlife." *Restoration Ecology* 9 (3): 293–303. doi: 10.1046/j.1526-100x.2001.009003293.x.

Blois, Jessica L., John W. Williams, Matthew C. Fitzpatrick, Stephan T. Jackson, and Simon Ferrier. 2012. "Space Can Substitute for Time in Predicting Climate-change Effects on Biodiversity." *PNAS* 110 (23): 9374–9379. doi: 10.1073/pnas.1220228110.

Blume, Louis J., Craig J. Palmer, Molly Middlebrook Amos, Justin Telech. 2013. *Development of a Graded Approach to Project-level Quality Documentation for Habitat Restoration Projects*. PowerPoint. Chicago, IL: U.S. EPA Great Lakes National Program Office. Accessed May 2, 2017. http://conference.ifas.ufl.edu/ncer2013/Presentations/6-Connection/4-Friday/47-Session/YES/0930%20Blume.pdf.

Clark County. 2016. *2016 Adaptive Management Report, Clark County Multiple Species Habitat Conservation Plan.* Clark County, NV: Clark County Desert Conservation Program.

Clark, Malcom J. R., and Paul H. Whitfield. 1994. "Conflicting Perspectives About Detection Limits and About the Censoring of Environmental Data." *Journal of the American Water Resources Association* 30 (6): 1063-1079. doi: 10.1111/j.1752-1688.1994.tb03353.x.

Clewell, Andre, John Rieger, and John Munro. 2005. *Guidelines for Developing and Managing Ecological Restoration Project, 2nd Edition*. Tucson, AZ: Society for Ecological Restoration International.

Consolidated Appropriations Act of 2001, Pub. L. No. 106-154, § 515.

Cross-Smiecinski, Amy, and Linda D. Stetzenbach. 1994. *Quality Planning for the Life Science Researcher: Meeting Quality Assurance Requirements*. Boca Raton, FL: CRC Press, Inc.

Davis, Philip M. 2012. "The Persistence of Error: A Study of Retracted Articles on the Internet and in Personal Libraries." *J Med Libr Assoc* 100 (3): 184-189. doi: 10.3163/1536-5050.100.3.008.

Dean R. B., and W. J. Dixon. 1951. "Simplified Statistics for Small Numbers of Observations." *Anal. Chem.* 23 (4): 636–638. doi: 10.1021/ac60052a025.

Doran, George T. 1981. "There's a S.M.A.R.T. Way to Write Management's Goals and Objectives." *Management Review* 70 (11): 35.

Drew, C. Ashton, Yolanda F. Wiersma, and Falk Huettmann. 2010. *Predictive Species and Habitat Modeling in Landscape Ecology: Concepts and Applications*. New York, NY: Springer Science & Business Media.

Elzinga, Caryl L., Daniel W. Salzer, and John W. Willoughby. 1998. *Measuring and Monitoring Plant Populations*. Publication No. BLM/RS/ST-987/005+1730. Denver, CO: U.S. Dept. of the Interior Bureau of Land Management

Fang, Ferric C., R. Grant Steen, and Arturo Casadevall. 2012. "Misconduct Accounts for the Majority of Retracted Scientific Publications." *Proc Natl Acad Sci USA* 109 (42): 17028-17033. doi: 10.1073/pnas.1212247109.

Fischenich, Craig, and Craig Vogt. 2012. *The Application of Adaptive Management to ecosystem restoration projects*. Environmental Benefits Assessment Technical Notes Collection. ERDC TN-EMRRP-EBA-10. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Forage Task Group. 2013. *Report of the Lake Erie Forage Task Group, March 2013*. Accessed May 22, 2017. http://www.glfc.org/pubs/lake_committees/erie/FTG_docs/annual_reports/FTG_report_2013.pdf.

Gartner, David, and Bethany Schulz. 2009. "Vegetation Diversity and Structure Indicator." In *FIA National Assessment of Data Quality for Forest Health Indicators*, edited by James A. Westfall. General Technical Report NRS-53. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Service.

Gitzen, Robert A. 2012. *Design and Analysis of Long-term Ecological Monitoring Studies*. Edited by Robert A. Gitzen, Joshua J. Millspaugh, Andrew B. Cooper, Daniel S. Licht. Cambridge, England: Cambridge University Press.

Grams, Paul E., John C. Schmidt, Scott A. Wright, David J. Topping, Theodore S. Melis, and David M. Rubin. 2015. "Building Sandbars in the Grand Canyon." *EOS* 96. doi: 10.1029/2015EO030349.

Grubbs, Frank E. 1969. "Procedures for Detecting Outlying Observations in Samples." *Technometrics* 11 (1): 1-21. doi: 10.1080/00401706.1969.10490657.

Gy, Pierre. 1998. *Sampling for Analytical Purposes*. West Sussex, England: John Wiley & Sons.

Hilderbrand, Robert H., Adam C. Watts, and April M. Randle. 2005. "The Myths of Restoration Ecology." *Ecology and Society* 10(1): 19. http://www.ecologyandsociety.org/vol10/iss1/art19/.

Holling, Crawford S. 1978. *Adaptive Environmental Assessment and Management*. New York, NY: John Wiley and Sons.

International Organization for Standardization. 2015a. *ISO 9000:2015, Quality Management Systems – Fundamentals and Vocabulary*. Geneva, Switzerland: International Organization for Standardization.

International Organization for Standardization. 2015b. *ISO 9001:2015, Quality Management Systems – Requirements*. Geneva, Switzerland: International Organization for Standardization.

International Organization for Standardization. 2017. *ISO/IEC 17025:2017, General requirements for the competence of testing and calibration laboratories.* Geneva, Switzerland: International Organization for Standardization.

Keeney, Ralph L. 1982. "Decision Analysis: An Overview." *Operations Research* 30 (5): 803-838. http://www.jstor.org/stable/170347.

Kelly, Marion, and Lynn Walters. 2014. *Quality Assurance Strategies for the Use of Existing Data*. Training Session for EPA National Program Office Quality Community, presented March 18 and 20.

Kepler, C. B., and J. Michael Scott. 1981. "Reducing Bird Count Variability by Training Observers." In *Studies in Avian Biology*, edited by C. John Ralph and J. Michael Scott. San Jose, CA: Cooper Ornithological Society.

Kercher, Suzanne M., Christin B. Frieswyk, and Joy B. Zedler. 2003. "Effects of Sampling Teams and Estimation Methods on the Assessment of Plant Cover." *Journal of Vegetation Science* 14: 899-906.

Kish, Leslie. 1965. *Survey Sampling*. New York, NY: John Wiley & Sons.

Larsen, David P., Philip R. Kaufamann, Thomas M. Kincaid, N. Scott Urquhart. 2004. "Detecting Persistent Change in the Habitat of Salmon-bearing Streams in the Pacific Northwest." *Can. J. Fish Aquat. Sci* 61: 283-291. doi: 10.1139/F03-157.

Lee, Kai N. 1999. "Appraising Adaptive Management." *Conservation Ecology* 3 (2): 3. http://www.consecol.org/vol3/iss2/art3/.

Lesser, Virginia M., and William D. Kalsbeek. 1999. "Nonsampling Errors in Environmental Surveys." *Journal of Agricultural, Biological, and Environmental Statistics* 4 (4): 473-488.

Lindenmayer, David B., and Gene E. Likens. 2010. *Effective Ecological Monitoring*. London, UK: Earthscan.

Lohr, Sharon L. 2010. Sampling: Design and Analysis (Edition 2). Boston, MA: Brooks/Cole.

Lyons, James E., Michael C. Runge, Harold P. Laskowski, and William L. Kendall. 2008. "Monitoring in the Context of Structured Decision-making and Adaptive Management." *Journal of Wildlife Management* 72 (8): 1683-1692. doi: 10.2193/2008-141.

Mack, John J. 2001. *Ohio Rapid Assessment Method for Wetlands, Manual for Using Version 5.0. Ohio EPA Technical Bulletin Wetland/2001-1-1.* Columbus, OH: Ohio Environmental Protection Agency, Division of Surface Water, 401 Wetland Ecology Unit.

McDonald, Tein, George D. Gann, Justin Jonson, Kingsley W. Dixon. 2016. *International Standards for the Practice of Ecological Restoration-Including Principles and Key Concepts, First Edition*. Washington D.C.: Society for Ecological Restoration.

Medema, Wietske, Brian S. McIntosh, and Paul J. Jeffrey. 2008. "From Premise to Practice: A Critical Assessment of Integrated Water Resources Management and Adaptive Management Approaches in the Water Sector." *Ecology and Society* 13 (2): 29. http://www.ecologyandsociety.org/vol13/iss2/art29/.

Millard, Steven P., and Nagaraj K. Neerchal. (2001). *Environmental Statistics with S-Plus*. Boca Raton, FL: CRC Press.

Morrison, Michael L., William M. Block, M. Dale Strickland, Bret A. Collier, Markus J. Peterson. 2008. *Wildlife Study Design (2nd edition)*. New York, NY: Springer.

Mulder, Barry S., Barry R. Noon, Thomas A. Spies, Martin G. Raphael, Craig J. Palmer, Anthony R. Olsen, Gordon H. Reeves, and Hartwell H. Welsh. 1999. *The strategy and design of the effectiveness monitoring program for the Northwest Forest Plan*. Gen. Tech. Rep. PNW-GTR-437. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

National Estuarine Research Reserve System. 2015. Tributary Water Quality and Storm Water Monitoring, Old Woman Creek NERR. Accessed February 20, 2018. http://www.epa.ohio.gov/Portals/35/owrc_wq_monitoring/Arend_OWRC_WMWG_2015.pdf

National Oceanic and Atmospheric Administration. 2013. *Project Design and Evaluation: Logic Model Development for Restoration Practitioners*. Charleston, SC: National Oceanic and Atmospheric Administration, Office for Coastal Management.

Nichols, James D., and Byron K. Williams. 2006. "Monitoring for Conservation." *Trends in Ecology and Evolution* 21 (12): 668-673. doi: 10.1016/j.tree.2006.08.007.

Oakley, Karen L., Susan L. Boudreau, and Sioux-Z Humphrey. 2001. "Recommended Features of Protocols for Long-term Ecological Monitoring." In *Crossing Boundaries in Park Management: Proceedings of the 11th Conference on Research and Resource Management in Parks and on Public Lands*, edited by David Harmon. Hancock, Michigan: The George Wright Society.

Oakley, Karen L., Lisa P. Thomas, and Seven G. Fancy. 2003. "Guidelines for Long-term Monitoring Protocols." *Wildlife Society Bulletin* 31 (4): 1000-1003.

Ogden, John C., Steve M. Davis, Kimberly J. Jacobs, Tomma Barnes, and Holly E. Fling. 2005. The Use of Conceptual Ecological Models to Guide Ecosystem Restoration in South Florida. *Wetland* 25 (4): 795-809. doi: 10.1672/0277-5212(2005)025[0795:TUOCEM]2.0.CO;2.

Parsons, Arielle W., Theodore R. Simons, Kenneth H. Pollock, Michael K. Stoskopf, Jessica J. Stocking, and Allan F. O'Connell Jr. 2015. "Camera Traps and Mark-resight Models: The Value of Ancillary Data for Evaluating Assumptions." *The Journal of Wildlife Management* 79 (7): 1163-1172.

Peters, R.J., J.J. Duda, G.R. Pess, M. Zimmerman, P. Crain, Z. Hughes, A. Wilson, M.C. Liermann, S.A. Morley, J.R. McMillan, K. Denton, D. Morrill, and K. Warheit. 2014. *Guidelines for Monitoring and Adaptively Managing Restoration of Chinook Salmon (Oncorhynchus tshawytscha) and Steelhead (O. mykiss) on the Elwha River*. Lacey, WA: U.S. Fish and Wildlife Service, Washington Fish & Wildlife Office, Fisheries Division.

Pirsig, Robert. 1974. *Zen and the Art of Motorcycle Maintenance*. New York, NY: Bantam Books.

Platt, John R. 1964. "Strong Inference: Certain Systematic Methods of Scientific Thinking May Produce Much More Rapid Progress than Others." *Science* 146 (3642): 347-353. doi: 10.1126/science.146.3642.347.

Project Management Institute. 2014. *A Guide to the Project Management Body of Knowledge (PMBOK Guide, Fifth Edition)*. Newtown Square, PA: Project Management Institute. https://www.pmi.org/pmbok-guide-standards

Quality Assurance, 48 C.F.R. § 46.

Quinn, Gerry P., and Michael J. Keough. 2002. *Experimental Design and Data Analysis for Biologists*. Cambridge, United Kingdom: Cambridge University Press.

Roche, Dominique G., Loeske E. B. Kruuk, Robert Lanfear, and Sandra A. Binning. 2015. "Public Data Archiving in Ecology and Evolution: How Well Are We Doing?" *PLOS Biology* 13 (11): e1002295 doi: 10.1371/journal.pbio.1002295.

Roux, Dirk J., and Llewellyn C. Foxcroft. 2011. "The Development and Application of Strategic Adaptive Management within South African National Parks." *Koedoe* 53 (2), Article #1049, 5 pages. doi: 10.4102/koedoe.v53i2.1049.

Runge, Michael C. and Melissa G. Knutson. 2012. "When is Adaptive Management Appropriate?" Chapter 3 in *Adaptive Management: Structured Decision-making for Recurrent Decisions*. Shepherdstown, WV: U.S. Fish and Wildlife Service, National Conservation Training Center.

Schneider, James C., Percy W. Laarman, and Howard Gowing. 2000. "Length-weight Relationships." In *Manual of Fisheries Survey Methods II: With Periodic Updates*, edited by James C. Schneider. Ann Arbor, MI: Michigan Department of Natural Resources.

Society for Ecological Restoration, International Science and Policy Working Group. 2004. *The SER International Primer on Ecological Restoration.* Tucson, AZ: Society for Ecological Restoration.

Siitari, Kiera, Jim Martin, and William W. Taylor. 2014. "Information Flow in Fisheries Management: Systemic Distortion within Agency Hierarchies." *Fisheries* 39 (6): 246-250. doi: 10.1080/03632415.2014.915814.

Stankey, George H., Roger N. Clark, and Bernard T. Bormann. 2005. *Adaptive Management of Natural Resources: Theory, Concepts, and Management Institutions*. General Technical Report PNW-GTR-654. Portland, OR: U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station.

Stapanian, Martin A., Michael T. Bur, and Jean V. Adams. 2007. "Temporal Trends of Young-of-year Fishes in Lake Erie and Comparison of Diel Sampling Periods." *Environmental Monitoring and Assessment* 129 (1): 169-178. doi: 10.1007/s10661-006-9350-2.

Stapanian, Martin A., S.P. Cline, and D.L. Cassell. 1994. "Vegetation Structure Indicator for Evaluating Forest Health." In *Forest Health Monitoring Survey: A National Evaluation of Forest Health,* edited by T.E. Lewis and B.L. Conkling. Publication No. EPA/620/R-94/006.

Stapanian, Martin A., Timothy E. Lewis, Craig J. Palmer, and Molly M. Amos. 2016. "Assessing Accuracy and Precision for Field and Laboratory Data: A Perspective in Ecosystem Restoration." *Restoration Ecology* 24 (1): 18-26. doi: 10.1111/rec.12284.

State and Local Assistance Rule, 40 C.F.R. § 35. 2015.

Stevens, Don L. and Anthony R. Olsen. 2004. "Spatially Balanced Sampling of Natural Resources." *Journal of the American Statistical Association* 99 (465): 262-78. doi: 10.1198/016214504000000250.

Sutter, Robert D., and Brandon T. Rutledge. 2018. "Longleaf Pine Ecosystem Monitoring and Adaptive Management." In *Ecological Restoration of Longleaf Pine*, edited by L. Katherine Kirkman and Steven B. Jack, 265-288. Boca Raton, FL: CRC Press, Taylor & Francis Group.

Taylor, John K. 1987. *Quality Assurance of Chemical Measurements*. Chelsea, MI: Lewis Publishers.

Thayer, Gordon W., Teresa A. McTigue, Russell J. Bellmer, Felicity M. Burrows, David H. Merkey, Amy D. Nickens, Stephan J. Lozano, Perry F. Gayaldo, Pamela J. Polmateer, and P. Thomas Pinit. 2003. *Science-based Restoration Monitoring of Coastal Habitats, Volume One: A Framework for Monitoring Plans Under the Estuaries and Clean Waters Act of 2000 (Public Law 160-457)*. NOAA Coastal Ocean Program Decision Analysis Series No. 23, Volume 1. Silver Spring, MD: National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science.

Tyson, Jeffrey T., Timothy B. Johnson, Carey T. Knight, and Michael T. Bur. 2006. "Intercalibration of Research Survey Vessels on Lake Erie." *North American Journal of Fisheries Management* 26 (3): 559-570. doi: 10.1577/M05-027.1.

Uniform Administrative Requirements, Cost Principles, and Audit Requirements for Federal Awards, 48 C.F.R. § 1500.11. 2015.

U.S. Department of Agriculture. 2012. *Quality Assurance Plan for Forest Inventory in the South*. Knoxville, TN: U.S. Department of Agriculture, Forest Service, Southern Research Station, Forest Inventory and Analysis.

U.S. Environmental Protection Agency. 1998. *Guide to Laboratory Contracting*. Washington, DC: Office of Water.

U.S. Environmental Protection Agency. 2000a. *EPA Quality Manual for Environmental Programs (CIO 2105-P-01-0)*. Washington, DC: Office of Environmental Information.

U.S. Environmental Protection Agency. 2000b. *Policy and Program Requirements for the Mandatory Agency-Wide Quality System (CIO 2105.0)*. Washington, DC: Office of Environmental Information.

U.S. Environmental Protection Agency. 2001. *EPA Requirements for Quality Assurance Project Plans (EPA QA/R-5)*. Publication No. EPA/240/B-01/003. Washington, DC: Office of Environmental Information.

U.S. Environmental Protection Agency. 2002. *Guidance for Quality Assurance Project Plans (EPA QA/G-5).* Publication No. EPA/240/R-02/009. Washington, DC: Office of Environmental Information.

U.S. Environmental Protection Agency. 2003a. *Guidance for Geospatial Data Quality Assurance Project Plans (EPA QA/G-5G)*. Publication No. EPA/240/R-03/003. Washington, DC: Office of Environmental Information.

U.S. Environmental Protection Agency. 2003b. "A Summary of General Assessment Factors for Evaluating the Quality of Scientific and Technical Information." U.S. Environmental Protection Agency (Risk Assessment). Publication No. EPA/100/B-03/001. Washington, DC: Science Policy Council. https://www.epa.gov/sites/production/files/2015-01/documents/assess2.pdf.

U.S. Environmental Protection Agency. 2005a. *Guidance on Quality Assurance for Environmental Technology Design, Construction, and Operation (EPA QA/G-11).* Publication No. EPA/240/B-05/001. Washington, DC: Office of Environmental Information.

U.S. Environmental Protection Agency. 2005b. Quality Assurance Report for the National Study of Chemical Residues in Lake Fish Tissue: Analytical Data for Years 1 through 4. Publication No. EPA-823-R-05-005. Washington, DC: Office of Water.

U.S. Environmental Protection Agency. 2006a. *Data Quality Assessment: A Reviewer's Guide (EPA QA/G-9R)*. Publication No. EPA/240/B-06/002. Washington, D.C.: Office of Environmental Information.

U.S. Environmental Protection Agency. 2006b. *Guidance on Systematic Planning Using the Data Quality Objectives Process (EPA QA/G-4).* Publication No. EPA/240/B-06/001. Washington, DC: Office of Environmental Information.

U.S. Environmental Protection Agency. 2008. *Quality Program Policy for Agency Products and Services (CIO 2106.0)*. Washington, DC: Office of Environmental Information.

U.S. Environmental Protection Agency. 2012. *National Wetland Condition Assessment Quality Assurance Project Plan, Version 2.* Publication No. EPA 843-R-10-003. Washington, DC: Office of Water.

U.S. Environmental Protection Agency. *Heron in Wetlands*. 2013. EPA Flickr. Accessed February 20, 2018. https://www.flickr.com/photos/usepagov/albums/72157632912260109

U.S. Environmental Protection Agency. 2014a. *Great Lakes Restoration Initiative – Action Plan II*. Accessed May 2, 2017. https://www.glri.us/sites/default/files/glri-action-plan-2-201409-30pp.pdf.

U.S. Environmental Protection Agency, Office of Water, Office of Science and Technology. 2014b. *2010 GLHHFTS Fish Tissue Data Dictionary for Mercury, PFC, PBDE, and PCBs*. Accessed February 20, 2018. https://www.epa.gov/sites/production/files/2014-12/documents/glhhfts-data-dictionary-for-fish-tissue-data-09-30-2014.pdf.

U.S. Environmental Protection Agency. 2015. *Peer Review Handbook*. Publication No. EPA/100/B-15/001. Washington, DC: Science and Technology Policy Council.

U.S. Environmental Protection Agency. 2016. "Ensuring Measurement Competency." Last modified July 7. https://www.epa.gov/measurements/ensuring-measurement-competency.

U.S. Forest Service. 2009. *Southern Research Station Author's Guide*. Asheville, NC: U.S. Forest Service, Southern Research Station, Science Delivery Group.

U.S. Geological Survey. 2009. *Forest Vegetation Monitoring Protocol for National Parks in the North Coast and Cascades Network*. Chapter 8 of Section A, Biological Science; Book 2, Collection of Environmental Data. Accessed May 5. http://pubs.usgs.gov/tm/tm2a8/pdf/tm2a8.pdf.

U.S. Geological Survey. 2017a. "Instructions for Conducting the North American Breeding Bird Survey." USGS Patuxent Wildlife Research Center. Accessed May 19. https://www.pwrc.usgs.gov/bbs/participate/instructions.html#WIND.

U.S. Geological Survey. 2017b. "Why Share Your Data?" USGS (Supporting and Enabling USGS Data Management). Last modified March 23. https://www2.usgs.gov/datamanagement/share/guidance.php.

U.S. Office of Management and Budget. 2004. *Final Information Quality Bulletin for Peer Review*. Publication No. M-05-03. Washington, DC: Office of Management and Budget.

Uzarski, Donald G., Valerie J. Brady, and Matthew J. Cooper. 2015. GLIC: Implementing Great Lakes Coastal Wetland Monitoring: Semiannual Progress Report: April 1, 2015 - September 30, 2015. Accessed February 20, 2018. http://www.greatlakeswetlands.org/docs/Reports/GLIC-Semi_Annual-Sept-2015-final.pdf.

Uzarski, Donald G., Valerie J. Brady, Matthew J. Cooper, Douglas A. Wilcox, Dennis A. Albert, Richard P. Axler, Peg Bostwick, Terry N. Brown, Jan J. H. Ciborowski, Nicholas P. Danz, Joseph P. Gathman, Thomas M. Gehring, Greg P. Grabas, Anne Garwood, Robert W. Howe, Lucinda B. Johnson, Gary A. Lamberti, Ashley H. Moerke, Brent A. Murry, Gerald J. Niemi, Christopher J. Norment, Carl R. Ruetz III, Alan D. Steinman, Douglas C. Tozer, Ryan Wheeler, T. Kevin O'Donnell, John P. Schneider. 2017. "Standardized Measures of Coastal Wetland Condition: Implementation at a Laurentian Great Lakes Basin-Wide Scale." *Wetlands* 37 (1): 15-32. doi: 10.1007/s13157-016-0835-7.

Walters, Carl. 1986. *Adaptive Management of Renewable Resources*. New York, NY: MacMillan.

Westfall, James A., and Christopher W. Woodall. 2007. “Measurement Repeatability of a Large-scale Inventory of Forest Fuels.” *Forest Ecology and Management* 253 (1): 171-176. doi: 10.1016/j.foreco.2007.07.014.

Westgate, Martin J., Gene E. Likens, and David B. Lindenmayer. 2013. “Adaptive Management of Biological Systems: A Review.” *Biological Conservation* 158: 128-139. http://dx.doi.org/10.1016/j.biocon.2012.08.016.

Williams, Byron K., and G. Scott. Boomer. 2012. “A Typology of Adaptive Management.” Chapter 4 in *Adaptive Management: Structured Decision-Making for Recurrent Decisions*. Shepherdstown, WV: U.S. Fish and Wildlife Service, National Conservation Training Center.

Williams, Byron K., Robert C. Szaro, and Carl D. Shapiro. 2009. *Adaptive Management: The U.S. Department of the Interior Technical Guide*. Washington, DC: U.S. Department of the Interior, Adaptive Management Working Group.

Williams, Byron K., and Eleanor D. Brown. 2012. *Adaptive Management: The U.S. Department of the Interior Applications Guide.* Washington, DC: U.S. Department of the Interior, Adaptive Management Working Group.

Woodward, Andrea, Edward G. Schreiner, Patrick Crain, Samuel J. Brenkman, Patricia J. Happe, Steven A. Acker, and Catherine Hawkins-Hoffman. 2008. “Conceptual Models for Research and Monitoring of Elwha Dam Removal – Management Perspective.” *Northwest Science* 82 (1): 59-71. doi: http://dx.doi.org/10.3955/0029-344X-82.S.I.59.

Zhang, Chunlong. 2007. *Fundamentals of Environmental Sampling and Analysis*. Hoboken, NJ: John Wiley & Sons.

Appendix A

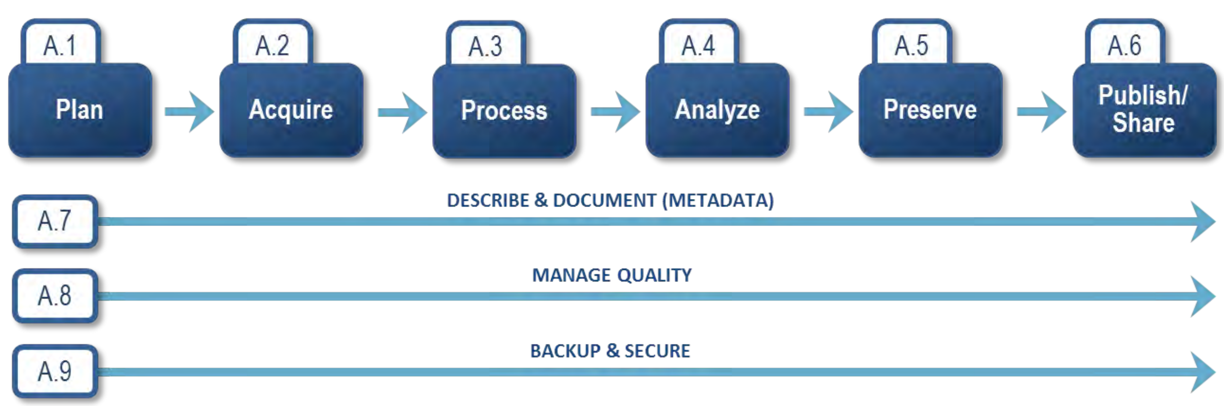
APPENDIX A: DATA MANAGEMENT BEST PRACTICES FOR ECOLOGICAL RESTORATION PROJECTS

Effective monitoring of ecological restoration must incorporate a sound strategy for managing information (i.e., data) drawn from multiple sources during the course of project activities. Data management is a formal, structured process that promotes data quality, availability and preservation, informed decision making, and data reuse. This process requires planning, documentation, and effective implementation of day-to-day workflow and procedures to facilitate the security, integrity and reliability of data collected to support project goals and objectives. Information that is formally managed using a structured process promotes openness and interoperability leading to more opportunities for sharing and reuse.

The specific steps of data management can be illustrated through a lifecycle model (Strasser et al. 2012; Faundeen et al. 2013; Sutter et al. 2015). In Faundeen et al. (2013), a model promoted by the U.S. Geological Survey (see **Exhibit A-1**), they identify six key phases involved in the management of scientific data, beginning with planning and proceeding through acquisition, processing, analysis, and preservation, conceptually ending when project managers share and publish their project data. These phases are generally sequential, but also can be overlapping and iterative.

This appendix provides guidance on these six phases, with a focus on aspects common to most ecological restoration projects that involve environmental monitoring. Each phase is addressed in a distinct section, noted by the section number (**A.1** through **A.6**). Each section also includes a checklist of primary activities for quick reference. Three activities – describe and document, manage quality, and backup and secure – are conducted throughout the entire data management lifecycle process and are discussed in three subsequent sections (**A.7** through **A.9**).

Exhibit A-1. Data Management Lifecycle



Source: *Modified from Faundeen et al. 2013; USGS 2017a.*

Data management is an integral part of the quality assurance (QA) process, which is focused, in part, on the security, integrity and reliability of data, none of which can be achieved without effective data management. This appendix includes recommended best practices concerning:

- QA strategies for addressing data management requirements in staff training programs and defining data management roles and responsibilities;
- design of standard operating procedures (SOPs) and field data collection forms to facilitate effective data management; and
- data management strategies during acquisition, processing, analysis, preservation and sharing.

In practice, QA and data management activities are closely related. Achievement of their objectives requires careful and well-planned coordination.

The focus of this appendix is on the management of *environmental information* broadly defined by the American Society for Quality (ASQ) and American National Standards Institute (ANSI) in their national standard, known as ASQ/ANSI E4 (ASQ 2014), to include:

> *"any data, measurements, or calculations that describe environmental processes, location, or conditions; ecological or health effects and consequences; or the performance of environmental technology."* – ASQ/ANSI E4

This ASQ/ANSI E4 standard further specifies that environmental information (or data) includes:

> "...*data collected directly from measurements, produced from models, and compiled from other sources such as data bases or the literature… Environmental information also includes data derived from samples collected from the environment, the results of other analytical testing (e.g., geophysical, hydrological) of environmental conditions, and process data or physical parameters collected from the operation of environmental technologies."* – ASQ/ANSI E4

For ecological restoration projects, environmental data include all information generated internally at the project level (primary data sources) as well as information acquired from secondary and external data sources that are independent of the project (secondary data sources). Project-level data include planning and reporting documentation; direct observations conducted by data collection teams; instrument-based measurements; all relevant supporting documentation (e.g., calibration logs, field journals, data forms); and all ecological, biological or physical samples (including the results and reports generated during laboratory analysis).

When designing data management strategies for their project, project and data managers will achieve their goals more effectively and efficiently if they consider the following principles of information science:

- *Discoverability* – the ability of specific pieces of information to be found. For example, metadata, or "information about information," maintained in a machine-readable format can allow information to be more readily identified. Organizing information by putting it into alphabetical order or including it in a search engine can also make it easier to find.
- *Accessibility* – the ability to access accurate project information and data quickly. Accessibility reflects the degree to which information is available to staff, partnership organizations and the

public, subject to privacy, sensitivity and confidentiality constraints. Accessibility for future uses should also be anticipated.

- *Usability* – the extent to which information can be used with effectiveness, efficiency and satisfaction. Data must be accurate and sufficiently documented to use and interpret the data correctly. Usability can be enhanced by *interoperability* among information systems for storage, analysis and display.

These principles are recognized by government institutions (McCulloch and McDonald 2008; NSTC 2016) and international organizations (Wilkinson et al. 2016) as fundamental elements of modernized data management to ensure collaboration and facilitate reuse of scientific data products.

A.1 DATA MANAGEMENT PLANNING

Developing a data management approach for ecological restoration projects begins with conceptualizing data management needs for three essential components: (1) data management policies, (2) a Data Management System (DMS) and (3) a Data Management Plan (DMP). Often these three components are co-developed and concurrently implemented using an adaptive and iterative approach instead of providing all levels of detail at once (Sutter et al. 2015). A particular challenge for large-scale monitoring of natural resources is supporting the interoperability of data that is consistent with changing technology, across programs and jurisdictions (Weltzin et al. 2017).

It should be noted that data management is as much about project planning and documentation as it is about implementation of data management procedures. As such, implementation of data management best practices occurs simultaneously with the design of restoration and monitoring strategies and other project planning activities, and continues throughout the remaining components of the project lifecycle. The following subsections outline and provide recommendations concerning the data management planning process.

A.1.1 Conceptualize Data Management Needs based on Project Scope

The scale and complexity of a restoration project will determine the appropriate data management strategies. This is consistent with the graded approach introduced in **Chapter 2** and defined as *"the process of applying management controls to an activity according to the intended use of results and the degree of confidence needed in the quality of the results"* (ASQ 2014). Sutter *et al.* (2015) identify several factors that operationalize the graded approach concept in context of the scope of a project, including any implied need for legal accountability, scientific defensibility, or logistical complexity and can serve as a guide for determining appropriate data management practices.

In general, a greater level of detail is needed in data management planning for projects that involve the following factors:

- large geographic scale or high levels of regional, national or institutional significance in terms of potential impacts on social, economic or environmental resources;

- high levels of complexity in terms of (1) decision making at multiple levels, (2) greater sophistication in scientific or construction applications, (3) regional, national or international collaboration, or (4) dependence on a consortium of organizations and individuals;
- lengthy projects that involve long-term planning in monitoring or construction;
- funding from institutions that mandate high levels of project documentation (e.g., federal agencies or private foundations that are investing significant financial resources); and
- a high likelihood that practices, results or other outcomes will be contested in a court of law, such as projects involving regulatory compliance or remediation and mitigation actions that impact human and environmental health.

Several examples of implementing the graded approach are provided in Sutter *et al.* (2015).

The project goals and objectives should clearly articulate the scope of a project (**Chapter 3**, **Sections 3.1** – **3.3**), all of which are often included in project funding proposals and project quality documentation (e.g., QAPPs, QMPs, SOPs). Such documents can provide information necessary to identify the essential elements and relevant institutional requirements to include in a data management plan. An assessment of project data management needs should also identify anticipated demands for routine data processing and analysis to support reporting at regular intervals across the timeline.

A.1.2 Data Management Components Common to All Restoration Projects

As noted above, no matter the size or scope of a project, restoration planners all share a common need to address three essential components of data management: (1) data management policies, (2) a data management system, and (3) a data management plan. These three components are described below.

A.1.2.1 Data Management Policies

Just as SOPs (**Section A.2.1**) stipulate guidelines for how data are collected, data management policies set guidelines for how data are maintained, distributed, and used, and typically reflect higher-level policies established by an organization. In some cases, and where relevant policy on data management is deficient or absent, project planners are encouraged to develop rules and administrative procedures to guide data management, and that in effect serve as policy during the project lifecycle. Policies are not only for the intended use, but also for future unanticipated uses (secondary use). Anticipating future data uses (and user groups) can provide insight into what supporting information may be necessary to inform the appropriate application of the data. Policies also define how and when data quality reviews are to be conducted, confirmed and reported. Data policies should specify the protocols required to protect the integrity and security of project data—both during project implementation and upon final archival and distribution of the data. This includes requirements and procedures for identifying, segregating and protecting sensitive data, as well as policies regarding data backup, recovery and record retention.

Restoration projects that receive funding from a federal agency may be required to adopt existing federal policies to be compliant with executive federal memoranda published by the Office of Science and Technology Policy (OSTP 2013) and the Office of Management and Budget (OMB 2013). These policies aim to enhance public access to results of research and information supported by the federal government. Planners should identify and incorporate these data management policies, as well as developing policies that are specific to the data management needs of the project. Thus, a project's data management policies include those that are unique to the project, as well as those necessary for compliance with applicable federal memoranda, and established institutional, corporate and/or departmental requirements.

A.1.2.2 Data Management System

The DMS is the computer environment, including system hardware and software, used to electronically manage the data. Designing and implementing a DMS improves management and data review functionality, data security (including protection against data corruption and loss), and overall project performance and efficiency. Generally, increased project complexity and scope increases the reliance on integrated solutions to ensure that project data are managed effectively and securely. Restoration projects typically employ interim strategies using conventional file-based methods on one or more personal computers to manage data acquired during the pre-planning and planning phases for comprehensive project design. Ideally, interim strategies are replaced as soon as feasible, with long-term solutions that include use of an integrated DMS that leverages the functionality of a relational database management system (RDBMS).

A DMS should generally include (1) a computer and/or server workspace that is accessible to all approved project participants, (2) effective and clear policies on read/write permissions, and (3) well-defined procedures and locations for storing files and data. The DMS should be flexible so that individual components can be modified or added without compromising the functionality of other components or the whole system, as well as scalable so that it can support input, storage, and retrieval as the data volume increases. An effective DMS should also allow for data to be well documented and certified (to confirm quality and completeness) prior to public distribution. Exhibit A-2 provides a comparison of three computer environments with respect to various considerations and system features drawn, in part, from a case study of Great Lakes data (Kolb et al. 2013).

Exhibit A-2. Comparison of Three Computer Environments Commonly Used to Manage Information			
Consideration or System Feature	**File-Folder Structure**	**Integrated Systems**	
		Personal Relational Database	**Enterprise Relational Database**
Data Management System	None	Centralized	Decentralized or Distributed
Example Applications	OS[1], Microsoft Excel, Lotus 123, Quattro Pro	Access, Microsoft SQL, Express, SQLLite	SQL Server, Oracle, PostgreSQL, MySQL
Technical Capacity	Basic	Intermediate	Advanced
Desktop or Server-Based	Both	Both	Server-Based
Spatially Enabled	No	Optional	Optional
Security Options	Low	Moderate	High
Multiuser Data Entry	No	No	Yes
Size of Dataset	Unlimited	Limited	Unlimited
Web-Based	Optional	No	Yes
Cloud-Storage Use	Optional	Optional	No
Cost of Development[2]	Low	Intermediate	High
Level of Programming	Basic	Intermediate	Expert

The three categories of computer environments represented here (file-folder structure, personal relational database, and enterprise relational database) are not intended to be mutually exclusive, and a variety of circumstances may warrant hybrid applications of all three environments.

Source: *Modified from Kolb et al. 2013.*

[1] *Computer Operating System*

[2] *Cost of Development includes those costs associated with software license purchase, staffing and training, system maintenance, and application development*

A.1.2.3 Data Management Plan

The DMP is a guiding document that combines policy-based requirements, procedural guidelines, and SOPs to facilitate the effective management of project data for each component of the data management lifecycle. The plan should describe strategies that can create an efficient and effective flow of data from its original source to the final, archived database. Methods and terminology included in the DMP should be standardized to help ensure consistent data and information collection, analysis and reporting. A project's DMP should be comprehensive in breadth and detail yet practical and implementable. It should be viewed as a dynamic document subject to routine amendment as improvements or modifications in any of its components are identified. Data management plans, should reflect all applicable content and current policy imposed by the institution providing project funding, and when necessary, be made available in synopsis form to meet page-limit constraints stipulated by the funder (Michener 2015).

Project planners can find helpful resources (e.g., DMP templates, checklists, and other reference material) online to assist in developing DMPs, including:

- U.S. Geological Survey (USGS) – Supporting and Enabling USGS Data Management. https://www2.usgs.gov/datamanagement
- DataONE – Data Observation Network for Earth. https://www.dataone.org
- Open Data Policy – Managing Information as an Asset. https://project-open-data.cio.gov

Project planners should consider the following list of tasks and questions as they develop and implement their DMP:

Questions:

- What physical or biological samples and voucher specimens will be collected, and what procedures are necessary to ensure the integrity and security of the samples during all phases of the project (from sample collection to analysis, and ultimately to the reporting of results)?
- What is the estimated volume of data that will be generated over the lifespan of the project?
- What data management needs must be addressed over the lifespan of the project?
- How will data be collected (e.g., electronically and/or recorded on paper forms)?
- What procedures are necessary to accommodate documentation and file-versioning as result of routine evaluations for quality?
- How will completed field forms, hardcopy records, audio/video recordings, photographs, and data downloaded from electronic instruments be stored, accessed and archived?
- How will project instrumentation be handled, shipped and stored?
- How will project data be analyzed and published?
- How and in what timeframe should data be made publicly available?
- What is the preferred format to make data publicly available (i.e., as tabulated content in a published report, as stand-alone documented datasets, or as a complete relational database)?

Tasks:

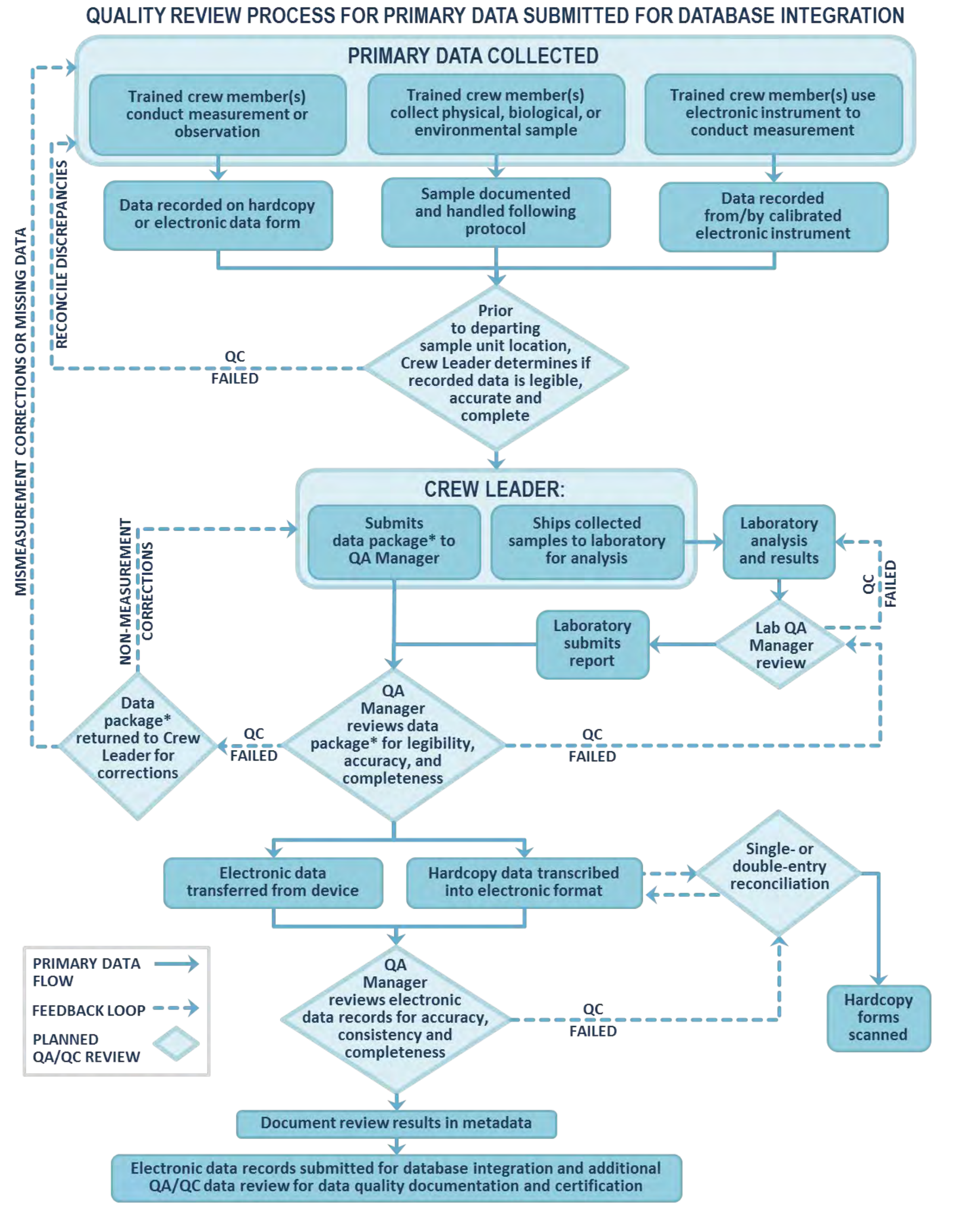
- Assess project-level quality documents and SOPs, and interview key participants to help identify data management and technology needs and preferences.

- Identify the essential data management policies, procedures and requirements.
- Identify key data management roles and responsibilities to be assigned to project staff.
- Identify data recording and data entry procedures that can be automated to facilitate cell-value selection and entry of valid values, and perform numeric value range checks.

A.1.3 Develop Process Flow Charts

Charts that graphically model data flow can help project staff comprehend and communicate complex or critical procedures, as well as how their activities fit into the big picture of data management. An example of a process flow chart is shown in **Exhibit A-3**. This chart illustrates the steps involved, from data collection to when these data are submitted for quality review and processing. Producing flow charts during the planning stage can help ensure that all aspects of the data management process are considered. A thorough evaluation and testing of the process, using these flow charts as a guide, can help expose weaknesses in project planning and design that might otherwise go undetected until it is too late to consider corrective actions.

Exhibit A-3. Example Process Flow Chart for Quality Review of Primary Data



NOTES: *Example data process flow illustrating planned QA/QC review (green diamonds) to reinforce quality management of primary data collected during ecological restoration monitoring.*

* ***Data package*** *refers to a collection of completed data forms and related documents (e.g., sample handling forms, copies of instrument calibration logs) organized by sampling event.*

A.1.4 Assign and Train Staff

Planners should assign data management roles and responsibilities for all activities considered instrumental in the oversight of both primary and secondary data. The project's organizational structure should reflect key positions included in quality documentation. See **Chapter 1**, **Section 1.6** for additional information on QA/QC roles and responsibilities that can be assigned to individuals involved in an ecological restoration project.

The goals of assigning and clearly documenting roles and responsibilities are to (1) establish the structure necessary to ensure that data management and QA/QC procedures are implemented as planned, (2) maintain data quality, (3) maximize the likelihood that finalized data products will support the project objectives, and (4) instill a sense of accountability (and stewardship) among all staff. Establishing accountability helps ensure that data quality management is conducted and documented in conformance with SOPs and policies as specified in the DMP and other project quality documentation.

Broadly stated, data management requires unique skills and expertise. Data management procedures will be effective and successful if staff are proficient in the use of relevant computer hardware and software applications and implement best practices consistently. Staff proficiency is achieved through comprehensive training, practice and experience. Project planners are encouraged to integrate data management training and competency testing into their training and certification programs just as they would for staff responsible for implementing one or more SOPs associated with data. Several academic institutions and other organizations have developed online training courses and provide a wealth of additional resources to help staff acquire the necessary skills and expertise required for effective data management. Examples of effective online programs include:

- University of Minnesota. https://www.lib.umn.edu/datamanagement/workshops
- Data ONE (Data Observation Network for Earth). https://www.dataone.org/education-modules
- Earth Science Information Partners Data Management Training Clearinghouse. http://commons.esipfed.org/datamanagementshortcourse

Project managers should involve data management specialists with a strong understanding of information management technologies and the capability to help select and/or design relevant technologies early in the project planning phase. Such individuals should be able to help with the following tasks:

- Identify, create, and evaluate the software and systems that are best suited to the project, in terms of availability, cost, flexibility and ease of use.
- Offer recommendations regarding the type and structure of databases (e.g., relational databases vs. files organized separately within a file-folder structure) and information technology (IT) interfaces

(e.g., graphic user interface vs. command line interface) capable of supporting project objectives and facilitating long-term storage and data sharing.

- Assist with new staff training.
- Advise on schedules and resources used to design (or adapt) and maintain the data management systems.

CHECKLIST FOR DATA MANAGEMENT PLANNING
☐ Assemble project funding proposals and quality system documentation (e.g., program and project-level quality documents, SOPs, and field operation manuals) to inform project needs assessment.
☐ Identify the phases of data management specific to the project and the institution or corporation; include considerations of logistical bottlenecks that impact how information is acquired, processed, and reviewed to inform project needs assessment.
☐ Identify and document data management policies unique to the needs of the project but that also comply with existing broader institutional, corporate and/or departmental policy.
☐ Identify or develop a DMS that is practical, scalable and secure, and that can accommodate expanding project scope and unanticipated volumes of information.
☐ Develop a DMP that includes detailed procedures in planning, collecting, processing, analyzing, preserving and publishing; include details related to the handling, shipment and long-term storage of completed field forms, instrumentation, multi-media data, physical samples and voucher specimens.
☐ Develop interim strategies of data management that coincide with early project planning and initial site assessment and that can be easily scaled or integrated into a long-term comprehensive strategy.
☐ Develop process flow charts to facilitate staff comprehension of complex and/or critical concepts and procedures.
☐ Integrate staff training, competency testing and certification in data management activities and responsibilities.
☐ Assign data management roles and responsibilities.

A.2 DATA ACQUISITION AND COLLECTION

Ecological restoration projects generate or acquire data that are obtained through numerous sources. Management of data acquisition and collection requires identification of the types of data to be collected and the tools required to collect the data. Exhibit A-4 provides examples of primary and secondary data acquired during a typical ecological restoration project. Refer to **Chapter 3**, **Section 3.5** for additional examples of secondary (existing) data, and discussion on important QA/QC topics related to quality assessment and the availability of metadata.

Exhibit A-4. Data Sources Acquired by a Typical Ecological Restoration Project	
Primary Data Sources	**Secondary Data Sources**
• Field observations based on best professional judgment • Field measurements collected by use of hand-held scientific instruments • Autonomous instruments (remote data-loggers) • Physical/chemical/biological samples • Results of laboratory sample analysis • Global positioning system (GPS) sample/sample-unit location coordinates • Photo and audio/video samples • Reference voucher specimens • Stakeholder forums and design charrettes	• National Weather Service (NWS) historical climate/weather data • Historical land cover/land use (includes Google Earth®) • U.S. Department of Agriculture (USDA) soil survey • USGS stream gauge (physical and environmental) • National/state/county inventories • Plant and animal taxonomic databases • Environmental data repositories • Taxonomic scientific collections • Agency publications, and metadata

A.2.1 Standard Operating Procedures

The success of ecological restoration monitoring is, in part, dependent upon the development of effective and comprehensive SOPs. An SOP is a:

> *"Set of written instructions that document a routine or repetitive activity followed by an organization...and are an integral part of a successful quality system as it provides individuals with the information to perform a job properly, and facilitates consistency in the quality and integrity of a product or end-result."* (EPA 2007)

SOPs vary from a one-page document detailing a simple procedure for a single variable, to a document with several pages of technical procedures for multiple variables. The basic structure of an SOP remains similar regardless of its scope and the data collection it supports. A comprehensive SOP will include details for each of the components listed in **Exhibit A-5** described in a concise, step-by-step and easy to read format.

Exhibit A-5. Structural Elements that Define a Comprehensive Standard Operating Procedure	
1. Title page 2. Table of Contents A. Purpose, Scope and Applicability B. Summary of Method C. Definitions D. Health & Safety Warnings E. Cautions and Interferences F. Personnel Qualifications G. Equipment and Supplies H. Procedural Steps I. Data and Records Management J. Quality Assurance/Quality Control 3. References 4. Attachments	Developing comprehensive SOPs – and well-designed data forms – are a QA strategy to support effective data management in ecological restoration monitoring. *See Chapter 4, Section 4.1 of the guidance document for a detailed discussion of SOPs.*

From a data management perspective, SOPs should include summary tables that list each type of data to be collected, including details specific to each type of data or variable (e.g., unit of measurement, domain or range of expected values, method descriptor, and equipment/instrument/crew type used for collection). Field SOPs also should describe how field results will be related to the crew that collected them in the same way that laboratory SOPs include procedures for relating name of the laboratory analysts and the serial number of the measurement device used to each result reported.

A.2.2 Design of Data Collection Forms

Project managers should work with data managers to develop data collection forms that will facilitate effective data transcription or transference; ideally, the forms should mimic the logical flow of data discovery and recording (Sutter et al. 2015). Not only are data forms used to record observations or measurements of target variables, they also capture essential event-related data for each sampling event. Event-related data identify when and where field activities occurred, who performed the activities, and ambient conditions at the time; data forms should be designed in a way to correlate this event-related information with the results of observations or measurements conducted on target variables. These data establish the context of sampling results, and represent ancillary information needed to perform within- and between-crew(s) data quality assessments. **Exhibit A-6** lists examples of essential event-related data and associated formats to record the information to facilitate their use in data management processes.

Exhibit A-6. Essential Event-Related Data and Their Recommended Data Formats for Recording

Collection Date	(YYYY-MM-DD)
Collection Time	(hh:mm:ss)
Start Time	
End Time	
Site Identification	
Intuitive Name	(text)
Unique ID	(alpha-numeric)
Plot or Sample Unit ID	(alpha-numeric)
Latitude (WGS84)	(00.000000)
Longitude (WGS84	(00.000000)
Elevation (meters)	(00000.00)
Observer(s) Full Name/Crew ID	(text/alpha-num)
Form Recorder Full Name or ID	(text/alpha-num)
Sampling Event Conditions	
Ambient Weather	(codified-numeric)
Ambient Disturbance	(codified-numeric)
Instrument Unit ID*	(alpha-numeric)

**repeat for each instrument used*

Defining data formatting prior to data collection is considered a QA strategy supporting data quality and effective data management.

Data format for continuous variables should be defined according to the level of implied precision determined by the method of measurement.

The naming or labeling of data fields should be clearly defined and consistent between SOPs, data collection forms and the DMS. Additional design elements that facilitate accurate and complete data recording include (1) ensuring legibility of form elements and field labels, (2) providing adequate space to record data, and (3) using a font size large enough to facilitate viewing by field staff with varying levels of visual acuity.

The elements within a data collection form should be organized according to the logical sequence in which data are collected. Event-related data are recorded first, followed by collection of the primary data elements. The design of the forms should prompt crews first to collect information determined sensitive to crew disturbance or presence (e.g., fragile soils or vegetation, animal behavior), and leave the collection of resilient or stable variables to the last entries.

The ease and accuracy of data collection can also be improved by providing crews with variable-specific field tools to facilitate standardized recording and documentation of data. Examples include the following:

- **Data dictionary:** A data dictionary describes and defines the expected content for each field, including the pre-determined format and the units used to report the value.
- **Option pick lists:** These lists define valid data entries, which help standardize cell-value entries and can include a category of "other" to allow for unexpected values.

- **Taxonomic references:** These references combine dichotomous keys, anatomical illustrations, and photographs to aid plant and animal identification. The specific taxonomic keys used for identification of biota should be recorded.

- **Standard reference materials:** Reference materials can include calibrated frames for smaller cover classes, scaled illustrations or images of cover or density, photos or drawings of disease conditions, or soil/water color, among other examples.

- **Example completed data form:** Example completed forms reinforce understanding of how to record data.

Well-designed data collection forms, along with well-trained crews, help ensure that all data are recorded accurately in a standardized and logical manner.

A.2.3 Data Capture and Field Logistics

The logistics of how data are collected and managed in the field and conveyed to an electronic workspace in a controlled environment should be determined prior to training a crew for data collection. A primary consideration is the selection of the capture system for data – and whether one uses data collection forms printed on durable paper or an electronic form displayed on a digital device such as a portable data recorder (PDR) (Sutter et al. 2015). PDRs can be an effective and efficient method of recording data since they can automatically enforce data recording protocols and improve data quality; these devices, however, are not without problems, such as device or battery failures and data entry errors caused by small screens and glare, which can compromise data management and data quality. The printed data form, despite the limitation of data needing to be transcribed, can be advantageous in circumstances where accommodating for device failure would be expensive (e.g., where travel costs are high, access to the sample site is difficult, the phenomenon of interest is ephemeral (wildlife observations), or sampling activities can alter measurements (wildlife observations, cover of fragile vegetation or community types). If used, paper data forms need to become part of the permanent record of project information and handled in a way that preserves their future interpretability and information content (Sutter et al. 2015).

Geospatial data require additional management considerations. In field settings, this type of data is often represented by point locational data obtained using a GPS device. Selection of the appropriate grade of GPS device (e.g., recreational grade vs. land surveyor grade), including its level of precision and accuracy to estimate a location, should be determined early in the planning phase. This is also true for data transfer (i.e., uploading or downloading of data) and post-processing methods that assist in ensuring that data accuracy and precision are maintained, documented, and support achievement of sampling objectives (Sutter et al. 2015). Regardless of the type of GPS device used, the unique record identifier generated by the device (used to uniquely identify each way point, path or route) should be maintained in association with each feature’s descriptive attributes when downloading and importing the GPS data into a new or existing feature class (or shapefile) attribute table. Maintaining the feature’s original unique identifier can allow for the creation of table record relationships within a RDBMS and enable data users to link back to the original data files, as well as the GPS device and user-operator responsible for creating the new feature.

SOPs should identify the level of resolution (i.e., horizontal/vertical accuracy, number of pixels, high vs. low resolution) so that the capture and storage of geospatial features including imagery, and multi-media data, including digital photographs, video and audio recordings, meets the minimum resolution suitable for supporting project objectives. Project staff that generate geospatial or multi-media data should adopt file naming conventions, appropriate to the data type, that are intuitive and can be used to identify and relate associated metadata that provides descriptive information on the format, resolution and other details of the data.

To facilitate efficient field logistics, daily or weekly debriefings during data collection allow field crew members to identify problems or issues and gain insight into what worked well and what needs to be improved or changed. This in turn allows for continuous improvement of data collection and management procedures throughout the course of a project.

A.2.4 Completed Forms and Sample Custody Protocols

Data management includes the accurate and efficient tracking of completed data forms and collected samples, as well as reference voucher specimens collected in the field. The latter requires the development of a process to record and resolve unidentified specimens. There are several options to address this need, and most include special protocols for integration and documentation of unidentified specimens in a voucher collection (i.e., to be uniquely accessioned), including tracking methods during storage and identification. Strategies to effectively track all field samples (including completed data forms) and voucher specimens should be planned in advance. A common strategy is to develop and deploy chain-of-custody (COC) forms to document the *what*, *who*, *when* and *where* related to sample handling (from collection through analysis) in order to maintain their integrity and security.

CHECKLIST FOR DATA ACQUISITION AND COLLECTION
☐ Identify the type of data to be collected and the methods and tools required to collect the data.
☐ Develop comprehensive SOPs for data collection to encompass all stages in the project lifecycle.
☐ Design data collection forms that are intuitive, easy to read and understand, include essential event-data, and facilitate data discovery and recording that follows a logical sequence.
☐ Select file-naming conventions and version controls that facilitate consistent tracking of data.
☐ Develop data entry, transcription and transference, and field logistics for tabular, geospatial and multi-media data.
☐ Describe COC protocols, and develop forms for handling field samples and voucher specimens.

A.3 DATA PROCESSING

Data processing is a fundamental activity throughout a data management lifecycle that includes the manual handling and electronic manipulation to convert primary and secondary data into a format for project applications. It includes (but is not limited to) methods, software and equipment used in: data capture, data entry, transcription and transference, data retrieval and simplification, normalizing variables of interest, variable conversion to a common unit, and use of random or systematic procedures to extract a subset of data records for a particular project need. Data processing activities include the following key components:

- documenting all processing steps in detail, and recording the steps as metadata to maintain data transparency and ensure reproducibility;
- creating digital copies of completed data forms prior to any annotations made during data entry, data validation, and quality review;
- ensuring that copies of original or raw data are backed up and securely archived on retrievable media prior to processing;
- ensuring consistent handling of field samples and management of completed forms, laboratory reports, voucher specimens and multi-media data;
- ensuring accurate and complete migration of disparate types (and formats) of data and information into a DMS; and
- using flow charts (see **Exhibit A-3**) and other visual aids to help project staff understand the specific steps in data management.

The following sections expand on these components by providing additional discussion on identifying data and processing needs, effective management of data forms and physical samples, processing specialized data, and the integration of all data into an electronic database environment or DMS.

A.3.1 Identify Data and Processing Needs

When data managers anticipate all necessary processing steps, they can help ensure data integrity and usability. Data managers can identify the types of data that need to be processed by conducting the following activities:

- Review project planning documentation, such as QA plans and operating procedures (SOPs, field operation manuals).
- Review field and laboratory journals, equipment/instrument calibration logs and preliminary records, such as laboratory bench sheets.
- Review all existing data forms (electronic and hardcopy formats) and standard reference documents used by field and laboratory personnel.

- Review metadata documentation related to secondary data sources to identify important assumptions or data references that may otherwise remain unidentified.

Depending on the type of data acquired, data managers should understand the implications and considerations unique to a data capture method or a particular type of data when determining appropriate processing needs. See **Exhibit A-7** for more details.

Exhibit A-7. Important Considerations for Identifying Processing Needs for Several Types of Data Commonly Acquired During an Ecological Restoration Project

Data Acquired	Considerations
Documents consisting primarily of descriptive text including tabulated information contained in formatted tables, figures and appendices	These documents contain information to be extracted or excerpted for transcription into an electronic spreadsheet format prior to processing and application. The information source, date accessed and metadata (e.g., data that defines and describes other data) should be documented.
Data obtained from observer interpretation, field measurement devices and analytical laboratories	These types of data are commonly recorded directly in tabular form either on a hardcopy or electronic data collection form, but can also be recorded on digital media or device memory and transferred from a proprietary format type (e.g., DAT, GPX) to a non-proprietary format (e.g., comma separated value (CSV), tab-delimited text (TXT) or ASCII). Variable documentation is usually presented in a table format, with the variables as rows and the characteristics (i.e., description, units, format) as columns (Hook et al. 2010).
Physical samples collected for laboratory processing or taxonomic vouchering	Restoration projects can produce significant amounts of physical samples that are perishable or time-sensitive. It is important to develop and document management strategies for sample handling, COC and inventory to ensure the quality and integrity of all samples.
Geospatial data (satellite, high-altitude sensor and GPS data, and web-based mapping products)	This type of data, in addition to photos and video, represents essential information used during the early planning and design of ecological restoration projects. It is commonly referred to as "Geographic Information System (GIS) data," and often requires specialized software for visualization, pre- and post-processing, and landscape-level analysis.
Digital photographs and video (hand-held and deployable equipment)	Similar to geospatial data, use of photography and video (and audio) recordings can play an important role during project planning and design, as well as during effectiveness monitoring and sample voucher or procedural documentation. Contemporary methods and equipment typically produce photos and video in digital formats that are easily transferrable from the device to a computer environment where post processing and application can occur.

Exhibit A-7. Important Considerations for Identifying Processing Needs for Several Types of Data Commonly Acquired During an Ecological Restoration Project	
Data Acquired	**Considerations**
Land-based remote sensors (i.e., remote data logger enabled instrumentation)	Terrestrial remote sensing technology has advanced considerably during the last twenty years, and has increased its utility and application in ecological restoration monitoring. Examples include stream gauges and weather stations with automated air and water samplers and/or thermal, conductance, and barometric pressure sensors that also record date and time. Most of these devices generate data in digital or binary format that requires little memory space in digital storage media.
Secondary data obtained from a known source but of unknown quality *(Data of unknown quality and unknown source should never be used!)*	Refers to data acquired from a known source that lacks adequate documentation to confirm its reliability. When circumstances justify their use, the data should be fully evaluated for potential errors, and the results of the evaluation included as new metadata that document the data source, date and time obtained, plus a disclaimer that the reliability is unknown.

A.3.2 Manage Completed Forms and Physical Samples

Management of completed data forms consists of (1) reviewing each form for accuracy, completeness and legibility; (2) organizing the forms either by site and/or in chronological order; and (3) storing the forms securely, once the data they contain have been entered in the DMS. The complexity of this process depends on the levels of quality review; the format of the forms (i.e., hardcopy or electronic); and the need to link the forms to physical samples, voucher specimens, multi-media products and laboratory reports. Additional complexity may arise, for example, when data collection forms and specimen samples are subjected to COC procedures for projects when the results and outcomes require federal or state oversight and/or documentation for potential litigation purposes. Unique identifiers should be created for all instrumentation, regardless of whether it is a single device or one of several used in the project; identifiers should be embedded in the device's operating software and recorded on a label that is attached to the device.

Completed Forms – Field Crews generate sets of completed forms as a result of conducting monitoring efforts across multiple sites or sampling units. This can also be true for physical field samples that require special handing (e.g., soil or water samples) or voucher specimens that need to be submitted for taxonomic identification and to obtain total counts per taxa or group. In most cases, maintaining related data forms and samples as a package can facilitate a more thorough and efficient quality inspection, and can streamline the data entry or shipping process. Laboratories commonly use batch analysis procedures to relate QA/QC performance results. Field-derived data can be similarly packaged, or batched, to facilitate performance assessment against existing performance criteria, such as results obtained from related QC checks (**Chapter 5**, **Section 5.2** – **5.3**). Field data can be packaged or compiled according to the sampling event information, such as location, sample unit, date, time, and crew or observer ID. **Exhibit A-3** illustrates an example of this approach.

Standardized methods should be used during data entry when annotating completed data forms and when documenting the annotated notes as data qualifiers (i.e., flags) in the DMS. See **Chapter 6**, **Section 6.3** in the guidance document for information about using data qualifiers and flags as well as handling data discrepancies and other errors. Prior to annotation, completed data forms should be scanned or photographed with sufficient resolution to provide a permanent digital copy representing the original. Annotation methods should include use of a contrasting indelible ink to document corrective actions to an existing record. In these cases, the original information should not be eliminated; instead, the change should be annotated by striking through the original information, neatly writing the "corrected" data or datum, and initialing the change as near to the uncorrected (i.e., striked-through) information as possible. Other methods include the use of sequential numbers that relate to a descriptive key written in the margin to define the corrective action taken. Hardcopy laboratory reports can also be handled in a similar manner. Data forms should also be notated when data have been completely transcribed and the entry of the information from the completed form has been verified as accurate and complete.

Physical Samples – Best practices include the use of consistent and thorough labeling to ensure that samples, through their sample ID, will always remain associated with the date, time and location of collection. The site name and collector name is of secondary importance on sample labels, assuming that information can be determined through the sample ID. Practices now commonly require recording the latitude and longitude obtained from a GPS device to represent the sample location with acceptable precision and accuracy. Other practices include the use of pre-printed field labels printed with an indelible ink, and that are securely affixed to the sample containers prior to sampling, shipping, and short- or long-term storage. Attached labels should be durable at high or low storage temperatures. Sample labels should include a description of handling procedures such as 'samples placed on-ice' or, where applicable, a description of the type and volume of preservative added to stabilize the sample). In certain applications, use of radio frequency identifiers – or electronically coded labels or tags (e.g., pit tags) typically inserted or attached to individual animals captured for subsequent release (e.g., fish, small mammals), can also be attached to physical samples or inserted in shipment packaging increasing accuracy and efficiency in sample processing. Physical samples intended for transport to a laboratory for processing should be packaged as lots or batches that represent similar field-collection procedures. A common QC procedure is to include a field and/or trip blank sample with these routine sample lots to detect potential influence arising from inconsistencies in sample handling. When working on EPA projects, scientific collections are considered assets of the federal government and their ownership carries with it trust responsibilities. EPA issued a policy (EPA 2015) to improve management and long-term preservation of scientific collections based on the International Society for Biological and Environmental Repositories (ISBER) Best Practices for Repositories (ISBER 2012). Both documents provide best practices on Information Management for scientific collections.

A.3.3 Process Specialized Data

> **The Importance of File Names and Version Control**
>
> **Use of file-naming conventions facilitates consistent tracking of electronic data across sample units and sample sites, and over time. Workflows should include adoption of naming conventions when employing standard electronic file \ folder \ subfolder structure common to all computer environments. Version control is especially difficult if there are many editors or reviewers. Version numbers should be sequential and file dates should be recorded following the international standard YYYY-MM-DD to facilitate sorting.**

GIS/GPS Data – GIS/GPS data are generated or acquired by use of a GIS that is accessed through a cloud-based server, Web-based mapping tool, or a GPS device. These data often require special hardware and software along with specialized knowledge to transfer, visualize and process native file formats. Common processing needs include digitizing information from printed and digital maps, and conducting file conversions (e.g., converting a file from an open-source format such as TXT or CSV to a proprietary format such as GPX, KMZ or SHP) to facilitate data display, analysis and management. Other common processing needs include data simplification or reduction (e.g., raster to vector, pixel resampling), and use of transformation and projection models to convert from one geographic datum, coordinate system, or projection to another. Each procedure can involve several steps automated by industry-standard and proprietary software programs (e.g., ArcGIS® or QGIS®, AutoCAD®) and/or through operator use of code written in one or more proprietary program languages (e.g., Python®, C++®, SQL®) or open-source code (e.g., R, ASCII). When using proprietary software, data managers need to understand the procedural options (utility functions) provided by the software to ensure the validity of the resulting data output. Use of a programming language or code contributes to data management efficiency (since, by definition, the processing details are documented by the code itself) and these can be exported into metadata to document the procedures used. Documenting all steps and procedures using standardized geospatial metadata formats (see FGDC 2001), and using an open-source file format (e.g., extensible markup language (XML), TXT), are considered industry best practices.

Remote-Sensors (Data Loggers) & Instrumentation – File formats vary for remote sensors since these sensors represent a diverse set of instrumentation and proprietary software for data processing, visualization and analysis. The data processing needs are similar to those for data obtained using standard hand-held scientific instrumentation. Individual devices should be configured with a unique device ID using the device's internal programming, and that unique ID should be placed on a durable label attached to the exterior of the device. This helps ensure that data can be directly linked to the device and the site or sample unit.

Multi-Media (Photography and Video) – An important practice in managing digital photography is to establish an electronic file-naming protocol that retains the original alphanumeric filename automatically generated by the device. Most devices generate file-property metadata that are automatically tagged to the file and represent a unique file identifier; a date and time stamp; device settings (e.g., aperture, f-stop); as well as the device ID, make and model. Analog devices (audio/video recorders) are generally not designed to generate this information; the burden is placed on the operator to fully document essential information for later retrieval. Photo media, including satellite imagery in raster format, require substantial amounts of computer memory storage since they are not easily reduced in size by use of file compression software.

A.3.4 Integrate Data into an Electronic Database Environment or DMS

Project data, regardless of type and format, are eventually transcribed, transferred, or converted to an electronic format and integrated into an electronic computer environment that when even in rudimentary form, will represent an interim-strategy as the project's DMS. Exhibit A-2 presents a comparison of three computing environments commonly used to manage and process data associated with ecological restoration projects. Regardless of whether project data are managed within a centralized environment, de-centralized environment, or a combination of the two, data managers should consider maintaining all data within an integrated DMS that uses RDBMS software (e.g., Oracle®, PostgreSQL®, MS Access®) to offer greater versioning or editing control during simultaneous access by multiple users across a network. Maintaining a code repository within the DMS is a valuable data management activity to ensure reproducibility of the data processing steps. Other notable benefits include a variety of pre- and post-processing applications that can streamline data processing, analysis and visualization, and reporting.

It is beyond the scope of this appendix to go into depth on any specific software applications, however, the widespread use of spreadsheet software (e.g., Microsoft Excel) to manage environmental monitoring data warrants specific mention. Although spreadsheet software can include many advanced features dedicated to the storage and manipulation of data, including advanced processing, analysis and visualization, such software platforms promote features to optimize convenience of use and data exploration at the cost of scalability, maintenance of database integrity and interoperability. Use of spreadsheet software as a DMS generally should be constrained as an interim strategy as part of, or to be replaced by, RDBMS software with enhanced utilities as core features specifically designed to promote scalability, the maintenance of database integrity, and interoperability.

CHECKLIST FOR DATA PROCESSING
☐ Identify all processing steps required to convert each type of data into a usable format suitable to achieve project objectives.
☐ Compile completed data forms into data packages representing discrete sampling events to facilitate quality inspection and review.
☐ Create digital copies of completed data forms prior to any annotations performed during data entry and subsequent data quality review.
☐ Maintain copies of all types of data in their original format in the event procedural error corrupts working copies and/or to demonstrate reproducible results beginning with the original data.
☐ Develop standardized procedures for labeling and handling samples and specimens that effectively relate sample ID and handling conditions with all associated data.
☐ Create unique identifiers for all instrumentation, regardless if it is a single device or one of several used in the project; embed this identifier in the device software as well as attaching it externally.
☐ Maintain original filenames or identifiers that are generated by electronic instrumentation, including digital cameras and audio recorders, GPS, and remote-sensor devices.
☐ Compile all project data into an integrated DMS that uses RDBMS software to increase efficiency in data management, processing and subsequent analyses.
☐ Document all procedures and steps used to process each type of data and record the procedures and steps as metadata.

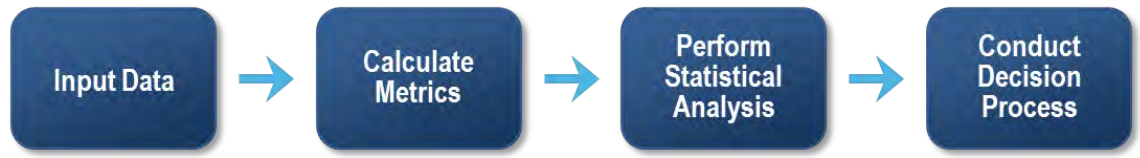
A.4 DATA SUMMARY AND ANALYSIS

Similar to data processing, data analysis can occur across multiple phases of the data management lifecycle. The procedures and applications used during each phase depend on the question being asked and whether the final results will be used for descriptive purposes or to test one or more statistical hypotheses. For example, during project planning, descriptive methods for data analysis are commonly used to identify key or target variables and to estimate sample size requirements. During the later stages of an ecological restoration project, data analysis becomes a paramount and essential activity to assess the effectiveness of restoration treatments and other prescriptive actions.

A.4.1 Prepare Data for Analysis

Preparing data for analysis requires coordination between project planners, data managers and data analysts or statisticians. During the project planning phase, individuals performing these roles often naturally generate a workflow that allows them to prepare data for analysis in the most logical and efficient manner (see **Exhibit A-8**).

Exhibit A-8. A Simplified Data Workflow



Data are often reduced or summarized as an integral step in the application of more sophisticated analyses. Data reduction involves distilling multiple records of repeated measurements to one or more representative statistics suitable for integration, analysis or display. For example, datasets may be reduced to basic statistical parameters by (1) grouping (partitioning), (2) aggregating (pooling) and (3) producing statistics that describe a particular sample or population (for example, using a mean and variance to summarize data from sample units within a site).

A.4.2 Document Procedures Used in Sample Metric Calculations

Sample metric calculation encompasses a variety of statistical and non-statistical procedures used to process data in order to generate a derived statistic (e.g., mean, standard deviation (SD), coefficient of variation) or variable suitable to support advanced analyses and hypothesis testing. Multiple steps may be required during data reduction and metric calculations, as well as during transformation of data from one measurement scale or unit to another, linear or logarithmic scale, or during the derivation of a composite statistic such as an index. Project managers should document the full data lineage (i.e., the historical record or lifecycle of the data), including the origin of the data and all data reduction and processing steps and equations used in calculations.

A.4.3 Document Procedures Used for Validating Compliance with Statistical Assumptions

Data analysts and project planners should document all analysis procedures performed to validate statistical assumptions (see **Chapter 7**, **Section 7.3.4**). This includes the evaluation of the assumptions that a sample accurately represents the population of interest and the independence between experimental units (EUs) or sample-units.

A.4.4 Document Steps and Procedures Used in Statistical Analysis

Data analysts and project planners should also document all steps performed during statistical analyses, including criteria for variable selection, procedures used during pre-analysis processing, equations and formulas used to derive metrics, software applications (including software publisher and version number), and the analytical procedures or statistical models used. Use of statistical procedures that operate by programming code (e.g., R, Python, SQL) should be prioritized so that analytical procedures can be repeated easily. Computer programming code used should be documented, including inputs and outputs, selected parameters and applied data filters. Complete documentation of these steps and procedures ensures that the necessary information is available to repeat the procedures in a consistent manner and to confirm results.

CHECKLIST FOR DATA SUMMARY AND ANALYSIS
☐ Document all data sources and inputs, processing steps (including data transformation), development of calculated metrics, and the analytical methods and decision processes used to interpret statistical results.
☐ Document all specialized procedures that specifically transform variable(s) from one measurement scale to another, including calculations used for unconventional transformations.
☐ Document the use of all computer software applications, including (1) the specific function(s) or module(s) selected to perform an analysis; (2) the associated results generated by the application; and (3) the software publisher name and the software's publication, build or version date.
☐ Prioritize use of statistical procedures that operate by use of programming or code so that analytical procedures or tests can be easily and reliably repeated and the reproducibility of the test results can be evaluated.
☐ Document the computer programming code used in the analyses, including inputs, outputs, selected parameters and applied filters.
☐ Document all implied statistical assumptions used to support statistical inference and decision making associated with data analyses.

A.5 DATA PRESERVATION

Planning and implementing data preservation procedures is central to good project governance (International Council on Archives 2017). Well-managed archives and records are the means by which decision-makers and stakeholders can understand the "*who*, *when*, *where*, *what, how* and *why"* of project activities. A good data archive provides evidence, explanation and justification, both for past actions and current decisions (International Council on Archives 2017).

Data preservation involves the long-term protection and archiving of interim data products at specified points during the project, as well as final data products at the end of the project. To successfully preserve project information, project planners must develop and implement effective procedures for "backing up" and "securing data" (see **Section A.9** for details on these processes). In general, data are archived in order to "preserve" them in a state that reflects a level of certified quality or finality. Data are considered preserved when they are archived using (1) a managed and secure environment, (2) lossless data format and storage media that preserve original native resolution and content, and (3) data access and distribution protocols governed by protective policy. Proper identification, description, maintenance and access ensure that project data will serve project stakeholders and allow for secondary uses of the data. Data preservation ensures efficient and timely retrieval that, in turn, support decisions and future related activities at the project site.

Restoration project data identified for archiving may include physical materials (e.g., voucher specimens, photos, hardcopy reports) and electronic information (e.g., XML files, PDF files). Each type of data can require different processing procedures to ensure they are properly preserved and archived. For scientific projects, organizations generally focus on preserving information for three different purposes, each with distinct preservation processes, as described below.

1) *Provide Empirical Evidence* – Preserve as a permanent record of evidence to support (1) scientific findings, management, and regulatory decisions related to human health or public policy; or (2) project outcomes that may be contested or litigated.
2) *Protect Voucher Collection* – Preserve historical, archaeological, biological, or environmental specimens and materials as comparative or reference material.
3) *Support Secondary Use* – Preserve the integrity and quality of a dataset in an incorruptible form accessible internally or externally by other users for the explicit purpose of secondary applications.

A.5.1 Policies to Guide Data Archiving

Most public institutions and agencies have well established policies regarding long-term archiving and preservation of digital and non-digital information they create and manage. Project planners and data managers use these policies to determine applicable guidelines and the types of data that should be preserved and archived. Project SOPs should be consistent with the requirements for data archiving. Policy components of particular relevance to ecological restoration projects are often those that provide guidance on procedures relating to file redundancy, data retention and disposition, data censorship, and proprietary ownership as discussed below.

Data Redundancy – This component outlines the policies that inform the types of data or files requiring backup and the frequency with which those backups should occur. Generally, more frequent data backups are preferable. See **Section A.9** for more details on this topic.

Data Retention and Disposition – The diversity and volume of data produced by restoration projects can be substantial over the course of a project lifecycle. When considering the need to back up and archive data across multiple time periods and physical locations, the management of such large volumes and types of data can become cumbersome and costly. The *de facto* decision to “just save everything” is a good policy when no policy exists. However, minimizing retention of unessential interim data products and associated files can represent good policy in the context of reducing project cost and effort associated with data storage and management. Project planners should coordinate development of data retention and disposition (permanent disposal of data) policies with their institution or organization (e.g., GPO 2011; National Institutes of Health 2008) as well as with vested collaborators and stakeholders, including funding organizations.

Data Censorship – The archival or sharing of sensitive information on a publicly accessible repository is considered inappropriate by most standards. Policy components should provide guidance that identifies the specific project information required to be omitted from any archival or storage environments (including portable devices) that may be accessed by individuals that do not have approved clearance. Examples of information that may require censorship, may include details related to the administration of the project, such as personal information of project personnel (including volunteers) and collaborators, account identifiers of financial institutions, and parcel ownership information (among others). Other information that may be considered sensitive, include: locational data of endangered, threatened or rare species, or species vulnerable to unregulated collection or hunting; the location of easily disturbed natural features (e.g., caves, springs, hibernacula); and the location of sensitive cultural features (e.g., American Indian burial mounds, archaeological sites).

Proprietary Ownership – Prior to archiving data on a public server or open-source repository, consider the interests of, and the intellectual and financial investments made by, project collaborators and associated stakeholders (including funding organizations). In some cases, information may be considered privately owned and not permissible for archival, or is listed in existing memoranda of agreements stipulating certain proprietary rights related to priority of data use (e.g., scientific publication).

When it is necessary to govern access to specific project information, project planners should work with data managers and their respective institution (e.g., through its information technology staff) to identify internal archival locations that are secure, but not publicly accessible, until all collaborators and stakeholders have provided consent to do otherwise. See **Section A.6.4** for a partial list of data repositories.

A.5.2 Prepare Data for Archiving

In ecological restoration projects, project managers actively manage data acquired from primary and secondary sources throughout the entire project lifecycle. Regardless of the source, it is important to properly prepare data for long-term archiving, addressing both the technical aspects (e.g., file structure and format) and documentation needs (e.g., metadata), regardless of whether they will be archived internally or archived within a public data repository. For data acquired from secondary sources, project managers should refer to, and comply with, any policy associated with the data and existing constraints on use and sharing.

Questions that project planners should consider when preparing data for archiving include:

- What standard of quality should the data achieve as it relates to completeness, accuracy and precision?
- What type of documentation and what level of detail is needed when the data are submitted for archiving?
- What supporting information is necessary for the effective use of the data by secondary data users?
- Are certain data considered more sensitive than others? If so, a memorandum of agreement (MOA) or memorandum of understanding (MOU) may be required to help inform policies that guide future access or distribution.
- Are there proprietary concerns such as data ownership, intellectual property rights or established policy on disposition of the data that need to be considered?
- Who will be responsible for updates or corrections once data have been submitted for archiving?
- How should access by external data users be managed or governed?

- How long data should be retained? Does the shelf life of the data preclude its use at a certain point in time? (U.S. GPO 2011)

The formatting of data has the potential to compromise ease of access and readability, particularly when data are stored in proprietary formats that require specialized software (or hardware) to interpret and "read." Data loss is a real threat when the ability to access the data is dependent upon copyrighted products that may not be maintained in the future. The National Archives and Records Administration (NARA) provides guidance on the use of file formats to ensure long-term stability and low risk of data loss. See Exhibit A-9 for specific guidance pertaining to different file types.

Exhibit A-9. File Formats Recommended for Long-Term Storage and Archiving

File Type	Description and Recommendation
Text	Store tabular data in non-proprietary plain text format using ASCII code. Other suitable formats include: comma separated value (CSV) and tab-delimited text (TXT).
Image	Store digital photography and similar imagery in uncompressed TIFF format or in "lossless" JPEG formats at native resolution when practical.
Audio	Store digital audio recordings in "waveform" (WAV) audio format, audio lossless (ALS) coding format, or motion pictures expert group (MPEG) 4 format.
Video	Store digital video recordings in the audio-video interleave (AVI) format, material exchange format (MXF), or QuickTime™ format (MOV).
Recommended by NARA for long-term archiving. See: https://www.archives.gov/records-mgmt/policy/transfer-guidance-tables.html.	

A.5.3 Identify Archive Locations and Preserve Project Data

Once project information is collected, formatted and stored in a data management system, project planners will need to identify a final location for long-term storage and archiving. The location and processes will depend on the type of information, but the final goal of data archiving is to ensure that information can be easily and efficiently retrieved and accurately interpreted. This goal is supported by identifying the appropriate location, format and governing procedures.

The following data management best practices should be followed, where practical, to prepare electronic information or physical materials for preservation and long-term archiving.

Preparing Electronic Information:

- Store archived data in machine-readable formats using free open source software.
- Store archived data in multiple archives (e.g., enterprise or cloud server, mobile digital media), including use of free open source hardware.

- Store archived data in unencrypted and uncompressed formats.
- Store uncorrected datasets in addition to validated versions of datasets, if space permits.
- Use ISO standards for the creation, processing and sharing of standardized metadata for digital documents and datasets.
- Use XML or extensible metadata platform (XMP) formats to ensure compliance (see **Section A.7**).
- Use consistent file names and standard nomenclature across all files included in the set of data to be archived.
- Document all decisions and procedures associated with the conversion of data or file types into non-proprietary or open source formats.
- Include all project documentation required to describe the data, including project identity and point of contact information.

Preparing Physical Materials:

- Establish SOPs for the collection, handling, preservation, labeling and shipment of samples and specimens in collaboration and compliance with the institution to which you plan to submit your material for archiving (archival institution).
- Incorporate QC oversight during collection and handling to ensure your collection will reflect the quality expected by the archival institution.
- Submit an entire set of specimens as a voucher collection that represents your unique study or sampling effort (unless otherwise requested by the archival institution).
- Establish an MOA or MOU with the archival institution that requires the return of any unwanted specimens so that those specimens may be submitted to an alternate institution.
- Use high-resolution digital photography to photo-document representative specimens (e.g., each species, age class and gender), if applicable, as soon as practical shortly after capture, preservation and labeling.
- Package copies of all SOPs, digital photos, field journal notes and other relevant supplemental information, and submit these materials as part of the voucher collection.
- Include a cover letter that describes the purpose of the submitted material; a copy of the MOA or MOU; and details on the project title, administrative organization, sample location(s), duration of the sampling effort and primary contact information.

CHECKLIST FOR DATA PRESERVATION
☐ Identify policies that govern data preservation.
☐ Identify the purpose and preservation needs for each type of data to be archived.
☐ Coordinate SOPs used for data and sample collection, preservation, handling, labeling and shipment to ensure compliance with the selected archival institution or data archive.
☐ Identify any supporting information that is necessary to ensure effective use of the data by secondary data users.
☐ Document all decisions and procedures associated with the conversion of data or file types into non-proprietary or open-source formats prior to their submission to any long-term archives.
☐ Develop policies and procedures for data/record backup and file retention.

A.6 DATA SHARING AND PUBLISHING

"Well organized, well documented, preserved and shared data are invaluable to advance scientific inquiry and to increase opportunities for learning and innovation"

– UK Data Service 2017

Completing the data management lifecycle involves submitting documented datasets to publicly accessible data repositories to ensure the data are readily available and can be used by the broader scientific community. Scientists and other researchers who share their data foster "open science" (Rüegg et al. 2014), and support the goal to improve the work of the ecological restoration community. As introduced in **Section A.1.2.1**, projects that operate with federal funding, or are conducted on behalf of a federal agency, may be required as per OSTP (2013) and OMB (2013) to make their data publicly accessible and discoverable. In all cases, project planners should understand existing policies by their institution or funding organization regarding any mandates or other stipulations relating to data sharing and publishing. To maximize the usability of project data for secondary uses, including results generated during the data analysis phase, project planners should consider (1) technical (e.g., specific data file format), (2) documentation (e.g., metadata), and (3) policy-based (e.g., use-constraints and limitations) requirements of the data repositories (Hook et al. 2010). Project managers should consider the community of interest when determining where to publish project data and, before publishing or sharing, should always identify and comply with policy requirements regarding the protection of sensitive or confidential data.

A.6.1 Identify the Community of Interest

The community of potential users of restoration project data is diverse. The primary audience generally consists of (1) individuals who oversee similar projects (which could be within the same organization, a local or regional initiative, or located in the same geographic area); or (2) individuals working on the same or similar species, habitats, and ecosystems (either in the U.S. or at other locations around the world). The community of interest may include various project stakeholders, such as local communities, government agencies, and funding organizations. These stakeholders are often particularly interested in the final results, whether the results met the stated objectives of the project, and whether the funds were efficiently used.

Interested parties may request information on how the project was designed, what procedures were used, how data were analyzed, and/or the final results and other project outcomes, all of which can be used to help them make informed decisions and improve their work. Other researchers may be interested in combining data from multiple projects to assess restoration results across space and time, or reusing the data to examine long-term trends at the same site. Sharing data generally increases the value of a dataset and enhances the community knowledge base associated with ecological restoration efforts.

A.6.2 Prepare Final Data Products

To ensure the usability of data for outside parties, all of the dataset contents need to be defined and understandable, including variable names, units of measure, formats, coded fields, file names and dataset titles. Variable documentation is usually presented in a table format, with the variables as rows and the characteristics (description, units, format, etc.) as columns (Hook et al. 2010). File names and dataset titles should be as descriptive as possible. In addition, the organization and structure of the datasets should be presented in a consistent manner. Statements of quality and completeness are common requirements for data sharing, metadata development and data certification (see **Chapter 6**, **Section 6.4** of this document). Policy requirements and submittal instructions for the chosen data repository will dictate preparation of data products and documentation.

A.6.3 Assess Use Constraints

Before sharing and publishing data, the data should be evaluated to identify confidential and sensitive information such as locational information on endangered, threatened or rare species, protected natural features and cultural resources and information that is considered private or personal (e.g., identification of individuals), or identifies account information of financial institutions. Depending on the purpose for sharing information or the protective policies of the repository, any data identified as confidential, sensitive or personally identifiable may need to be removed from the dataset (described in **Section A.5.1**). Data managers should include statements regarding data ownership, time periods represented by the data, and use limitations with the dataset. While all potential future uses cannot be anticipated, it is important to consider future data users and identify important constraints on how the data can be used. This information should be clearly outlined and published along with the dataset so that users are fully informed about appropriate use.

A.6.4 Determine Where to Publish Data

The identified communities of interest will influence where to publish documented datasets, in addition to the project manager's administrative institution, the funding organization, and when applicable, and the scientific journal(s) in which results of project outcomes are published. There are several levels to data sharing, from self-publishing and organizational websites to global data repositories. Project managers should select a level of data sharing that maximizes the discoverability of the dataset for the community of interest while at the same time complying with policies to safeguard confidential and sensitive information. In addition, selecting repositories that require all data to be associated with quality review documentation can add credibility. When legal policy does not mandate restrictions on public access, project managers should consider publishing or sharing data across two or more independent repositories (i.e., cross-listing), including at least one open-source repository, which will help prevent future data loss due to intentional or unintentional censorship.

Cloud-based computer technology has revolutionized how data are preserved, published and shared, and it provides project planners with a variety of options for data publishing and repositories. The policies and access for data archives and repositories can vary considerably, especially for specific communities. An example list of organizations, including the U.S. government, that provide resources for the publishing and sharing of environmental data are listed in **Exhibit A-10**.

Exhibit A-10. Example List of Organizations Providing Resources for Publishing and Sharing Environmental Data

Site Name	Description
Ecological Society of America Data Registry	A publicly accessible registry where contributors can register the formal title, description and archival location of scientific datasets on ecology and the environment. This registry offers keyword and spatial search tools that can help users discover datasets of interest. http://data.esa.org/esa/
Knowledge Network for Biocomplexity	A long-term national data repository and data access portal that is also a DataONE member node that replicates submitted data securely across multiple servers. Provides a permanent identifier, including a searchable data object identifier (DOI) to facilitate data sharing and source citation. https://knb.ecoinformatics.org.
DRYAD Digital Repository	An international and open-source digital repository providing curatorial services for data submitted in association with scientific publications. Datadryad also assigns a DOI to facilitate data sharing and source citation. http://www.datadryad.org
VegBank	VegBank is maintained and co-operated by the Ecological Society of America Vegetation Panel and the National Center for Ecological Analysis and Synthesis. VegBank represents a publicly accessible data repository where contributors submit their vegetation plot data to be linked to standardized vegetation types as recognized in the U.S. National Vegetation Classification, and also to taxonomic information recognized and maintained by the Integrated Taxonomic Information System (ITIS) and the USDA. All vegetation plot records, their community types and associated plant taxa can be reviewed, annotated, and downloaded for secondary uses and applications. http://vegbank.org/vegbank/index.jsp
Long-term Ecological Research (LTER)	The LTER Network Information System Data Portal is a Web-based portal that allows for contributions and access to data represented by current and historic LTER sites. https://portal.lternet.edu/nis/home.jsp
Great Lakes DIVER Explorer (GL-DIVER)	GL-DIVER is a Web-based query tool for registered users that allows for "data Integration, visualization, exploration and reporting" of scientific data collected within the Great Lakes basin in response to the restoration and monitoring of Areas of Concern with Beneficial Use Impairments. The primary purpose of GL-DIVER is to facilitate the sharing and application of data. It is not intended to serve as a final data

Exhibit A-10. Example List of Organizations Providing Resources for Publishing and Sharing Environmental Data	
Site Name	**Description**
	repository. https://www.diver.orr.noaa.gov/diver-explorer?siteid=6&subtitle=Great+Lakes
U.S. Federal Open Data	Federal Open Data is a data, application and information hub managed by the U.S. General Services Administration to provide public access to over 200,000 datasets representing topics as diverse as: agriculture, ecosystems, climate-change, energy, science and research, manufacturing, health, among others. Its purpose is to provide access to a variety of tools and resources to facilitate entrepreneurship, economic growth, scientific research, and more. https://data.gov

CHECKLIST FOR DATA SHARING AND PUBLISHING
☐ Identify the community of interest for the documented dataset, analyses and results.
☐ Prepare final data products to facilitate understanding by future users.
☐ Assess use constraints and limitations; protect confidential or sensitive data.
☐ Select a location for sharing and publishing that maximizes the discoverability of the dataset for the primary community of interest.

A.7 METADATA

Metadata consists of data or information that "defines and describes other data" (International Organization for Standardization 2004). In ecological restoration, metadata are generally descriptive and provide information on what users need in order to accurately interpret and use a dataset. Metadata should be readily available to users and easily discoverable by web-based search engines. Metadata describes:

- *what* the data include and represent,
- *why* and *where* the data were collected,
- *when and how* the data were collected,
- the specific data-quality checks performed and results of these checks,
- idiosyncrasies and limitations of the data,
- *who* owns or manages the data, and
- *whom* to contact if there are questions about the data.

This information is typically structured using a standardized textual format (e.g., TXT, XML), and is either embedded or maintained separately from the project dataset. In practice, metadata generated during the project lifecycle may also include text, numeric output, diagrams, flow charts, images, video, sound files or other descriptive information (Sutter et al. 2015). Project managers are responsible for recording metadata.

Metadata are essential for all projects and enhance the discoverability and future use of data. They characterize the types of data within a dataset and facilitate the identification of data by other researchers. Reproducibility is a primary principle of the scientific method, and a good rule of thumb when compiling metadata is to provide sufficient information to facilitate reproducibility of the results. Complete and well-written metadata can be viewed as an extension of good data management practices, and should conform to the 4 Cs: correct, complete, comprehensive and comprehensible (Sutter et al. 2015), as described below.

- Correct: The metadata content accurately describes the data.
- Complete: All relevant metadata elements are present.
- Comprehensive: The metadata content fully describes the dataset.
- Comprehensible: Someone not associated with the project can understand the metadata content.

There are four characteristics of metadata that assure that the data will be accessible to others in the future:

1. **File Formats that are Non-Proprietary.** Approved standards for formal metadata currently rely on expressing the content in XML to facilitate computer searching and conversion of the document in multiple formats. For current applications of XML, see the *Extensible Markup Language (XML) 1.0 (Fifth Edition)*. Because of the complexity of using XML and the need to address all metadata elements in a consistent manner, metadata are often written using one of several software editing tools, such as Metavist (Rugg 2004), Ecological Metadata Language (Fegraus et al. 2005), EPA Metadata Editor (EPA 2017), USGS Metadata Editor (USGS 2017b), and others that provide plain language instruction through a convenient graphic user interface. There are also proprietary applications designed specifically for the development of metadata for geospatial data (e.g., ArcGIS 10®, MapInfo®). These applications include the ability to automatically populate certain metadata elements by extracting content from the original data. However, regardless of the editing tool used or standard adopted, the final metadata file should be saved (archived) in an open-source format such as XML or TXT.

   Metadata can also be generated using any text editor, such as Notepad® or WordPad® (for PC), or TextEdit® (for Apple™) when working from a standardized metadata template. Several metadata standards and templates are available to document ecological data, and the selection of a specific standard or template is dependent upon the type of data requiring description.

2. **File Content that Conforms to U.S. Federal or International Standards.** Ecological restoration projects funded by a U.S. federal agency may be required to use content standards endorsed by

the Federal Geographic Data Committee (FGDC). **Exhibit A-11** provides a list of standards that meet this requirement.

Exhibit A-11. Metadata Standards Endorsed by the Federal Geographic Data Commission
FGDC Endorsed Extensions to the CSDGM Version 2 (FGDC-STD-001-1998): **FGDC-STD-012-2002**. *Content Standard for Digital Geospatial Metadata: Extensions for Remote Sensing Metadata* – The purpose of these Extensions for Remote Sensing Metadata is to provide a common terminology and set of definitions for documenting geospatial data obtained by remote sensing, within the framework of the FGDC (1998) Content Standard for Digital Geospatial Metadata. (FGDC 1998; FGDC 2002)
FGDC Endorsed Profiles of the CSDGM Version 2 (FGDC-STD-001-1998): **FGDC-STD-001.1-1999.** *Biological Data Profile of the Content Standard for Digital Geospatial Metadata* – The objective of the profile is to provide a common set of terminology and definitions for the documentation of biological data through the creation of extended elements and a profile of the FGDC Content Standard for Digital Geospatial Metadata. (FGDC 1999) **FGDC-STD-001.2-2001.** *Metadata Profile for Shoreline Data* – Provides the format and content for describing datasets related to shoreline and other coastal datasets. It provides additional terms and data elements required to support metadata for shoreline and coastal datasets. (FGDC 2001)
ISO - International Organization on Standardization ISO 19115: The FGDC CSDGM standards are transitioning to ISO standards. The ISO standards endorsed by FGDC in 2010 include: **ISO 19139:2007.** Geographic information – Metadata – XML schema implementation (ISO 2007) **ISO 19115-2:2009.** Geographic information – Metadata – Part 2: Extensions for imagery and gridded data (ISO 2009)
Source: Federal Geographic Data Commission: https://www.fgdc.gov/metadata/csdgm-standard.

3. **File Structure that is Consistent and Logical.** Files should be organized into logical directories and uniquely identified using descriptive filenames consistent in syntax. File metadata documentation should include content describing the time period the information was created or obtained using international standard date (e.g., YYYY-MM-DD) and time (e.g., hh:mm:ss ± UTC) formats, respectively).
4. **Terms and Concepts that are Defined and Consistent.** Terminology, concepts, symbols and measurement units should be either standard to the science or explicitly defined.

Metadata are often compiled at the end of a project, which can be difficult given all the important aspects of the data that need to be considered. It is best, and most efficient, to begin compiling metadata as a project is designed, followed by refinement and augmentation over the course of the project.

CHECKLIST FOR METADATA
☐ Initiate the design and development of metadata at the beginning of a project. ☐ Adopt content standards and profiles that conform to U.S. or international standards. ☐ Develop metadata that thoroughly and clearly describe the datasets so that other users can successfully understand and use them (i.e., answer *what, why, where, when* and *how*, and *who*). ☐ Maintain metadata using non-proprietary formats (e.g., XML, TXT). ☐ Incorporate characteristics that ensure metadata are available and searchable.

A.8 QUALITY ASSURANCE IN DATA MANAGEMENT

Quality assurance is considered at each step of the data management lifecycle (see Exhibit A-1) to ensure the quality and integrity of project data during acquisition, processing, analysis, and preservation. Each step in the data management lifecycle supports quality assurance as detailed below.

Data Management Planning – During the planning step of the data management lifecycle, project managers should fully document all decisions made during the development of procedures and the DMP, as well as during the selection of the DMS. Project managers also should incorporate data management into staff training programs to facilitate accurate and consistent data recording and version control of data files.

Data Acquisition – The procedures and quality standards (e.g., data quality acceptance criteria) that are defined in SOPs and other project documentation establish the level of quality that needs to be maintained during the recording, management and interpretation of data. In most projects, the clarity and completeness of these documents, along with the management solutions applied during data acquisition, have a significant influence on project managers' ability to maintain data quality when conducting subsequent data management activities.

Data Processing – Ensuring transparency of procedures when calculating and reducing data to a usable format is a key QA strategy and facilitates data management, as well as informed secondary use of the data. A variety of best practices and automated tools are available to ensure the consistent application of routine processing steps and the effective management of data. A critical QA activity is to adopt the *modus operandi* of "check, double-check, then check again." For example, to help ensure accurate entry in cases where data need to be manually entered into a DMS, data managers may require two individuals to enter the same data so that any discrepancies can be easily identified, reconciled and corrected.

Data Summary & Analysis – QA strategies should include QC checks (reviews) to confirm that planned data analysis and documentation strategies were applied correctly, that any deviations from those plans were appropriate and approved, and all conclusions drawn from the data analysis activities are scientifically sound.

Data Preservation, Sharing & Publishing – Strategic planning, acquisition, processing and analysis of project data are of little value if data are lost or corrupted. The effective management and preservation of project data for primary and secondary uses are, by definition, quality assurance strategies – to preserve is to protect. Data protected are data that can be shared.

As with data collection, regular debriefings to review the data management process and gain insight into what is working well and what needs to be improved is recommended.

A.9 BACKUP AND SECURE DATA

Minimizing or eliminating the loss of data throughout the data management lifecycle – a fundamental condition of data preservation – is a data management absolute. Loss and corruption of data (intentionally or unintentionally) are significant threats to data preservation. System operator error, virus attacks, hardware failures, power failures, fire, natural disasters and other events can impact data integrity. Project planners should develop and implement procedures to avoid and prevent data loss. These procedures should be in place for the physical data representing voucher or sample collections, as well as electronic data and project documentation.

Backup and recovery procedures need to be planned and implemented throughout the data management lifecycle for data and associated metadata, including temporary and intermediate products. Backups should be scheduled regularly during the project and replicated at different secure locations. Archived backups protect against unanticipated events that can result in data loss. Multiple approaches are available for on-site and off-site backups, such as copying data to external hard drives, multiple network servers, or the cloud using internet cloud backup services. To ensure data reliability, any revisions to the data or metadata (and the associated reason(s) for those revisions) need to be documented (see **Chapter 7**, **Section 7.3** of the guidance document and **Section A.7** of this appendix). The backup and archival procedures should be fully coordinated and documented with data preservation policies (see **Section A.5**), which typically include specific guidance and rules for version control.

Data backup and security procedures should be conducted at various stages of implementation. Ensuring the security of sensitive or confidential information is always a consideration. As such, backups need to be protected from unauthorized access as the data are duplicated and protected. In general, best practices include incorporating automated routine backup procedures as an important role of the DMS. Procedures may include use of back-up and archival software, or computer programming code, that allow a data manager to establish regular time intervals for file or complete system backup to one or more central or cloud-based server storage devices. Equally important is the routine testing of data recovery protocols to verify protection against data loss, and to minimize costly delays or redoing effort.

CHECKLIST FOR BACKUPS AND DATA SECURITY
☐ Prepare a backup procedure that details the schedule for backups and assigns responsibilities.
☐ Replicate archived data at multiple physical locations.
☐ Include all relevant metadata and documentation needed to interpret the data for quality assessment and use.
☐ Protect and secure sensitive or confidential information.
☐ Test your backup recovery procedure.

A.10 ADDITIONAL READINGS

- Borer, Elizabeth T., Eric W. Seabloom, Matthew B. Jones, and Mark Schildhauer. 2009. "Some Simple Guidelines for Effective Data Management." *Bulletin of the Ecological Society of America* 90 (2): 205-214. doi: 10.1890/0012-9623-90.2.205.
- British Ecological Society. 2014. A Guide to Data Management in Ecology and Evolution. Available online at: http://www.britishecologicalsociety.org/publications/guides-to/.
- Martín, E. and G. Ballard. 2010. Data Management Best Practices and Standards for Biodiversity Data Applicable to Bird Monitoring Data. U.S. North American Bird Conservation Initiative Monitoring Subcommittee. Available online at http://www.nabci-us.org/.
- Michener, William K. and James W. Brunt (Editors). 2000. Ecological Data: Design, Management and Processing. Wiley-Blackwell.
- U.S. Environmental Protection Agency. 2002. *Overview of the EPA Quality System for Environmental Data and Technology*. Publication No. EPA/240/R-02/003. Washington, D.C.: Office of Environmental Information. Available online at: https://www.epa.gov/quality/agency-wide-quality-system-documents.

A.11 APPENDIX A REFERENCES

American Society for Quality. 2014. *ASQ/ANSI E4:2014: Quality Management Systems for Environmental Information and Technology Programs*. Milwaukee, WI: ASQ Quality Press.

Faundeen, John L., Thomas E. Burley, Jennifer A. Carlino, David L. Govoni, Heather S. Henkel, Sally L. Holl, Vivian B. Hutchison, Elizabeth Martín, Ellyn T. Montgomery, Cassandra C. Ladino, Steven Tessler, and Lisa S. Zolly. 2013. *The United States Geological Survey Science Data Lifecycle Model*. U.S. Geological Survey Open-File Report 2013–1265. doi: 10.3133/ofr20131265.

Federal Geographic Data Committee. 1998. *Content Standard for Digital Geospatial Metadata*. FGDC-STD-001-1998. Washington, DC: Federal Geographic Data Committee.

Federal Geographic Data Committee. 1999. *Content Standard for Digital Geospatial Metadata - Biological Data Profile.* Biological Data Working Group and USGS Biological Resources Division. Publication No. FGDC-STD-001.1-1999. Washington, DC: Federal Geographic Data Committee.

Federal Geographic Data Committee. 2001. *Shoreline Metadata Profile of the Content Standard for Digital Geospatial Metadata*. Publication No. FGDC-STD-001.2-2001. Washington, DC: Federal Geographic Data Committee.

Federal Geographic Data Committee. 2002. *Content Standard for Digital Geospatial Metadata: Extensions for Remote Sensing Metadata*. Publication No. FGDC-STD-012-2002. Washington, DC: Federal Geographic Data Committee.

Fegraus, Eric H., Sandy J. Andelman, Matthew B. Jones, and Mark Schildhauer. 2005. "Maximizing the Value of Ecological Data with Structured Metadata: An Introduction to Ecological Metadata Language (EML) and Principles for Metadata Creation." *Bulletin of the Ecological Society of America* 86 (3): 158–168. doi: 10.1890/0012-9623(2005)86[158:MTVOED]2.0.CO;2.

Government Publishing Office (GPO). 2011. 40 CFR 160.195 – Retention of Records. Code of Federal Regulations. U.S. Government Publishing Office. https://www.gpo.gov/fdsys/granule/CFR-2011-title40-vol24/CFR-2011-title40-vol24-sec160-195.

Hook, Les A., Suresh K. Santhana Vannan, Tammy W. Beaty, Robert B. Cook, and Bruce E. Wilson. 2010. *Best Practices for Preparing Environmental Data Sets to Share and Archive*. Oak Ridge, TN: Oak Ridge National Laboratory Distributed Active Archive Center. doi: 10.3334/ORNLDAAC/BestPractices-2010.

International Council on Archives. 2017. *Guidance*. Accessed April 15, 2017. http://www.ica.org/en/guidance-0.

International Organization for Standardization. 2004. *International Standard: Information technology - Metadata Registries (MDR) - Part 1: Framework (Second Ed.)*. International Electrotechnical Commission. Publication No. ISO/IEC 11179-1:2004(E). Geneva, Switzerland: International Organization for Standardization.

International Organization for Standardization. 2007. *Geographic information -- Metadata -- XML Schema Implementation*. Technical Specification. Publication No. ISO/TS 19139:2007. Geneva, Switzerland: International Organization for Standardization.

International Organization for Standardization. 2009. *Geographic information - Metadata - Part 2: Extensions for Imagery and Gridded Data*. Publication No. ISO 19115-2:2009. Geneva, Switzerland: International Organization for Standardization.

International Society for Biological and Environmental Repositories (ISBER). April 2012. "Best Practices for Repositories: Collection, Storage, Retrieval, and Distribution of Biological Materials for Research. *Biopreservation and Biobanking (BIO)*.

Kolb, Tracy L., E. Agnes Blukacz-Richards, Andrew M. Muir, Randall M. Claramunt, Marten A. Koops, William W. Taylor, Trent M. Sutton, Michael T. Arts, and Ed Bissel. 2013. "How to Manage Data to Enhance Their Potential for Synthesis, Preservation, Sharing, and Reuse—A Great Lakes Case Study." *Fisheries* 38 (2): 52-64. doi: 10.1080/03632415.2013.757975.

McCulloch, Lewis, D. and Kenneth, R. McDonald. 2008. *NOAA's GEO-IDE Initiative - Enhancing the Discoverability, Accessibility, and Usability of Environmental Information.* American Geophysical Union, 89 (53), Fall Meet. Suppl., Abstract IN33A-1157. Abstract available at: https://www.researchgate.net/publication/252672077_NOAA's_GEO-IDE_Initiative_-_Enhancing_the_Discoverability_Accessibility_and_Usability_of_Environmental_Information.

Michener, William K. 2015. "Ten Simple Rules for Creating a Good Data Management Plan." PLoS Computational Biology 11 (10): e1004525. doi.org/10.1371/journal.pcbi.1004525. Available online at: http://journals.plos.org/ploscompbiol/article?id=10.1371/journal.pcbi.1004525#sec011.

National Institutes of Health. 2008. *Guidelines for Scientific Record Keeping in the Intramural Research Program at the NIH*. Bethesda, MD: U.S. Department of Health and Human Services, National Institutes of Health, Office of the Director.

National Science on Technology Council (NSTC). 2016. *Principles for Promoting Access to Federal Government-Supported Scientific Data and Research Findings through International Scientific Cooperation.* A report prepared by the: National Science and Technology Council Committee on Science Subcommittee on International Issues Interagency Working Group on Open Data Sharing Policy. J.P. Holdren. Executive Office of the President, Office of Science and Technology Policy. Accessed February 2, 2018. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/NSTC/iwgodsp_principles_0.pdf.

Office of Management and Budget (OMB). 2013. M-13-13. Open Data Policy-Managing Information as an Asset. In *Memorandum for the Heads of Executive Departments and Agencies, From Silvia M. Burwell, Steven VanRoekel, Todd Park, and Dominic J. Mancini. Executive Office of the President, Office of Management and Budget*. Accessed January 15, 2018. https://www.whitehouse.gov/sites/whitehouse.gov/files/omb/memoranda/2013/m-13-13.pdf.

Office of Science and Technology Policy (OSTP). 2013. "Increasing Access to the Results of Federally Funded Scientific Research." In *Memorandum for the Heads of Executive Departments and Agencies, From J.P. Holdren*. Executive Office of the President, Office of Science and Technology Policy. Accessed January 15, 2018. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/ostp_public_access_memo_2013.pdf.

Rüegg, Janine, Corinna Gries, Ben Bond-Lamberty, Gabriel J. Bowen, Benjamin S. Felzer, Nancy E. McIntyre, Patricia A. Soranno, Kristin L. Vanderbilt, and Kathleen C. Weathers. 2014.

"Completing the Data Life Cycle: Using Information Management in Macrosystems Ecology Research." *Frontiers in Ecology and the Environment* 12 (1): 24–30. doi: 10.1890/120375.

Rugg, David J. 2004. *Creating FGDC and NBII metadata with Metavist 2005*. General Technical Report NC-255. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station.

Strasser, Carly, Robert Cook, William Michener, and Amber Budden. 2012. "Primer on Data Management: What you always wanted to know." *UC Office of the President: California Digital Library*. doi: 10.5060/D2251G48.

Sutter, Robert D., Susan Wainscott, John R. Boetsch, Craig J. Palmer, and David J. Rugg. 2015. "Practical Guidance for Integrating Data Management into Long-term Ecological Monitoring Projects." *The Wildlife Society Bulletin* 39 (3): 451-463. doi: 10.1002/wsb.548.

UK Data Service. 2017. *Research Data Lifecycle*. Accessed April 18, 2017. https://www.ukdataservice.ac.uk/manage-data/lifecycle.

U.S. Environmental Protection Agency. 2007. *Guidance for Preparing Standard Operating Procedures (SOPs) (EPA QA/G-6)*. Publication No. EPA/600/B-07/001. Washington, DC: Office of Environmental Information.

U.S. Environmental Protection Agency. 2015. "Scientific Collections Policy: Improving the Management of and Access to Scientific Collections." Office of the Science Advisor. Accessed May 19. https://www.epa.gov/sites/production/files/2015-12/documents/epa_scientific_collections_policy_final_11-30-15.pdf.

U.S. Environmental Protection Agency. 2017. "Geospatial Resources at EPA: EPA Metadata Editor." Office of the Science Advisor. Accessed May 19, 2017. https://www.epa.gov/geospatial/EPA-Metadata-Editor.

U.S. Geological Survey. 2017a. "Data Lifecycle Overview." USGS Data Management. Last modified March 22. https://www2.usgs.gov/datamanagement/why-dm/lifecycleoverview.php.

U.S. Geological Survey. 2017b. Core Science Analytics, Synthesis, and Libraries (CSAS&L) - Online Metadata Editor (OME). Accessed April 18, 2017. https://www1.usgs.gov/csas/ome/.

Weltzin, Jake F., Jennifer M. Bayer, Rebecca A. Scully. 2017. Defining opportunities for collaboration across data life cycles, Eos, 98. Available at: https://doi.org/10.1029/2017EO072689.

Wilkinson, Mark D., Michel Dumontier, IJsbrand Jan Aalbersberg, Gabrielle Appleton, Myles Axton, Arie Baak, Niklas Blomberg,…and Barend Mons. 2016. "The FAIR Guiding Principles for scientific data management and stewardship." Sci. Data 3:160018. doi: 10.1038/sdata.2016.18. Available online at: https://www.nature.com/articles/sdata201618.

Appendix B

APPENDIX B: THE ASSESSMENT OF DATA QUALITY INDICATORS IN ECOLOGICAL RESTORATION MONITORING

This appendix provides guidance on statistical procedures that are commonly used to evaluate the reliability of categorical and numerical data acquired during ecological restoration monitoring. The results of these procedures can serve as performance indicators useful to project planners and data users to assess the reliability of data when they are compared against established data quality acceptance criteria developed for the following data quality indicators (DQI): precision, bias, accuracy, representativeness, comparability, completeness, and detectability. Refer to **Chapter 3**, **Section 3.4** of the guidance document for DQI definitions and discussion on how to establish data quality acceptance criteria.

Ecological restoration monitoring can generate a diverse set of both quantitative and qualitative environmental data. Each type of data may require different statistical procedures to assess their precision and accuracy, and determine if the data are sufficiently reliable to support adaptive management or objective inference decisions. Evaluating and reporting data quality assessments are essential given that a majority of data generated by an ecological restoration monitoring project will reflect, in addition to natural variability, a total cumulative error contributed by multiple sources. These sources include error as a result of an imperfect sampling design and error due to the combined variance associated with the measurement process, along with any outstanding random or fixed errors not accounted for in the project study design **(Exhibit B-1)**.

Exhibit B-1. Source Partitioning of Total Error in Ecological Restoration Monitoring

$$\text{Total Error } (S^2) = S^2_{\text{Sampling Error}} + S^2_{\text{Measurement Error}} + S^2_{\text{Unaccounted for Error}}$$

$$\text{Total Error } (S^2) = (S^2_A) + (S^2_B + S^2_C + S^2_D + S^2_E + S^2_F + S^2_G + S^2_H) + S^2_U$$

Total Error (S^2) = sample variance, due to error in:

- S^2_A = sample design
- S^2_B = conducting field sampling
- S^2_C = sample processing
- S^2_D = observer variable assessment
- S^2_E = observer variable enumeration assessment
- S^2_F = data transcription from observation to database
- S^2_G = post data entry variable or metric processing
- S^2_H = variable assessment and interpretation
- S^2_U = remaining sources of error not accounted for in the sampling design or the measurement process

Modified from: Flotemersch et al. 2006; Stribling J.B. 2011.

It is generally impractical to develop a project study design that completely eliminates all sampling and measurement error. Typically, sampling error is assessed by analyzing data pooled across multiple sampling units, sites, and/or time. Standard equations can be used to calculate a metric or sample statistic representing one or more population parameters (e.g., relative abundance, total biomass, species- or community-composition, net carbon sequestration, relative total phosphorus discharge) at the treatment or site level. Efforts to quantify and document sampling error are important for determining the usability of a particular dataset to address project sampling objectives. It is beyond the scope of this appendix to discuss statistical procedures used to assess DQIs in context of sampling error, and such procedures will not be addressed in any detail. However, there are many credible and readily available publications that provide statistical guidance to assess a variety of error-related issues associated with environmental data (see Additional Readings). One recommended source is the U.S. Environmental Protection Agency (EPA) publication that provides such guidance developed for environmental managers and natural resource practitioners: EPA QA/G-9S. 2006. *Data Quality Assessment: Statistical Methods for Practitioners*. Online at: https://www.epa.gov/quality/guidance-data-quality-assessment.

Sections B.1 and **B.2** of this appendix lay the foundation for understanding both the statistical limitations associated with data representing different measurement scales and the unique attributes of measurement error associated with data collected under different levels of control. **Section B.3** presents important considerations related to preparing data for quality assessment. **Section B.4** describes common statistical procedures used for the assessment of data precision, bias and accuracy by comparing the differences between sample means, or individual measurements or observations, when collected by the same routine crew at different times or by different routine crews, and between a routine crew and a QA expert. **Section B.5** identifies a simple method to quantify the level of completeness in obtaining planned samples, measurements or observations. **Section B.6** distinguishes sensitivity and specificity, two fundamental components that are complimentary to the assessment of detectability. **Section B.7** places the context of data quality in terms of their representativeness and comparability. **Section B.8** concludes the appendix by describing a simple statistical procedure that can be used to quantify the repeatability (precision) within and between observers, crew(s) or samples, as well as compare the efficacy between two or more procedures.

All data users are encouraged to work with a statistician familiar with environmental and ecological data analysis to identify statistical procedures that are most appropriate for the specific application. A statistician will be able to provide recommendations that draw from a variety of parametric and non-parametric procedures. While these procedures are not discussed here, the recommendations can help support analysis and planning efforts, and ensure the appropriate treatment of data given the specific scale of measurement (i.e., nominal, ordinal, interval or ratio).

B.1 MEASUREMENT SCALES AND THEIR STATISTICAL PROPERTIES OF VALUE

Given the diversity of environmental data and their formats, it is often difficult to identify the appropriate statistical procedures to assess their reliability. This is particularly true when the data are not continuous – such as when data represent discrete variables, including numeric data that have been "categorized" or simplified to a categorical variable that can be ranked or ordered. Consequently, in order to accurately assess data quality, it is important to first identify the appropriate measurement scale represented by each variable of interest and understand their limitations and inherent statistical properties. **Exhibit B-2** summarizes important statistical considerations between categorical and numeric data and four main types of measurement scale (nominal, ordinal, interval, and ratio) as proposed by Stevens (1946, 1951). Despite the debate that ensued regarding the merits of Stevens' measurement scale and his associated statistical considerations (Michell 1986; Velleman et al. 1993; Duncan et al. 2006), the measurement scale concept has been broadly accepted and applied in a variety of statistical references (Conover 1999; Zar 2010; McDonald 2014) and used by specific statistical software applications (Wilkinson et al. 1996; Carlberg 2014; Mangiafico 2016).

In Velleman et al. (1993), measurement scale is described as an important concept, and Stevens' terminology often suitable, however they argue that scale type (and implied limits of statistical treatments) and their assignment be understood based on the awareness of how the data have been collected (i.e., measured or observed) and the questions intended to be addressed by the data.

For the purposes of data quality assessment, environmental data are obtained through the following two types of processes:

- A **Measurement** can be defined as any numeric value associated with a unit of measurement. A measurement represents variables typically quantified with the aid of a mechanical graduated device or instrument (e.g., a tape measure or bulb thermometer) or an electronic analog instrument, such as a device that displays results along a continuous scale, or digital instrument that displays results as a discrete, numeric value. Numeric data are considered "quantitative" and, depending on sample size and distribution, may be appropriate for use in parametric statistical methods.
- An **Observation** can be defined as a categorical or numeric value that, with some exceptions, typically lacks a unit of measurement. Examples of observations that may require a unit of measurement include counts of occurrence or estimates of individual abundance (e.g., individuals per taxonomic unit) and percent cover (e.g., vegetation cover per unit area). These data, regardless of whether they are numeric or categorical, represent variables typically determined by an observer's perception and best professional judgment. When observations represent non-numeric, categorical data, they are often considered to be "qualitative" and generally require use of non-parametric statistical methods.

Exhibit B-2. Measurement Scales and their Statistical Properties				
	Categorical Data		Numeric Data[1]	
	Labels	Rank Order	Discrete or Continuous[2]	
Statistical Property of Value	**Nominal**	**Ordinal**	**Interval**	**Ratio**
Order of values is meaningful		✓	✓	✓
Values can be counted or tallied	✓	✓	✓	✓
Sample Mode is meaningful	✓	✓	✓	✓
Sample Median is meaningful		✓	✓	✓
Sample Mean is meaningful			✓	✓
Difference or distance between values is meaningful			✓	✓
Values can be added or subtracted			✓	✓
Values can be multiplied and divided				✓
Values have a true zero				✓

[1]**Numeric data** can be simplified to categorical data.
[2]**Continuous data** have implied limits of precision.
Table modified from http://www.mymarketresearchmethods.com/types-of-data-nominal-ordinal-interval-ratio/.

Environmental data that are based on observation, or the visual and/or aural acuity of an observer applying best professional judgment (i.e., observer-determined), are typically coarse in resolution and lack the implied precision often associated with a measurement obtained by a mechanical or electronic scientific instrument. However, when measurements are collected with the assistance of a scientific instrument, the results (e.g., GPS location, pH, electrical conductance, temperature, relative humidity, stream flow) may be reported as continuous data and at a level of precision designed into the instrument. Under certain circumstances, the level of precision reported by a scientific instrument may be unwarranted, exceeding the implied limit of precision for a particular variable and the methods applied to quantify it. For example, recording the pH to a precision of three decimal places (e.g., 8.328) for a surface water grab sample is likely inappropriate, and would be better recorded with fewer decimal places (e.g., 8.3) to avoid implying a greater level of precision in the estimate than is meaningful. In other situations, a measurement may have been initially quantified as a continuous variable, but then later transformed (categorized or simplified) by the observer and recorded as a categorical data element on a data collection form. Because of the variety of methods used to record or transform raw data from one measurement scale to another, it is important for the data analyst to understand the unique properties of each data or variable type when considering appropriate statistical procedures.

Exhibit B-3 provides examples of common measurements or observations in each of the nominal, ordinal, interval, or ratio scales. The examples represent variables recorded in a field setting and obtained from an electronic instrument, or based on visual or aural assessment and applying best professional judgment.

Exhibit B-3. Examples of Common Measurements or Observations in each of the Nominal, Ordinal, Interval and Ratio Scales			
Nominal	**Ordinal**	**Interval**	**Ratio**
Crew ID	Dominance Class	Time (12hr)	Elapsed Time (hr)
Instrument ID	Age Class	Azimuth (°)	Counts (organisms)
Taxonomic ID	Vigor Class	Temperature (° C/ ° F)	Proportions (%)
Gender	Beaufort Wind Scale	Distance Interval (m/ft)	Length (cm)
Yes / No	Abundance Class	Atmospheric Pressure (psi)	Area (ha/acre)
Functional Guild	Canopy Class	Elevation (± sea level)	Volume (cm^3)
Reproductive Status	Low/Med/High	Calendar Year	Slope (%)
Color	Soil Color	Latitude and Longitude	Age (years)
Names	Levels of Agreement	pH ($-log[H^+]$)	Concentration (ppm)

B.2 DATA COLLECTION AND MEASUREMENT ERROR

Environmental data for an ecological restoration project may be produced under a variety of scenarios, each with its own unique contributions to measurement error. **Exhibit 3-4** in **Chapter 3**, **Section 3.4** of the guidance document distinguishes among different types of data commonly collected in support of ecological restoration monitoring projects. Anticipating the need for additional efforts to assess data reliability requires a qualitative understanding of how the data were generated, including the effectiveness of project procedures to control measurement error. The following list describes three data collection scenarios (or environments), typical to many ecological restoration monitoring projects, that broadly represent the conditions for which environmental data are generated. The list provides additional description of how QA/QC conditions may differ for each.

1) *On-site measurements or observations* - data typically collected in outdoor settings often under physically and mentally demanding environmental conditions that can impose distractions during the implementation of standard operating procedures (SOPs). These data may not be subjected to rigorous, routine QA/QC oversight and, consequently, results may be reported with unknown levels of precision and accuracy. The quality of measured or observer-determined results may also be affected by multiple observers or crews implementing procedures across one or more geographic locations or temporal periods. Obtaining measurements or interpreting observations are often associated with the use of:

    - observer-assessment based on visual- and/or aural-sensory systems (e.g., vegetation, avian, or anuran surveys);
    - portable electronic devices or scientific instruments (e.g., GPS, multi-parameter water quality meter);
    - a combination of observer assessment and a scientific instrument, with or without the aid of additional calibrated equipment (e.g., ruler, quadrat, wristwatch); and/or

- professional, junior, or entry-level seasonal staff (and may include individuals or groups part of citizen monitoring) who are not equally proficient in the implementation of SOPs or analytical methods, or in the calibration and use of field equipment.

2) *Field laboratory (or temporary research station)* - data collected indoors (e.g., in a trailer or other mobile laboratory setting) with reduced exposure to environmental hazards, reasonable control of air temperature and lighting, provision of a dedicated work space, and access to precision analytical instrumentation. Obtaining measurements or interpreting observations often involves:

   - using instrumentation ranging from field equipment to dedicated laboratory equipment optimized for increased precision and accuracy,
   - applying analytical procedures that may or may not equal those in a fixed laboratory setting,
   - addressing potential trade-offs in terms of QA/QC procedures to accommodate logistical constraints, and/or
   - modifying procedures to accommodate the availability of computer resources used for direct data collection.

3) *Fixed laboratory (or permanent research station)* - data generated under controlled conditions suitable for performing complex analytical procedures (e.g., chemical, microbiological, geophysical analyses). The laboratory may or may not be accredited by an outside organization, depending on the specific measurements involved. Ideally:

   - Measurements or observations in these facilities are associated with a rigorous QA/QC oversight program, where reported results provide QC assessments of precision and accuracy during batch processing of environmental samples (e.g., blanks, replicates, calibrations, and matrix spike recoveries).
   - Analytical methods and procedures are based on those from EPA or a voluntary consensus standards body (e.g., ASTM, AOAC, APHA), and are implemented via SOPs that require initial and ongoing demonstrations of performance with known precision and accuracy.
   - Reference materials, obtained from a recognized provider, are employed for QC comparison of results during batch processing.
   - High precision instrumentation is maintained and operated in a fixed location.
   - Professional (and often full-time) staff that are proficient in SOP/analytical method implementation and laboratory equipment calibration and use, and are familiar with all QA procedural requirements.

Some circumstances may necessitate the use of procedures that deviate from the norm. For example, analytical requirements may not fall under the auspices of any accrediting body, or laboratories may be selected based on other considerations, including geographic proximity to the site or an affiliation with a partner organization contributing to the restoration project (e.g., academic research laboratories). Those circumstances may involve:

- alternative analytical methods and procedures that may not be associated with a published standard or may not have been demonstrated and validated to produce consistent performance with high precision and accuracy;
- reference materials that may be represented by a biological voucher or specimen for use in taxonomic identification, biological pathology and physical anatomy;
- mid- to high-level precision instrumentation operated in either a mobile or fixed location; and/or professional, junior, or entry-level seasonal-staff who may or may not be equally proficient in the implementation of SOPs (analytical methods) or the calibration and use of laboratory equipment.

<u>Example scenario</u>*: An observer or crew is required to deploy a multiple-sensor sonde instrument from a boat to measure and record the dissolved oxygen, temperature, and pH in an open lake, at a depth that coincides with the maximum Secchi-disk depth. When completed, the observer collects a physical water sample at the same depth for analysis of chlorophyll-a concentration at a fixed laboratory or permanent research station. This monitoring effort is performed by multiple crews, across a large region, under varying weather conditions and equipment availability.*

The scenario described above illustrates the potential complexity associated with interpreting, recording, and collecting reliable estimates for an environmental variable in a "field" setting. The measurement errors associated with the data collected will reflect the contributions of both the field and fixed laboratory settings, and include the combined error contributed by the specific method of observation and/or measurement involved in quantifying the variable.

B.3 PREPARING DATA FOR QUALITY ASSESSMENT

The remaining sections of this appendix are organized based on the DQI of interest. There are several steps a data analyst should consider to prepare data for quality assessment using statistical procedures. A first step is to confirm that all data to be assessed have undergone a formal data review process and that errors introduced during data transcription and other non-conformities have been corrected and documented. **Chapter 6** of the guidance document provides an in-depth description of the data review process. Working with data that include correctable errors can produce misleading results during the data quality assessment process, and unnecessarily creates additional effort. It is also helpful to organize data chronologically and into logical sets according to one or more ancillary variables of interest, such as the site ID, sample year, observer or crew ID, and if documented, the device ID for any instrumentation used; and is a conventional practice in order to facilitate the selection of a subset of a larger dataset in order to confirm that they meet established criteria or levels of quality. For example, a data analyst may be interested in evaluating survey results obtained during a specific year or time period, or collected by a specific crew or from a specific site, or to assess batch results reported by an independent laboratory. In these cases, and for monitoring results that produce small sample sizes (e.g., fewer than 30), the data analyst should consider what effect a reduction of sample size will have on the precision and accuracy of a sample mean statistic when its representativeness of the sampled population mean is dependent upon the application of the central limit theorem (Devore 2012; Walpole et al. 2012).

It is considered standard practice to summarize any given sample (or set) of data using descriptive statistics in order to parameterize the sample based on the minimum and maximum values, standard deviation (a measure of the spread of the data), and, as stated previously, a measure of central tendency such as the sample mean, median, or mode. Typically, the process of describing data coincides with the use of one or more graphical analysis tools to visually inspect the shape or distribution of the sample data – and often evaluated to whether the data are approximately normally distributed. Graphical analysis tools commonly used include scatter plots, box-and-whisker plots, pareto- and control- charts, cumulative frequency plots, and histograms – all of which can help a data analyst detect problems and potential errors (e.g., extreme or invalid values) – and to determine whether a discrete or continuous numeric variable may require statistical transformation in order to conform to an assumed probability distribution. When combined, the graphical analysis and review of the descriptive statistics for each variable provides a "big picture" perspective from which a determination can be made regarding whether the data quality is adequate to proceed with more rigorous statistical assessments.

B.4 PRECISION, BIAS, AND ACCURACY

Precision and bias (and thus, accuracy) are related error terms and can be influenced by random and systematic errors in a measurement process (EPA 2006). Precision is the degree of agreement among repeated measurements or observations of the same attribute and is not dependent upon the true value. Measurement precision represents the total variation for a given set of measurements produced by the measuring device, the procedure used, and the proficiency of the device operator. By analogy, this is also true for a given set of observations produced by an individual applying best professional judgment (e.g., visual assessment) and a standard protocol (Stapanian et al. 2016). When a scientific instrument is used that can evaluate a continuous variable with increased resolution (i.e., to finer fractional or decimal precision), the degree of precision reported will have a direct effect on the magnitude of the variance for that variable (Walther et al. 2005). In this context, the level of resolution used to evaluate and report a categorical (nominal or ordinal) or numerical (discrete or continuous) variable based on observation will similarly impact the magnitude of the variance for that variable.

As introduced in **Chapter 3**, **Section 3.4** of the guidance document, data quality acceptance criteria for precision, bias, and accuracy collectively, can be represented and expressed in terms of a measurement error tolerance and a frequency of compliance rate for achieving that tolerance. All three terms are combined in this manner as a QA strategy to increase the efficiency in QA/QC oversight during data collection. Combining the terms also facilitates coordinating the quality assessment of results related to a specific site or sampling unit (e.g., transect or plot array) or an event period (e.g., month or season), much like the evaluation of batch-specific QC results in a laboratory. Therefore, the most basic method to evaluate the combined error associated with precision, bias, and accuracy is the evaluation of the frequency with which a measured value falls within the acceptable error tolerance for that variable (Westfall 2009, Stapanian et al. 2016). This approach is an intuitive and practical method to assess discrete and categorical data types as part of QA assessment and continual improvement during data collection activities.

However, use of the combined error tolerance and compliance rate method may not be as rigorous or as efficient for all types of data, measurement scales, or large numbers of repeated measurements or observations, nor is it practical during latter stages of data quality assessment. The remainder of this section presents common statistical procedures that can be used to complete a more robust quantitative assessment of precision and bias for a specific variable representing a set of measurements or observations reported in their original units (i.e., variables that are not derived from an equation or based on a modeled response). Accuracy is assessed qualitatively by evaluating the combined performance of precision and bias and represents the total error or uncertainty associated with an individual measurement or set of measurements.

B.4.1 Standard Statistical Equations to Assess Precision, Bias, and Accuracy for Repeated Measurements

Precision is the degree of agreement among repeated measurements or observations of the same attribute under the same or very similar conditions. For situations where the true value is not known, such as when it is not possible to provide a QA crew or an expert evaluation, it is still possible to evaluate precision of repeated measurements within the same or between two different routine crews. The statistical procedure evaluates the variability in crew performance to consistently measure or estimate a true value by calculating the squares of the differences between the repeated measurements (to remove the direction of the difference), and then averaging these results. The variance (VAR) is expressed as the average (corrected by n-1 degrees of freedom) of these squared differences. The calculated statistic thus represents an estimation of the variance for the variable measured or assessed either within or between observers or crews. To return this estimate of precision to the same units or scale of the original measurement, the square root of the variance is calculated and is termed the standard deviation (SD).

Bias evaluates systematic differences that could lead to an underestimate or overestimate of the true value. Bias can be calculated as the average (or mean) difference between the values obtained by a routine crew and the values obtained by an expert or QA crew for the sample variable at the same location.

Accuracy describes the degree of closeness of a set of measurements to a known or reference value (see **Exhibit 2-3** in **Chapter 2**, **Section 2.5**). Accuracy can be estimated as Mean Squared Error (MSE) and is calculated as the square of the differences between measured (or observed) and true values to eliminate the direction of these differences and therefore only takes into consideration the magnitude of the differences. To return this estimate of accuracy to the same units or scale of the original measurement, the square root of the MSE is calculated and is termed the root mean square error (RMSE).

Statistical equations are provided for each of these DQIs and are listed in Exhibit B-4.

Exhibit B-4. Standard Statistical Equations to Assess Bias, Precision and Accuracy	
Data Quality Indicator	**Formula for Statistical Procedures**
Bias	$\mathrm{ME} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i=1}}^{\mathrm{n}}\left(y_{i_{\mathrm{(routine)}}} - y_{i_{\mathrm{(expert)}}}\right)$
Precision	$\mathrm{VAR} = \frac{1}{\mathrm{n}-1}\sum_{\mathrm{i=1}}^{\mathrm{n}}\left(y_{i_{\mathrm{(routine)}}} - \bar{y}_{\mathrm{(routine)}}\right)^2$ $\mathrm{SD} = \sqrt{\frac{1}{\mathrm{n}-1}\sum_{\mathrm{i=1}}^{\mathrm{n}}\left(y_{i_{\mathrm{(routine)}}} - \bar{y}_{\mathrm{(routine)}}\right)^2}$
Accuracy	$\mathrm{MSE} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i=1}}^{\mathrm{n}}\left(y_{i\,\mathrm{(routine)}} - y_{i\,\mathrm{(expert)}}\right)^2$ $\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{n}}\sum_{\mathrm{i=1}}^{\mathrm{n}}\left(y_{i_{\mathrm{(routine)}}} - \bar{y}_{\mathrm{(routine)}}\right)^2}$
Formulas are for ME (mean error), VAR (variance), SD (standard deviation), MSE (mean squared error) and RMSE (root mean square error). $y_{\mathrm{i\ (routine)}}$ is the i[th] value obtained by a routine crew for an attribute. $y_{\mathrm{i\ (expert)}}$ is the i[th] value obtained by an QA expert for that same attribute at the same location. $\bar{y}_{\mathrm{(routine)}}$ is the average value for an attribute as measured by a routine crew across all locations.	

B.4.2 Alternative Methods and Statistical Equations to Assess Precision, Bias, and Accuracy for Repeated Measurements

For monitoring results that are quantitative, it is also possible to conduct some additional statistical procedures to provide quantitative assessments of precision, bias, and accuracy. Common mathematical procedures used to assess precision, bias, and accuracy for repeated measurements (Stribling et al. 2008; 2011 and EPA 2012) are described next. Specific guidance is organized according to (1) when sample sizes are sufficient to produce a sample mean representative of the sampled population; in other words, when sample sizes are sufficient (e.g., $n > 30$) to apply the Central Limit Theorem (Devore 2012; Walpole et al. 2012), and (2) when comparing two individual measurements or observations, or where the analyst makes no assumption on whether the measurements or observations are representative of the sampled population.

B.4.2.1 *When sample sizes are sufficient to produce a sample mean representative of the sampled population (assumes n accurately reflects population characteristics)*

Percent Relative Standard Deviation - %RSD

Precision: The %RSD is a useful metric by which to compare the variance between results obtained by repeated measurements (or observations) on the same sample by the same observer (within crew) or between observers (between crew) – but its performance or reliability generally decreases as sample size decreases. An important statistical consideration when using %RSD is that it should only be used for continuous variables (or the differences when comparing between repeated measurements) that have a true zero point – such as length, height, weight, or area, and those variables with a conceptual zero point like diameter breast height (DBH), among others. However, when the mean value is close to zero, %RSD will approach infinity and is therefore sensitive to small changes in the mean. Of equal importance, is that the measurements or observations be drawn randomly from the sampled population.

$$\% RSD = \frac{\sqrt{\frac{1}{\mathrm{n}-1}\sum_{\mathrm{j}=1}^{\mathrm{n}}\left(y_{i_{(\mathrm{routine})}} - \bar{y}_{(\mathrm{routine})}\right)^2}}{\bar{y}_{(\mathrm{routine})}} \times 100$$

Where:
n = total # routine measurements or observations
i = independent measurement or observation
y_i = value for i^{th} routine measurement or observation
$\bar{y}$ = average value for all routine measurements or observations

*Note: %RSD can be represented more simply as: 100*SD/$\bar{y}$.*

The %RSD is calculated by first obtaining the SD of a set of measurements, or the differences between repeated measurements, dividing that result by the average of those measurements or their differences, and then multiplying by 100 to represent it as a percentage. The %RSD is also known as the coefficient of variation (CV).

Accuracy and Bias: With minor modification, the %RSD can be used as a procedure to assess measurement accuracy (Stapanian et al. 2016). This is accomplished by replacing the term [$\bar{y}$ *(routine)*] in the numerator with the term [$\bar{y}$ *(expert)*] to represent the estimated average or mean value determined by a QA expert or that was determined *a priori* to represent an accepted true mean value.

Bias can be expressed as a percentage indicating the direction and magnitude of the difference between the mean value of a set of measurements (or observations) and the known or true value relative to the known or true value. It represents relative bias, and indicates the ability of an observer, crew or procedure to over- or underestimate a variable. The equation for relative bias is:

$$Bias\ (\%) = \frac{\bar{x} - E}{E} \times 100$$

Where: $\bar{x}$ = the mean value for the set of measurements or observations

E = the expert or accepted true value of a variable

<u>95% Confidence Interval (CI) of the mean</u>

Precision: The average or mean value $\bar{x}$ of a given set of measurements collected randomly from a sampled population can be considered an estimate of the true population mean μ. Because of sampling variability, this estimate is however likely different from the true mean. Information about the precision and reliability of the estimation can be provided by reporting an interval of plausible values, also known as a confidence interval. The computation of a confidence interval requires first the selection of a confidence level 1-α, which is a measure of the degree of reliability of the interval. The higher the confidence level, the more likely the value of the true mean lies within that interval. A 95% CI is presented here because of its conventional use in ecology. Project planners should consider alternative confidence levels (e.g., 90%, 99%, 99.9%) based on one or more of the following: (1) the level of error (or precision) tolerable in the estimation of a sample mean for a given variable of interest, (2) logistics and resources involved with increased sampling effort, and (3) the effect-size necessary to correctly assess decision error for a given hypothesis test. Ideally, confidence (and statistical significance) levels should be determined *a priori* to effectiveness monitoring and subsequent statistical analysis tests on the effects of their restoration actions.

The lower and upper limits of the 95% confidence interval are computed as follows:

$$95\ \%\ Confidence\ Interval\ of\ the\ Mean = \bar{x} \pm \left(t \times \frac{SD}{\sqrt{n}}\right)$$

Where: $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$

$$\text{Standard Deviation (SD)} = \sqrt{\frac{1}{\mathrm{n}-1}\sum_{\mathrm{i}=1}^{\mathrm{n}}(x_i - \bar{x})^2}$$

Where: n = total # measurements or observations

$\bar{x}$ = average or mean value

x_i = value for i^{th} measurement or observation

SD = standard deviation of the sample estimate

t = statistic from t-distribution table

Note: A 95% confidence interval is derived by dividing the SD by the square root of the number of measurements (n) and multiplying by a critical value t with α = 0.05 and n-1 degrees of freedom.

Together, the SD and the confidence interval can serve other valuable purposes; for instance, to compare the level of precision between two different estimates of the same measurement using different procedures (Bland and Altman 1986). Assuming that sample sizes are comparable between each set of measurements, the measurement procedure with a SD and CI (specifically the lower and upper limits) characterized by the least variability and narrowest range of minimum and maximum values, respectively, represents the procedure with the greatest precision in measurement.

Accuracy: The accuracy is defined in terms of whether or not the confidence interval contains the true population mean, which is typically unknown in practice. For the purpose of estimating a difference between results obtained by a routine crew member and results obtained by a QA expert, an analyst could use $\bar{y}_{(expert)}$ to represent the true population mean. Then, check whether this value is included in the confidence interval computed from measurements $y_{i\ (routine)}$, and replacing x_i with $y_{i\ (routine)}$, in the equations above.

An alternative approach, which accounts for the uncertainty included in $\bar{y}_{(expert)}$, is to also compute a confidence interval for $\bar{y}_{(expert)}$ and replacing x_i with $\bar{y}_{(expert)}$ in the equations above. The confidence intervals for $y_{i\ (routine)}$ and $\bar{y}_{(expert)}$ can then be compared. If these two intervals do not overlap, then the difference between the two means is significantly different from zero. If there is an overlap then a statistical test, i.e. two sample t-test (Devore 2012), needs to be performed to decide whether the difference is significant for a given α-level. This approach can be applied more generally to compare the means of two sets of data (e.g., measurements collected by the same crew on the same plots at different times, or by different crews on the same plots at similar times).

95% Confidence Interval (CI) of the mean difference (MD) – 95% CI of MD

The comparison of two means using the overlap of their confidence intervals is very general in that the number of measurements do not need to equal the number of experimental units (EU) being sampled (e.g., points, quadrats, transects). There are however situations in which there is only one EU and two sets of measurements are made on that unit. For example, consider the scenario where each 1-m^2 quadrat along a 100 meter line-transect has been visited by two routine crews or by a routine crew and a QA crew, resulting in a set of *n* paired samples $\{(y_{i\ (routine)}, y_{i\ (expert)})\ i = 1, \dots, n\}$. Comparing the two samples represented by the two crews is best done by first computing the difference between measurements for each pair of observations: $d_i = y_{i\ (crew\ 1)} - y_{i\ (crew\ 2)}$. A confidence interval for the mean difference between the paired samples can then be computed as follows:

$$95\ \%\ Confidence\ Interval\ of\ the\ Mean\ Difference\ = \bar{d} \pm \left(t \times \frac{SD}{\sqrt{n}}\right)$$

Where: $\bar{d} = \frac{1}{n}\sum_{i=1}^{n} d_i$

$$\text{Standard Deviation (SD)} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(d_i - \bar{d})^2}$$

Where: n = total # paired differences

$\bar{d}$ = average or mean difference

SD = standard deviation of the data

t = statistic from t-distribution table

Notes: 1) If the confidence interval does not include zero, then we can be highly confident that the two means are different. 2) When paired differences represent measurements conducted between two different routine crews, then the mean difference is representative of precision only.

B.4.2.2 When comparing between two individual measurements or sample results with no assumption regarding their representativeness of the sampled population

There are times when QA managers may wish to compare the level of precision or agreement between two individuals or crews (e.g., within- and between-crew assessment), or between a routine crew estimate and that of a QA expert, but where a meaningful sample average (i.e., sample mean) cannot be determined (e.g., when there are fewer than 30 samples). This scenario is particularly common during the early phases of project monitoring when sample sizes are low or incomplete, or when it is necessary to validate whether results are in compliance with performance objectives, as defined by data quality acceptance criteria. The procedures listed here may be used to evaluate performance related to specific periods of sampling effort, crew deployment, or when there may be procedural changes as result of revised SOPs. When applied in a laboratory environment, results are conventionally associated with batch analysis. This same concept can easily be applied to performance evaluation of data packages or sample units representing measurements conducted in field settings (e.g., one per transect, one per 10 plots, once per sampling event). It is important to point out that results produced from the following assessment procedures cannot necessarily be extrapolated to a population of interest, but rather serve as a QA strategy for the systematic performance assessment of observers or an entire crew.

Relative Percent Difference (RPD):

There are certain applications when it is useful to compare the proportional difference between two measurements or calculated values (Stribling et al. 2008). This is performed by calculating the RPD – a unit-less quantity where lower RPD values represent greater precision than higher RPD values. RPD is estimated based on the absolute value of the mathematical difference between two measured or calculated values (i.e., metric or index), then dividing that difference by their combined average. The result is multiplied by 100 to express the proportional difference as a percentage. The equation for RPD is calculated as*:*

$$Relative\ \%\ Difference\ (RPD)\ = \frac{|A - B|}{(A + B)/2} \times 100$$

Where: A = the first measured (or calculated) value

B = the second measured (or calculated) value

Note: A and B can represent measurements repeated at different times, conducted by different observers or crew, or estimated (e.g., indexes) using different instrumentation or procedures. Absolute values are included in the denominator when the sum of A + B results is zero. However, when either A or B are very small or zero, RPD can produce misleading results (Stribling et al. 2008).

The use of RPD is a common approach to compare results from laboratory sample analysis, but it is also useful as a QC inspection procedure to assess within- or between-crew performance for data derived from field measurements, such as stem or shoot density, tree height, and an object's distance from an observer.

Percent Taxonomic Disagreement (PTD):

The taxonomic identification of plant and animal species and their associated enumeration is a common component of ecological restoration monitoring. It typically produces two types of data, categorical (nominal) data for species identification, and discrete counts for numbers observed per species identified. Often, data of this type are evaluated for precision, bias, and accuracy by comparing whole-sample identifications completed by different taxonomists, field personnel or crews that specialize in one or more areas of botany or zoology. Data are typically generated by the analysis of collections of preserved sampled specimens (e.g., macro- or micro-invertebrates or fish) under controlled laboratory conditions. However, data can also be generated under field conditions by conducting repeated evaluations of the same sample unit (e.g., quadrat, transect, or point) by the same or different observer or crew member, or between a routine crew member and a QA expert. Generally, the accuracy of taxonomy is qualitatively evaluated based on the *a priori* specification of one or more target hierarchical levels (e.g., family, genus or species). PTD is calculated as:

$$Percent\ Taxonomic\ Disagreement\ (PTD)\ = \left[1 - \left(\frac{a}{n}\right)\right] \times 100$$

Where: a = the number of agreements

n = the total number of organisms in the larger of the two counts

Note: n is represented by the specification of a target hierarchical level (e.g., family, genus or species).

A lower PTD conveys a lower number of disagreements indicating a greater similarity for count estimates and the level of taxonomic precision between observers, crews or laboratories.

The use of PTD may also apply to certain field procedures used to enumerate the occurrence of one or more types of community classification or other categorical or nominal types of data, provided sample units are clearly delineated and evaluation methods are adequately documented to standardize observer interpretation for both unit classification and unit enumeration.

Percent Difference in Enumeration (PDE):

PDE quantifies the consistency of discrete counts of a particular taxonomic unit (or other classification) in samples and may apply in certain applications during field sampling to assess counts determined *in situ* for a given sample unit. PDE is determined by calculating the absolute value of the difference between two counts representing different observers, crews, or independent laboratories, and dividing that value by the sum of each total, and then multiplied by 100 to express it as a percentage. A lower PDE conveys a greater similarity between the counts or results of enumeration.

$$Percent\ Difference\ in\ Enumeration\ (PDE) = \frac{|n_1 - n_2|}{n_1 + n_2} \times 100$$

Where: n_1 = the total count in the first sample

n_2 = the total count in the second sample

Note: n is represented by the total count associated with the specification of the target hierarchical level (e.g., family, genus, or species).

Conceptually, performance in enumeration of any discrete level of classification (e.g., individuals per vigor class, decay class, substrate type, among others) might be evaluated with this procedure. Minimum count total requirements may apply depending upon the classification unit of the variable being enumerated.

Percent Taxonomic Completeness (PTC):

It may not always be possible to confirm the identity at a targeted taxonomic or hierarchical level for all specimens or units in a given sample (or within a given sample unit). This can impact the usefulness of estimates of PDE. In such instances, PTC is a metric that may be used to assess the proportion of specimens in a sample or sample unit that taxonomists were able to assign to a pre-determined taxonomic level. PTC is calculated as:

$$Percent\ Taxonomic\ Completeness\ (PTC) = \frac{x}{N} \times 100$$

Where: x = the number of specimens in a given sample correctly assigned to the targeted (or pre-determined) taxonomic level

N = the total number of specimens in a given sample expected to be assigned to the targeted (or pre-determined) taxonomic level

B.5 COMPLETENESS

Completeness is a metric for judging the overall success of a data collection effort with interest in establishing sufficient empirical evidence to test a hypothesis or evaluate the achievement of one or more project sampling objectives. It is most effective when the sampling design is based on using statistical procedures to determine the minimum number of samples (or measurements/observations) needed to achieve a specified level of confidence, or to achieve the sampling precision given the variance in the sampling and measurement process. In other words, assessing completeness is not a substitute for thoughtful sampling design. Percent completeness is calculated as shown below:

$$Percent\ Completeness\ (\%C) = \frac{V}{T} \times 100$$

Where: V = the number of valid measurements or samples ("Valid" refers to measurements, observations, or samples that meet predetermined data quality acceptance criteria)

T = the total number of planned or targeted measurements, observations, or samples for a given sample population (e.g., strata, treatment site, sample period or year)

The goal for completeness should be established during the study design process. As tempting as it may be, setting the completeness goal at 100% is usually counterproductive, since many conditions outside of the control of the project personnel can result in the inability to collect a "valid" measurement or observation. Common examples include persistent poor weather or unsafe conditions, faulty instrumentation, and samples that have been either compromised during transit or held beyond allowable holding times. For projects involving measurements of a large number of parameters (e.g., pollutants, conditions, or physical properties), it is often most efficient to assess completeness at the parameter level. For example, 50 samples (representing either samples collected for laboratory analyses or on-site sample units) analyzed for 20 parameters each means that "T" in the equation above is 1,000. The loss of one of those 50 samples represents 2% of the potential measurements, thus equating to 98% completeness, a completeness goal of 99% is no more achievable than a goal of 100% in this example.

The closer the *%C* is to 1 (or 100%), the greater the compliance of achieving a predetermined (targeted) number of valid samples. Unmet performance in %C can result in not achieving precise estimates in population parameters for a particular site or population of interest, and can impact their representativeness and comparability within and across sites and sample events.

The QA manager may decide to establish performance objectives or data quality acceptance criteria for *%C* depending upon the relative importance of the need for maximizing valid samples; such as individual samples or measurement variables considered necessary to produce unbiased and precise estimates for a multi-metric indicator (e.g., macroinvertebrate IBI, Floristic Quality Indicator). See discussion in Section B.4.2.2, where percent taxonomic completeness (or PTC) represents this type of example.

B.6 DETECTABILITY

Detectability in environmental or ecological monitoring is often represented simply as the sensitivity of an instrument or analytical method to accurately measure the minimum absolute quantity (e.g., limit of detection) of a given organic or inorganic compound, or the ability of an observer (e.g., taxonomist) to accurately distinguish the identity of an organism to its lowest (i.e., most precise*)* level of taxonomic classification. A more complete representation of detectability requires a description of its two principal components: (1) *sensitivity* – the true positive rate or the proportion of correct detections (i.e., true presence) when the condition is positive (e.g., when a species, ecological feature or environmental condition is present), and (2) *specificity* – the true negative rate or the proportion of correct times no detection (i.e., true absence) is determined when the condition is negative (e.g., a given species or ecological feature or condition is truly absent). Respectively, each can be calculated as:

Sensitivity = Sn = True Positive (TP) / (True Positive + False Negative (FN))

Specificity = Sp = True Negative (TN) / (True Negative + False Positive (FP))

Tradeoffs exist, however, when efforts are made to optimize sensitivity over specificity, given that they are inversely proportional (Allouche et al. 2006; Parikh et al. 2008). For example, Groom and Whild (2017), found that false negative errors increased during attempts to reduce the number of false positive observations of plant species reported as result of requiring additional confirmation prior to acceptance.

At a higher level, the lack of precision in detecting true ecological change is perhaps the largest concern for restoration project planners, and highlights the importance of establishing objective criteria such as significance tests and assessment of biologically meaningful effect-size to support effective decision making. No data should be assumed error-free and 100% reliable in their application to support all project decisions. The variability inherent in data precision as well as its accuracy, may lead to decision error that can compromise the ability of project planners in discerning whether their restoration prescriptions were effective in achieving stated restoration goals and objectives. Detectability is an important indicator to data quality, and any imprecision in estimates of its constituent components (Sn and Sp) can contribute to decision error in ecological restoration monitoring. In hypothesis testing, a false positive rate is equivalent to alpha or Type 1 error (1-specificity), and where in contrast, a false negative rate equals beta or Type 2 error (1-sensitivity) (Owusu-Ansah et al. 2016). Refer to **Chapter 7**, **Section 7.2** for additional discussion regarding considerations for assessing detectability.

B.7 REPRESENTATIVENESS AND COMPARABILITY

Representativeness is *"the degree to which the data accurately and precisely represent a characteristic of a population parameter, variation of a property, a process characteristic, or an operational condition"* (EPA 2002). Essentially, poor performance in one or more data quality indicator can directly or indirectly affect the representation of an estimated parameter of an ecological condition or community attribute. **Chapter 2**, **Section 2.8** emphasizes the importance of choosing an appropriate study design and monitoring strategy that incorporates probability-based sampling to measure change in one or more ecological attributes, and that can be considered representative of true change.

Comparability is a qualitative term and expresses the degree to which the data can be compared to or combined with other data collected using similar procedures. Crew training, strict adherence to SOPs, maintenance of all equipment to quality standards, use of consistent reporting units, and systematic assessment of whether QC samples comply with stated performance objectives provide the greatest benefit to QA managers for ensuring that data are comparable within- and between- crews, sites, and time periods for the duration of the monitoring program. Reliance upon a performance-based approach is recommended since it generally requires judicious use of quality performance documentation to support a continual improvement process. This documentation can be referred to at a later time if/when questions arise that may challenge the comparability of project results or outcomes.

B.8 MEASURING REPEATABILITY

In ecological restoration monitoring, it can be tempting to assume that observers or crews trained to implement an identical SOP will generate data comparable in quality sufficient to support stated project goals and objectives (i.e., their intended use). This assumption can also be extended to scientific instrumentation that observers or crews might rely upon to quantify certain parameters, such as dissolved oxygen or pH for a given water sample. Ideally, this assumption should be routinely validated using quantitative methods and analysis of re-measurement (QC) data to document the level of confidence or reliability in making this assumption. For example, observer counts of a discrete variable such as the number of trees with DBH ≥ 5 cm present in a 100 m^2 rectangular plot may have a high level of repeatability when measured (counted) by the same observer, or high reproducibility when counts are conducted by different observers within a short period of time. In contrast, repeatability (and reproducibility) may be considerably reduced as the level of difficulty in enumerating a discrete variable increases, such as counting the number of live basal stems for an abundant shrub species with numerous stems in the same plot size.

The level of uncertainty in data comparability can be further assessed by using a procedure to determine repeatability (within and between observers, crew(s), samples, or procedures). This repeatability determination addresses only the level of agreement in the precision of a sample estimate and not the actual accuracy in the measurements themselves. Repeatability (R) is an index or measure that ranges from 0 to 1.0 where 0 implies that results are least similar and a value of 1.0 implies that results are most similar – and is known also as the *intra-class correlation coefficient* (Krebs 1989, Sokal and Rohlf 1995). In Bartlett and Frost (2008), the intra-class correlation (ICC) coefficient is described as a "reliability parameter" that is a dimensionless quantity difficult to interpret at what value should it be considered representative of high reliability.

The method of calculating R relies upon analysis of variance (ANOVA) procedures (described in detail in most textbooks on statistical applications) to partition the sums of squares (SS) and mean squares (MS) for "within" a sample of repeated measurements collected by a specific observer, crew or procedure, and "between" (among or across) different samples of repeated measurements collected by different observers, crews or procedures. See Koo and Mae (2016) for additional guidance in the use and reporting of ICC results as a measure of reliability. Repeatability as presented in Krebs (1989), is calculated as shown below:

$$Repeatability\ (R) = \frac{S_A^2}{S_A^2 + S_E^2}$$

Where: S_A^2 = Variance between samples (i.e., repeated measurements or observations obtained by different observers, crews, groups or procedures)

S_E^2 = Variance within a sample (i.e., repeated measurements or observations obtained by the same observer, crew, groups or procedures)

Where: $$S_A^2 = \frac{MS_{(\text{between samples})} - MS_{(\text{within a sample})}}{n_0}$$

$$S_E^2 = MS_{(\text{within a sample})}$$

Note: Estimates for $MS_{(between\ samples)}$ and $MS_{(within\ a\ sample)}$ are derived by calculating the sums of squares (SS) and mean square (MS) for each, and can also be obtained directly from the respective error source presented in the ANOVA table results.

And, where: $$n_0 = \frac{1}{a-1}\left(\sum n_i - \frac{\sum n^2{}_i}{\sum n_i}\right)$$

n_0 = A coefficient representing the effective sample size per group

a = Number of distinct units or samples that are re-measured

n_i = Total number of re-measurements (for all observers, crews, groups or procedures) collected on unit *i*

Notes: 1) The effective sample size per group (n_0) is determined by multiplying the quotient of 1/(a-1) times the result of the sum of the total number of re-measurements on unit i (n_i) minus the result of dividing the sum of the total number of re-measurements squared ($n_i{}^2$) by the sum of the total number of re-

measurements (n_i). 2) Repeatability is a measure of the proportion of variance in the data that occurs between samples; when R = 1.0, variance within a sample or group will be equal to zero and measurements are perfectly repeatable (Krebs 1989).

95% Confidence Interval (CI) of repeatability – CI of R

Since R is an estimate of a parameter, equations are provided to estimate a 95% confidence interval around *R* in order to determine the precision of the estimate (Bartlett and Frost 2008), and can be useful when evaluating the significance between repeated trials to assess the significance of improvement in repeatability over time. The following CI equations are drawn from Krebs (1989).

$$R_L = 1 - \frac{n_0 MS_{(\text{within samples})} F}{MS_{(\text{between samples})} + MS_{(\text{within a sample})}(n_0 - 1)F}$$

Where: F = Critical value from F-distribution table for α/2 level of confidence (e.g., $F_{.025}(n_1, n_2)$ when α = 0.05) with n_1 = a – 1 degrees freedom and $n_2 = \sum(n_i - 1)$

$$R_U = 1 - \frac{n_0 MS_{(\text{within samples})} F}{MS_{(\text{between samples})} + MS_{(\text{within a sample})}(n_0 - 1)F}$$

Where: F = Critical value from F-distribution table for 1 – α/2 level of confidence (e.g., $F_{.975}(n_1, n_2)$ when α = 0.05) with n_1 = a – 1 degrees freedom and $n_2 = \sum(n_i - 1)$

Notes: 1) Confidence interval limits may not be symmetrical around R. 2) The lower (R_L) and upper (R_U) limits for the ninety-five percent confidence interval for repeatability are determined by subtracting from one, the result of the numerator [(n_0 x $MS_{(\text{within a sample})}$ x F)] *divided by the denominator* [($MS_{(\text{between samples})}$ + ($MS_{(\text{within a sample})}$ x (n_0 – 1) x F)].

B.9 ADDITIONAL READINGS

- Gitzen, Robert A., Joshua J. Millspaugh, Andrew B. Cooper and Daniel S. Licht. 2014. *Design and Analysis of Long-term Ecological Monitoring Studies (First Ed.)*. Cambridge, United Kingdom: Cambridge University Press.
- Michell, Joel. 1999. *Measurement in Psychology: A Critical History of a Methodological Concept*. New York, NY: Cambridge University Press.
- Sang Gyu Kwak and Jong Hae Kim. 2017. "Central Limit Theorem: The Cornerstone of Modern Statistics." *Korean J Anesthesiology*, 70 (2): 144–156. doi: 10.4097/kjae.2017.70.2.144.

- Stapanian Martin A., Forest C. Garner, Kirk E. Fitzgerald, George T. Flatman, and John M. Nocerino. 1993. “Finding Suspected Causes of Measurement Error in Multivariate Environmental Data.” *Journal of Chemometric*s, 7 (3): 165-176. doi: 10.1002/cem.1180070304.
- Tilmann, Deutler. 1991. Grubbs-Type Estimators for Reproducibility Variances in an Interlaboratory Test Study. *Journal of Quality Technology*, 23:4, pages 324-335.
- U.S. Environmental Protection Agency. 2004. *Wadeable Stream Assessment: Benthic Laboratory Methods*. Publication No. EPA 841-B-04-007. Washington, D.C.: Office of Environmental Information.
- U.S. Environmental Protection Agency. 2008. *National Rivers and Streams Assessment: Laboratory Methods Manual*. Publication No. EPA-841-B-07-010. Washington, D.C.: Office of Environmental Information.
- Wolak, Matthew E., Daphne J. Fairbairn, and Yale R. Paulsen. 2012. "Guidelines for Estimating Repeatability.” *Methods in Ecology and Evolution*, 3:129–137. doi: 10.1111/j.2041-210X.2011.00125.x.

B.10 APPENDIX B REFERENCES

Allouche, Omri, Asaf Tsoar, and Ronen Kadmon. 2006. “Assessing the Accuracy of Species Distribution Models: Prevalence, Kappa and the True Skill Statistic (TSS).” *Journal of Applied Ecology*, 43 (6): 1223–1232. doi: 10.1111/j.1365-2664.2006.01214.x.

Bartlett, Jonathan W. and Chris Frost. 2008. “Reliability, Repeatability and Reproducibility: Analysis of Measurement Errors in Continuous Variables.” *Ultrasound Obstetrics & Gynecology*, 31: 466–475. doi: 10.1002/uog.5256

Bland J. Martin, and Douglas G. Altman. 1986. “Statistical Methods for Assessing Agreement between Two Methods of Clinical Measurement.” *Lancet,* 327 (8476): 307-310. doi: 10.1016/S0140-6736(86)90837-8.

Carlberg, Conrad. 2014. *Statistical Analysis with Microsoft Excel 2013: About Variables and Values.* Que Publishing, Indianapolis, Indiana.

Conover, William J. 1999. *Practical Nonparametric Statistics (3rd Edition*). John Wiley & Sons, New York, NY.

Devore, Jay L. 2012. *Probability and Statistics for Engineering and the Sciences (Eighth Edition)*. Electronic Version. Brooks/Cole, Boston, MA.

Duncan, R. Luce, David H. Krantz, Patrick C. Suppes, Amos Tversky. 2006. *Foundations of Measurement Volume III: Representation, Axiomatization, and Invariance.* Dover Publications, Mineola, New York.

Flotemersch, Joseph E., James B. Stribling, and Michael J. Paul. 2006. *Concepts and Approaches for the Bioassessment of Non-wadeable Streams and Rivers.* EPA 600-R-06-127. US Environmental Protection Agency, Cincinnati, Ohio.

Groom, Quentin J. and Sarah J. Whild. 2017. "Characterisation of False-positive Observations in Botanical Surveys." *PeerJ,* 5:e3324. doi: 10.7717/peerj.3324.

Koo, Terry K. and Mae Y Li. 2016. "A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research." *Journal of Chiropractic Medicine,* 15 (2): 155-63. doi:10.1016/j.jcm.2016.02.012.

Krebs, Charles J. 1989. *Ecological Methodology*. Harper, New York, NY.

Mangiafico, Salvatore S. 2016. *Summary and Analysis of Extension Program Evaluation in R, version 1.1.1.* Rutgers Cooperative Extension, New Brunswick, NJ. Online: rcompanion.org/handbook/.

McDonald, John H. 2014. *Handbook of Biological Statistics (3rd. Ed.).* Sparky House Publishing, Baltimore, MD. Online: http://www.biostathandbook.com/HandbookBioStatThird.pdf.

Michell, Joel. 1986. "Measurement Scales and Statistics: A Clash of Paradigms." *Psychological Bulletin*, 100 (3): 398-407. doi: 10.1037/0033-2909.100.3.398

Owusu-Ansah, Emmanuel D.J., Angelina Sampson, Amponsah K. Samuel, and Abaidoo Robert. 2016. "Sensitivity and Specificity Analysis Relation to Statistical Hypothesis Testing and Its Errors: Application to Cryptosporidium Detection Techniques." *Open Journal of Applied Sciences*, 6 (4): 209-216. doi: 10.4236/ojapps.2016.64022.

Parikh, Rajul, Annie Mathai, Shefali Parikh, G Chandra Sekhar, and Ravi Thomas. 2008. "Understanding and Using Sensitivity, Specificity and Predictive Values." *Indian J Ophthalmology,* 56 (1): 45-50. doi: 10.4103/0301-4738.37595.

Stapanian, Martin A., Timothy E. Lewis, Craig J. Palmer, Molly M. Amos. 2016. "Assessing Accuracy and Precision for Field and Laboratory Data: A Perspective in Ecosystem Restoration." *Restoration Ecology,* 24 (1): 18-26. doi: 10.1111/rec.12284.

Sokal, Robert R. and James F. Rohlf. 1995. *Biometry the Principles and Practice of Statistics in Biological Research*, 3rd ed. W. H. Freeman and Company, New York.

Stevens, Stanley S. 1946. "On the Theory of Scales of Measurement." *Science*, 103: 677-680. doi: 10.1126/science.103.2684.677.

Stevens, Stanley S. 1951. "Mathematics, Measurement, and Psychophysics." In S.S. Stevens (Ed.), *Handbook of experimental psychology*. John Wiley, New York.

Stribling, James B., Kristen L. Pavlik, Susan M. Holdsworth, Erik W. Leppo. 2008. "Data Quality, Performance, and Uncertainty in Taxonomic Identification for Biological Assessments." *Journal of the North American Benthological Society,* 27 (4): 906-919. doi: 10.1899/07-175.1.

Stribling, James B. 2011. “Partitioning Error Sources for Quality Control and Comparability Analysis in Biological Monitoring and Assessment.” In *Modern Approaches to Quality Control*, edited by Ahmed Badr Eldin, 59-84. doi: 10.5772/22388.

U.S. Environmental Protection Agency. 2002. *Overview of the EPA Quality System for Environmental Data and Technology*. Publication No. EPA/240/R-02/003. Washington, DC: Office of Environmental Information.

U.S. Environmental Protection Agency. 2006. *Data Quality Assessment: Statistical Methods for Practitioners (EPA QA/G-9S*). Publication No. EPA/240/B-06/003. Washington, DC: Office of Environmental Information.

U.S. Environmental Protection Agency. 2012. *National Lakes Assessment: Laboratory Operations Manual (Version 1.1 October 9, 2012)*. Publication No. EPA-841-B-11-004. Washington, DC: Office of Water.

Velleman, Paul F. and Leland Wilkinson. 1993. “Nominal, Ordinal, Interval, and Ratio Typologies are Misleading.” *The American Statistician,* 47 (1): 65-72. doi: 10.2307/2684788.

Walpole, Ronald E., Raymond H. Myers, Sharon L. Myers, and Keying Ye. 2012. *Probability and Statistics for Engineers and Scientists (Ninth Edition)*. Prentice Hall, Boston, MA.

Walther, Bruno A. and Joslin L. Moore. 2005. “The Concepts of Bias, Precision and Accuracy, and their Use in Testing the Performance of Species Richness Estimators, with a Literature Review of Estimator Performance.” *Ecography,* 28 (6): 815-829. doi: 10.1111/j.2005.0906-7590.04112.x.

Westfall, James A. 2009. *FIA National Assessment of Data Quality for Forest Health Indicators*. General Technical Report NRS-53., U.S. Department of Agriculture Forest Service, Northeast Research Service, Newtown Square, PA.

Wilkinson, Leland, Grant Blank, and Christian Gruber. 1996. *Desktop Data Analysis with Systat*. Prentice Hall, Upper Saddle River, NJ

Zar, Jerrold H. 2010. *Biostatistical Analysis (5th Edition).* Pearson Prentice-Hall, Upper Saddle River, NJ.

Appendix C

APPENDIX C: QUALITY ASSURANCE PROJECT PLAN (QAPP) TEMPLATE FOR ECOLOGICAL RESTORATION PROJECTS

This template was created as a tool to assist with the development of quality assurance project plans (QAPPs) for projects focused on ecological restoration and the control of invasive species. It contains an outline of the major sections of a QAPP, based on EPA Requirements for Quality Assurance Project Plans *(EPA QA/R-5), EPA/240/B-01/003, March 2001*, some of which have been revised for the purposes of this template, based on strategies described in the Application of QA/QC Principles to Ecological Restoration Project Monitoring (referred to herein as the "IERQC Guidance") to better fit the needs of projects involving ecological restoration and/or control of invasive species. Each section summarizes suggested topics for users to include in their QAPP. Additional resources include: (1) example tables to help clearly present quality assurance (QA) and quality control (QC) approaches, (2) example text to assist with certain topics, (3) a table at the end of each section citing locations within the IERQC Guidance where more details can be found, and (4) helpful tips for consideration. Please note that the items listed in the IERQC Guidance Reference tables are based on Appendix D, Quality Assurance Project Plan Checklist for Ecological Restoration Projects. Items not covered in the IERQC Guidance are noted in the table.

Users of this QAPP template must consult EPA QA/R-5, or the more general Guidance for Quality Assurance Project Plans *(EPA QA/G-5), EPA/240/R-02/009, December 2002*, as needed to obtain additional details and guidance for development of a QAPP. Instances where the IERQC Guidance and EPA QA/R-5 differ in the use of specific terms are noted in this template.

Examples provided are for illustrative purposes only and may not apply directly to any specific project. The tables provided are meant to assist users; they are optional and can be edited to fit specific project needs. Project planners should ensure the application of QA/QC approaches are commensurate with factors such as project objectives, risks associated with decision errors, resources, and schedules. Any information provided in this template or the IERQC Guidance (including associated appendices) do not supersede requirements specified in EPA QA/R-5.

Acknowledgments:

This QAPP template was prepared by CSRA LLC under EPA contracts with the direction of Louis Blume, Quality Manager of EPA Great Lakes National Program Office.

DRAFT

QUALITY ASSURANCE PROJECT PLAN

Title of Project (or portion of project addressed by this QAPP)

Prepared for:

<*Enter the contact information including affiliation and physical address*>

Contract/WA/Grant No./Project Identifier <*Enter specific identifier*>

Prepared by:

<*Enter the contact information including affiliation and physical address*>

<*Enter date*>

<*Enter Version #*>

SECTION A – PROJECT MANAGEMENT

A.1 TITLE OF PLAN AND APPROVAL

Quality Assurance Project Plan

<Enter Title of Project>

Prepared by:

<Enter Affiliation>

____ Date: _______________
<*Enter name, Organization*>, Project Manager / Principal Investigator

____ Date: _______________
<*Enter name, Organization*>, Quality Assurance Manager (or equivalent)

____ Date: _______________
<*Enter additional contacts, as needed with names, organizations, titles or positions*>

____ Date: _______________
<*Enter name*>, US EPA, Project Officer

____ Date: _______________
<*Enter name*>, US EPA, Quality Assurance Manager

A.2 TABLE OF CONTENTS

<TOC must be regenerated upon completion of QAPP content>

Section A – Project Management 2
A.1 Title of Plan and Approval 2
A.2 Table of Contents 3
A.3 Distribution List 5
A.4 Project/Task Organization 5
A.5 Problem Definition/Background 5
A.6 Project/Task Description 6
A.7 Quality Objectives and Criteria for Measurement Data 7
A.8 Special Training Requirements or Certifications 8
A.9 Documents and Records 10
Section B – Data Generation and Acquisition 11
B.1 Sampling/Measurement Design 11
B.2 Field Data Collection and Sampling Method Requirements 11
B.3 Sample Handling and Custody Requirements 12
B.4 Laboratory Analytical Methods Requirements 12
B.5 Quality Control Requirements 13
B.6 Instrument/Equipment Testing, Inspection and Maintenance 13
B.7 Instrument/Equipment Calibration and Frequency 14
B.8 Inspection/Acceptance for Supplies and Consumables 14
B.9 Non-Direct Measurements 14
B.10 Data Management 15
Section C – Assessment and Oversight 16
C.1 Assessment and Response Actions 16
C.2 Reports to Management 16
Section D – Data Validation and Usability 17
D.1 Data Review, Verification and Validation Planning 17
D.2 Verification and Validation Methods 17
D.3 Reconciliation with User Requirements 18
Tables 19

Table C1. Roles and Responsibilities 19
Table C2. Project Schedule Timeline 19
Table C3. Target Variables for Field Measurement or Observation 19
Table C4. Data Quality Acceptance Criteria for Precision, Bias and Accuracy for Field Observations/Measurements 19
Table C5. Sampling Locations 20
Table C6. Standard Operating Procedures 20
Table C7. Sampling QC 20
Table C8. Analytical QC 21
Table C9. Reports 21
Exhibits 22
Exhibit 1. Types of QC Field Checks 22

Appendices

<*insert a list of appendices*>

A.3 DISTRIBUTION LIST

List the individuals and their associated organizations and titles that need copies of the approved QAPP and any subsequent revisions, including all persons responsible for implementation (e.g., project managers), QA managers, and representatives of all groups involved. This includes EPA roles.

IERQC Guidance References

Topic	IERQC Guidance
Distribution list	*This topic is not addressed in the IERQC Guidance*

A.4 PROJECT/TASK ORGANIZATION

Identify the individuals or organizations participating in the project and discuss their specific roles and responsibilities. Include the principal data users, the decision makers, the project QA manager, and all persons responsible for implementation. The Project QA manager position must indicate independence from the unit collecting and/or using the data. If this independence is not feasible, an explanation must be provided. Please refer to **Chapter 1**, **Exhibit 1-3** of the IERQC Guidance for a list of potential QA roles and responsibilities. (See **Table C1** of this template for an example table to present this information.)

Provide a concise organizational chart showing the relationships and the lines of communication among all project participants, including EPA. The organization chart must also identify any subcontractor relationships relevant to environmental data operations, including laboratories providing analytical services. (See Figure 3 of EPA QA/G-5 and **Chapter 1**, **Exhibit 1-2** of the IERQC Guidance for an example organizational chart.)

IERQC Guidance References

Topic	IERQC Guidance
Identifying key individuals	**Section 1.6**
Organizational chart	**Exhibit 1-2**
Independent Project QA Manager	**Exhibits 1-2** and **1-3**

A.5 PROBLEM DEFINITION/BACKGROUND

Describe: (1) the specific problem to be resolved, including sufficient background information that provides the historical, scientific and regulatory perspective for this particular project; and (2) the overall restoration project goal(s). More specific information, including suggested content, is provided below.

- Provide historical and background information, including the:
    - project location, boundaries, and ownership;
    - targets of restoration (e.g., ecosystems, natural communities, rare or protected species);
    - threats, need for restoration, and desired state and anticipated benefits from a successful project;
    - current condition of the site;
    - social, political, and physical context of the project; and
    - expectations from funding sources, stakeholders, and project staff.
- Include the overall restoration project goal(s), including the:

- subject or resource of concern (e.g., the particular species, biotic community, ecosystem process, ecosystem service, habitat type);
- attribute of interest for that subject or resource (e.g., species diversity, population size, functioning of an ecosystem process);
- conceptual target or condition for that attribute (e.g., optimum, proper, natural, maximum); and
- action(s) or effort(s) to be made relative to the target (e.g., restore, provide, achieve).

Example restoration project goal: Restore native wet prairie plant species cover to improve floristic quality on a 15-acre wet prairie degraded by historic drainage and invasive reed canarygrass, *Phalaris arundinacea*.

IERQC Guidance References

Topic	IERQC Guidance
Problem to be resolved	**Section 3.1**
Restoration project goals	**Section 3.1**

A.6 PROJECT/TASK DESCRIPTION

Provide a summary of work to be performed, products to be produced, and the schedule for implementation (See **Table C2** for an example table to present the project timeline). Include maps of the project area with pertinent information, such as site boundaries and land management areas. Based on overall restoration project goal(s) established in Section A.5 Problem Definition/Background, define restoration project objectives that are specific, measurable, achievable, results-oriented, and time-sensitive (SMART).

Refer to **Chapter 3**, **Exhibit 3-2** of the IERQC Guidance for examples of restoration project goals and corresponding SMART project objectives. Also, briefly describe any required regulatory permits (e.g., landowner, National Environmental Policy Act (NEPA), National Historic Preservation Act (NHPA)) for restoration activities or subsequent monitoring activities (e.g., wildlife or fish sampling permits, soil sampling permits).

Example restoration project objective that supports the example restoration project goal listed in Section A.5 Problem Definition/Background: Reduce total cover of reed canarygrass to less than 10% across the 15-acre wet prairie after four years.

IERQC Guidance References

Topic	IERQC Guidance
Restoration project objectives	**Section 3.2**
Required regulatory permits	**Section 4.3**
Map(s) of project area	**Section 4.3**; **Exhibit 4-2**
Work schedule	**Sections 3.2** and **4.3**; **Exhibit 4-6**

A.7 QUALITY OBJECTIVES AND CRITERIA FOR MEASUREMENT DATA

Based on the restoration project objectives established in Section A.6 Project Task/Definition, identify sampling objectives used to develop the project's monitoring or sampling plan. Discuss the data quality indicators (DQIs) for each observation or measurement and the associated acceptance criteria needed to achieve the sampling objectives.

Note: If available, it is strongly recommended that project teams consult with an experienced statistician for assistance in defining sampling objectives. Steps for determining data quality acceptance criteria for DQIs are provided below, but also refer to **Chapter 3**, **Section 3.3** of the IERQC Guidance for more details.

A Check on Terminology	
Term in EPA QA/R-5	**Equivalent Term in the IERQC Guidance**
Overarching goal(s)	Restoration project goal(s)
Project objectives	Restoration project objectives
Data quality objectives	Sampling objectives
Data quality indicators	Data quality indicators
Measurement quality objectives	Data quality acceptance criteria (e.g., tolerance plus compliance rate) objective

Example sampling objective that supports the example restoration project objectives listed in Section A.6 Project Task/Definition: Assess whether the total cover of reed canarygrass has been reduced to less than 10% across the 15-acre wet prairie after four years (and demonstrate with 80% certainty a reduction in total cover to less than 5%), with a 5% chance (α) of incorrectly concluding that the percent cover has decreased to below 10% when in fact it did not. **Note:** This example may not apply to projects not using a statistically-based study design.

The steps for determining data quality acceptance criteria for DQIs for observations or measurements are:

1. Based on restoration project objectives and associated sampling objectives, list and describe each planned observation or measurement and its units for data collection (e.g., cm, species codes, plant cover classes). Consider defining these variables as primary or ancillary (see **Chapter 6**, **Section 6.1.3.1** of the IERQC Guidance for more detail). (See **Table C3** for an example table to document this information.)
2. For each of these primary (or important ancillary) observations or measurements, identify the DQIs (i.e., precision, bias, accuracy, representativeness, comparability, completeness and detectability) that will be used to evaluate results (e.g., precision for measurements of length of a sample, percent accuracy for identification of a species, percent agreement between duplicate measurements of plant cover classes, percent completeness for collection of valid data). **Chapter 2**, **Exhibit 2-3** of the IERQC Guidance details each DQI.
3. State the acceptance criterion associated with each DQI. The acceptance criteria for precision, bias, accuracy, detectability and completeness will include a tolerance and an associated compliance rate (see **Chapter 3**, **Exhibits 3-5** and **3-7** of the IERQC Guidance for examples), whereas representativeness and comparability do not include a tolerance and, in some cases, are more qualitative in design (see **Chapter 3**, **Exhibits 3-6** and **3-7** of the IERQC Guidance for examples). These acceptance criteria should be stringent enough to control measurement error while also being achievable by properly trained staff using well-defined procedures.

4. Consider how each DQI and its associated acceptance criterion will be evaluated (e.g., readiness reviews after crew trainings on calibration plots; plot revisits as cold checks, blind checks or precision checks within a specified timeframe since original plot visit; independent re-measurements during hot checks). **Chapter 5**, **Exhibit 5-7** of the IERQC Guidance provides a helpful resource for determining which QC field checks are relevant and appropriate. An in-depth description is not necessary in this section since it is generally covered in Section B.5 Quality Control Requirements, but some basis for how each DQI will be assessed (e.g., type of QC check, an equation, brief narrative) should be included.

Please refer to **Chapter 3**, **Exhibit 3-7** of the IERQC Guidance for a more detailed, stepwise procedure, and **Table C4** for an example table to document the acceptance criteria for field measurements and observations for each DQI. **Table C4** is designed to capture precision, bias and accuracy. Representativeness, comparability, completeness and detectability can be captured separately as needed.

This section of the QAPP also should discuss DQIs for field and laboratory QC samples and the associated measurement quality objectives (MQOs) needed to achieve the sampling objectives. Please refer to Section 2.1.7 of EPA QA/G-5 for more information regarding the application of MQOs. If the project does not include field and laboratory QC samples, then these instructions can be ignored.

IERQC Guidance References

Topic	IERQC Guidance
Sampling objectives	**Section 3.3**
Planned observations or measurements	**Sections 3.3** and **3.4**
Measurement units	**Section 3.4**; **Exhibit 3-7**
DQIs for observations or measurements	**Sections 2.5** and **3.4**
Acceptance criteria	**Section 3.4**
Evaluating DQIs	**Sections 3.4**, **5.2**, and **5.3** (See **Section 5.2** for more detail on QC Field Checks)

A.8 SPECIAL TRAINING REQUIREMENTS OR CERTIFICATIONS

Identify and describe any special licenses, training, crew competency requirements, and/or certification (e.g., herbicide application, prescribed burn, taxonomic classification, GPS use, boat safety, drone operation) needed by personnel in order to successfully complete the project or task. Discuss how such training will be provided and how the necessary skills will be assured and documented. Describe the strategy for training and certification of replacement staff, if needed. Briefly discuss how training records will be documented and where they will be stored.

Helpful Tip

Observer-determined data can be subjective and variable by their nature. Training is particularly important for these data since they do not rely on a calibrated piece of equipment.

IERQC Guidance References

Topic	IERQC Guidance
Special licenses, training, crew competency requirements, and/or certification	**Section 4.2**
Training documentation	*This topic is not addressed in the IERQC Guidance*

A.9 DOCUMENTS AND RECORDS

Describe the process and responsibilities for ensuring the appropriate project personnel have the most current approved versions of project documentation, including relevant standard operating procedures (SOPs), data forms, and the QAPP. Include procedures for version control, updates, distribution, and disposition.

Itemize the information and records that must be included in data report packages and specify the reporting format for hard copies and any electronic forms. Records can include raw data, data from other sources such as data bases or literature, field logs, sample preparation and analysis logs, instrument printouts, model input and output files, and results of calibration and QC checks.

Specify or reference all applicable requirements for the final disposition of records and documents, including the location and length of retention period.

Guidance Document References

Topic	IERQC Guidance
Data report contents	**Section 7.5**
Retention time and location for records and reports	**Appendix A**, **Sections A.1.2** and **A.5**

SECTION B – DATA GENERATION AND ACQUISITION

B.1 SAMPLING/MEASUREMENT DESIGN

For measurements or observations being collected, describe the target population, sampling units (area, shape or volume), sample size to achieve sampling objectives, sampling design, and the rationale for the approach. Identify backup sites as alternate sampling locations (or plans for alternate sites) if conditions prevent sampling at original sites. Include the collection of any field samples and their coordinates (**Table C5**).

> **Helpful Tip**
>
> **In addition to a table with coordinates for proposed and alternate sampling locations, consider including a map displaying this information.**

Example sample design: For the 15-acre wet prairie restoration area (target population), we will evaluate 1-meter by 1-meter quadrats (sampling units) at 30 locations (sample size). Quadrats will be placed systematically on three N/S and three E/W transects identified in a stratified random manner (sampling design) to capture all vegetation zones at the site.

IERQC Guidance References

Topic	IERQC Guidance
Observations and measurements and/or sampling and rationale	**Section 3.3**
Selection of backup/alternate sampling locations	**Section 4.3**, **Exhibit 4-7**

B.2 FIELD DATA COLLECTION AND SAMPLING METHOD REQUIREMENTS

Describe or reference the SOPs for each field observation or measurement (e.g., species identification, ground cover estimates, GPS, photographs, sound recordings) and each sample or voucher collection procedure. (See **Table C6** for an example table to present this information.) Refer to **Chapter 4 Section 4.1.2** and **Exhibit 4-1** of the IERQC Guidance for more detail on recommended content for SOPs.

For field sample collection methods, identify:

- the number of samples to be collected and approximate sampling dates,
- implementation requirements, and
- sample preservation requirements.

For field observations or measurements and sample collection methods, provide sufficient detail so that procedures can:

- be performed consistently by multiple individuals and over long periods of time (both within and, where applicable, across projects);
- provide a basis for training project staff;
- provide tools for crews to use such as field sample collection forms, equipment, and supply lists;
- serve as references if confusion arises in the field or during data transfer, reduction, review, extraction or analysis; and
- serve as references to data users.

Describe specific performance requirements for each method, including:

- how to address a failure in the sampling or field measurement method,
- who will be responsible for the corrective action, and
- how the effectiveness of the corrective action will be evaluated and documented.

IERQC Guidance References

Topic	IERQC Guidance
Data collection methods for each field observation, measurement, and/or sample	**Sections 4.1** and **4.3**; **Appendix A**, **Section A.2.1**
Field sample collection equipment, and on-site supply lists	**Section 4.3**
Individuals responsible for corrective action	*This topic is not addressed in the IERQC Guidance*

B.3 SAMPLE HANDLING AND CUSTODY REQUIREMENTS

Describe the sample handling (e.g., labeling, field processing, shipment) and sample control (tracking, such as chain of custody) requirements for samples and voucher specimens.

IERQC Guidance References

Topic	IERQC Guidance
Sample handling and control requirements	**Section 4.3**; **Exhibit 5-1**; **Appendix A**, **Section A.2.4**

B.4 LABORATORY ANALYTICAL METHODS REQUIREMENTS

If laboratory analytical methods or equipment are needed:

- identify all such methods (e.g., provide method citations, provide step-by-step procedures, or append the methods to the QAPP) and equipment;
- state method performance criteria;
- identify the laboratories selected (or explain how they will be selected);
- state the requested laboratory turnaround time;
- identify all procedures that should be followed if failures occur; and
- identify all individuals responsible for corrective actions and appropriate documentation of the problem, including its ultimate solution.

IERQC Guidance References

Topic	IERQC Guidance
Arranging for laboratory analyses	**Section 4.4**

B.5 QUALITY CONTROL REQUIREMENTS

For each data collection activity, describe the QC checks or samples used to evaluate the data collection activity (including the frequency of the QC check or sample), the acceptance criteria for each type of QC check or sample and any planned corrective actions (if the acceptance criteria are not achieved).

For field observations and measurements, examples of QC checks include precision, hot, cold, blind and calibration (see **Exhibit 1** for more description of each).

> **Helpful Tip**
>
> **In addition to establishing compliance with data quality acceptance criteria, QC checks are a means to assess (1) adherence with SOPs, (2) measurement error arising from variability in the sample collection efforts, and (3) calibration of observers and equipment.**

For field QC samples, examples include field blanks, spikes, reference samples, and replicates or split samples. (See **Table C7** for an example table that shows how this information can be presented.)

For laboratory QC samples, examples include laboratory blanks, spikes, calibration controls, and replicates or split samples. (See **Table C8** for an example table that shows how this information can be presented.)

IERQC Guidance References

Topic	IERQC Guidance
Field QC checks	**Section 5.2**
Laboratory QC procedures, frequency, acceptance criteria, and corrective actions	**Section 4.4**

B.6 INSTRUMENT/EQUIPMENT TESTING, INSPECTION AND MAINTENANCE

List all instruments/equipment that will be used, and indicate any instruments/equipment that will require periodic maintenance, inspection, or testing. Describe how inspections and testing of instruments/equipment will be performed and documented to assure the intended use is appropriate for the project. Include the frequency of and individuals who will be responsible for these inspections. Describe how critical spare parts will be supplied and stocked.

Describe how deficiencies are to be resolved, when re-inspections will be performed, and how the effectiveness of the corrective actions will be determined and documented.

Example equipment testing: GPS units will be tested for accuracy on a daily basis with the use of a control point that has an established longitude and latitude. If a control point is not available at or near the project site, a reference point will be established that can be easily located using aerial photography. If accuracy is found to exceed the acceptance criterion of 10 feet, retesting will occur and/or further inspection of the unit will take place until the acceptance criterion is achieved. The team lead will troubleshoot the unit as needed. All test results and corrective actions will be recorded in the field log book.

IERQC Guidance References

Topic	IERQC Guidance
Acceptance testing of sampling and measurement systems	*These topic are not addressed in the IERQC Guidance*
Equipment maintenance and frequency	
Responsible individuals	

B.7 INSTRUMENT/EQUIPMENT CALIBRATION AND FREQUENCY

Identify all instruments/equipment, for either field or laboratory use, that need calibration. Include the calibration method, frequency for such calibration, and how calibration records will be maintained.

Example field instrument calibration: For the multi-parameter water quality meter, probes will be calibrated daily prior to each sampling event: temperature- traceable thermometer; dissolved oxygen – one-point saturated air method; pH- pH 4,7,10 buffers; and specific conductivity – two-point method using air to establish zero point and a 1 mS cm^{-1} conductivity standard. Crews will record calibration results on data entry sheets and these will be maintained by the project leader.

IERQC Guidance References

Topic	IERQC Guidance
Equipment calibration and frequency	*This topic is not addressed in the IERQC Guidance*

B.8 INSPECTION/ACCEPTANCE FOR SUPPLIES AND CONSUMABLES

Identify acceptance criteria for restoration supplies (e.g., expiration dates and dilution ratios for applied chemicals) and indicate who will be responsible for evaluation and acceptance of these supplies.

IERQC Guidance References

Topic	IERQC Guidance
Acceptance criteria for supplies	**Section 4.3**

B.9 NON-DIRECT MEASUREMENTS

Identify the type, source and intended use of the existing data needed. Define the data quality acceptance criteria to evaluate whether these data are acceptable for use. For example, if historical rainfall data are needed for the project, NOAA's climate database could be the data source and the acceptance criteria (or search criteria) could define the time period, location, and necessary metadata. Keep in mind that the acceptance criteria should reflect the overall quality needs of the project.

Helpful Tip

Non-Direct measurements (commonly referred to as secondary or existing data) include any data that are not directly generated as part of the project; see Chapter 3, Exhibit 3-8 of the Guidance for a list of existing data examples.

IERQC Guidance References

Topic	IERQC Guidance
Data needs	**Section 3.5**
Planned data sources	
Acceptance criteria for data selection and use	

B.10 DATA MANAGEMENT

Describe the data management scheme from generation to final use or storage. This includes any existing data previously discussed in Section B.9 Non-Direct Measurements.

Describe methods for minimizing errors in recording, transcribing, and entering data into data forms or electronic files; conducting file backups; archiving data; storing data sheets or field files; and sharing or publishing data.

Describe data handling equipment (e.g., computer hardware and software) and procedures used to process and compile data (e.g., management of GPS data and photo files).

Include any forms or checklists that will be used (e.g., field forms, analytical bench sheets, chain-of-custody forms).

IERQC Guidance References

Topic	IERQC Guidance
Data management scheme from generation or acquisition to final use or storage	**Section 3.5**; **Appendix A**, **Sections A.2** through **A.6**
Minimizing errors in data records	**Appendix A**, **Sections A.1.3** and **A.8**
Data handling equipment	**Appendix A**, **Section A.1.2**
Forms or checklists	**Exhibits 4-9** and **5-3**; **Appendix A**, **Section A.2.2**

SECTION C – ASSESSMENT AND OVERSIGHT

C.1 ASSESSMENT AND RESPONSE ACTIONS

EPA QA/R-5 describes various types of assessments (e.g., surveillance, management systems reviews, readiness reviews, technical systems audits, performance evaluations, audits of data quality, and data quality assessments) that can be conducted during a project. Personnel may conduct any of these assessments to support their ecological restoration projects. The purpose of this section is to describe what assessments are planned, when and how they will be implemented, and how the information collected from these assessments will be evaluated.

> **Helpful Tip**
>
> **A debriefing at the end of a field season or data collection effort is recommended to obtain valuable feedback from the field personnel's point of view. See Chapter 5, Section 5.3.2 of the IERQC Guidance for more details.**

Describe response actions to each assessment, including how corrective actions will be addressed, verified, documented, and communicated to management or other decision makers. Identify the individual(s) responsible for corrective actions.

IERQC GUIDANCE REFERENCES

Topic	IERQC Guidance
Type of assessment	*This topic is not addressed in the IERQC Guidance*
Timing and frequency of assessment	
Use of assessment results	

C.2 REPORTS TO MANAGEMENT

Identify the frequency, content, and distribution of reports per requirements established in the funding agency's agreement or other project documentation. Identify who is responsible for writing and reviewing these reports (consider using an independent reviewer). Types of reports include, but are not limited to, internal, periodic, publications, and final. (See **Table C9** for an example table to present this information.)

IERQC GUIDANCE REFERENCES

Topic	IERQC Guidance
Preparer and recipient of reports	**Exhibit 1-3**
Frequency, content, and distribution of reports	**Section 7.5**

SECTION D – DATA VALIDATION AND USABILITY

D.1 DATA REVIEW, VERIFICATION AND VALIDATION PLANNING

Describe the planned data review process. Include the timing of the review, what data will be reviewed, and how results will be documented. Also, list the criteria for accepting, rejecting, or qualifying each data type that will be part of the review process. Each component of the project for which criteria were listed previously (in the data generation and acquisition sections) should be identified here. Criteria should be quantitative when possible, and qualitative otherwise.

Helpful Tip

Data review is the process of evaluating data quality and documenting data limitations. It includes data verification and data validation. Consider certifying the data (Chapter 6, Section 6.4 of the IERQC Guidance) as a final step to this process.

IERQC Guidance References

Topic	IERQC Guidance
Planning data review procedures	**Section 6.1**
Criteria for accepting, rejecting or qualifying data	**Section 6.3**

D.2 VERIFICATION AND VALIDATION METHODS

Describe the process for verifying and validating each data type described in Section D.1 Data Review, Verification and Validation Planning. Identify issue resolution procedures and responsible individuals.

Data verification includes ensuring that: (1) specified procedures were followed, (2) data generated or gathered during the project met specified data quality requirements, and (3) data integrity has been protected. In other words, "Were the data collected properly?" Examples include: determining whether established acceptance criteria were achieved, checking for data entry and data calculations errors, assessing QC samples, and evaluating calibration records.

Data validation includes ensuring the data are scientifically valid and support broader project and sampling objectives. In other words, "Do the data make sense?" Consider using range checks to identify questionable data that may be impossible, illogical, or outside of anticipated ranges and/or consistency checks to compare results from related variables or similar ecosystems. Mapping Geographic Information System (GIS) data may also be used to visually assess GPS collected data against aerial photography. For more information on range and consistency checks refer to **Chapter 6**, **Section 6.2.3.2** of the IERQC Guidance.

IERQC Guidance References

Topic	IERQC Guidance
Data verification and validation process	**Section 6.2**
Handling data discrepancies and errors	**Section 6.3**; **Exhibit 6-8**

D.3 RECONCILIATION WITH USER REQUIREMENTS

Describe the process for determining if overall project objectives have been met. Outline the proposed methods to analyze the data and determine departures from assumptions established in the planning phase of data collection. Describe how limitations on the use of the data will be reported to decision makers.

IERQC Guidance References

Topic	IERQC Guidance
Determining if overall project objectives have been met and reporting limitations on use of data	**Section 7.2**

TABLES

TABLE C1. ROLES AND RESPONSIBILITIES

Individual Assigned	Responsible for:
Name Title Organization	• Responsibility • Responsibility

TABLE C2. PROJECT SCHEDULE TIMELINE

Activity	Anticipated Date of Initiation	Anticipated Date of Completion

TABLE C3. TARGET VARIABLES FOR FIELD MEASUREMENT OR OBSERVATION

Variable	Variable Type*	Unit of Measure	Expected Range of Values

*Primary or Ancillary

TABLE C4. DATA QUALITY ACCEPTANCE CRITERIA FOR PRECISION, BIAS AND ACCURACY FOR FIELD OBSERVATIONS/MEASUREMENTS

Variable	Method of Measurement*	Data Quality Acceptance Criteria		QC Field Check Used to Assess Measurement Performance
		Error Tolerance	Compliance Rate	

*Observer Determined or Field Measurement

TABLE C5. SAMPLING LOCATIONS

Location ID	Longitude*	Latitude*

**<insert coordinate system>*

TABLE C6. STANDARD OPERATING PROCEDURES

Variable(s) and/or Sample Type(s)	SOP

TABLE C7. SAMPLING QC

(ONLY APPLICABLE TO PROJECTS INVOLVED IN THE COLLECTION OF FIELD SAMPLES)

Matrix:
Analytical Parameter:

Field QC Sample	Frequency/ Number	Method/ SOP QC Acceptance Limit	Corrective Action (CA)	Person(s) Responsible for CA	Data Quality Indicators Assessed	Measurement Quality Objectives
Equipment Blanks						
Field Blanks						
Trip Blanks						
Cooler Temperature						
Field Duplicate Pairs						
Collocated Samples						
Field Splits						
Field Matrix Spikes						

TABLE C8. ANALYTICAL QC

(ONLY APPLICABLE TO PROJECTS INVOLVED IN THE ANALYSIS OF FIELD SAMPLES)

Matrix:
Analytical Parameter:

Laboratory QC	Frequency/ Number	Method/ SOP QC Acceptance Limit	Corrective Action (CA)	Person(s) Responsible for CA	Data Quality Indicator	Measurement Quality Objectives
Method Blank						
Reagent Blank						
Storage Blank						
Instrument Blank						
Lab Duplicate						
Lab Matrix Spike						
Matrix Spike Duplicate						
Lab Control Sample						
Surrogates						
Internal Standards						

TABLE C9. REPORTS

Type of Report	Frequency (e.g., daily, weekly, monthly, quarterly, annually	Projected Delivery Date(s)	Person(s) Responsible for Report Preparation	Report Recipients

EXHIBITS

EXHIBIT 1. TYPES OF QC FIELD CHECKS

Type of QC Field Check	Description of the QC Field Check
Hot Check	Used to determine if data collection activities are being implemented as planned as part of training or during data collection to examine crew performance and the efficacy of SOPs. The QA crew is present along with the trainee/routine crew. The QA crew observes the routine crew activities, examines the data collected, and provides immediate feedback regarding crew/trainee performance. Hot checks are also used to evaluate the quality of collected data, particularly for transitory variables.
Cold Check	Used to qualitatively evaluate method implementation. These checks are conducted by a separate QA crew that independently measures or observes all (or a subset) of the sampling unit or variables that have been previously assessed by a routine field as part of either their training efforts or an ongoing QC program. Cold checks are objective and systematic assessments that determine whether data collection activities are being implemented as planned and are suitable to achieve data quality acceptance criteria. The routine field crew may or may not be present at the time of the cold check. During these checks, the QA crew has access to the completed routine crew data.
Blind Check	Used to quantitatively evaluate method implementation. The check is conducted by a QA crew that independently measures or observes all (or a subset) of the sampling unit or variables that have been previously assessed by a routine field crew. Blind checks determine whether data collection activities are being implemented as planned and are suitable to achieve data quality acceptance criteria. The QA crew does not have access to the completed routine crew data.
Precision Check	Used to quantitatively evaluate method implementation and provide an unbiased estimate of precision. Members of the routine field crew use precision check to independently assess a subset of the sampling unit. This QC check are conducted by one or more field crew members to measure or observe the same target variables for the same sample unit or at the same location. Precision checks can be used to measure precision both within-crew and between-crews.
Calibration Check	Involves routine field crew members measuring or observing stable variables that have been previously determined by an expert. This check can be performed on one or more variables independent of a sampling unit or plot, staged under controlled conditions, or using established calibration plots within or representative of the project area that have been fully characterized by a QA crew. Results are used to evaluate the data collection abilities of routine field crew members and can support determination of achievable sampling objectives and data quality acceptance criteria.

Appendix D

APPENDIX D: QUALITY ASSURANCE PROJECT PLAN (QAPP) REVIEW CHECKLIST FOR ECOLOGICAL RESTORATION PROJECTS

This checklist was created as a tool to assist with the review of quality assurance project plans (QAPPs) for projects focused on ecological restoration and the control of invasive species. It contains the major sections of a QAPP, based on *EPA Requirements for Quality Assurance Project Plans* (EPA QA/R-5), EPA/240/B-01/003, March 2001, some of which have been revised for the purposes of this checklist, based on strategies described in the Application of QA/QC Principles to Ecological Restoration Project Monitoring (referred to herein as the "IERQC Guidance") to better fit the needs of projects involving ecological restoration and/or control of invasive species.

The major sections within the QAPP review checklist and their corresponding items follow the outline presented in **Appendix C**: Quality Assurance Project Plan (QAPP) Template for Ecological Restoration Projects (for more detail on each item see the IERQC Reference tables). Users who create their QAPP based on the template provided in **Appendix C** will be able to easily use this QAPP review checklist as a quick guide during QAPP development and as a tool to better understand what components of a QAPP will come under scrutiny during the QAPP review process.

Users of this QAPP review checklist must consult EPA QA/R-5, or the more general *Guidance for Quality Assurance Project Plans* (EPA QA/G-5), EPA/240/R-02/009, December 2002, as needed to obtain additional details and guidance for review of a QAPP.

QAPP reviewers should ensure the application of QA/QC approaches are commensurate with factors such as project objectives, risks associated with decision errors, resources, and schedules. Any information provided in this checklist or the IERQC Guidance (including their associated appendices) does not supersede requirements specified in EPA QA/R-5.

QAPP Review Checklist for Ecological Restoration Projects

QAPP Title ______________________

Grant/Contract/Project # ______________________

Date of Review ______________________

Key: IA=Included and acceptable; IU=Included and unacceptable; NI=Not included; NA=Not applicable

Topic	IA	IU	NI	NA	Comments
A1. Title and Approval Sheet					
Project title					
Organization’s name					
Effective date and/or version identifier					
Dated signature of Organization’s project manager					
Dated signature of Organization’s QA manager					
Other signatures, as needed (e.g., GLNPO Project Officer, GLNPO QA Manager)					
A2. Table of Contents					
A3. Distribution List					
Includes all individuals who are to implement or otherwise receive the QAPP and identifies their organization					
A4. Project/Task Organization					
Identifies key individuals with their responsibilities (e.g., data users, decision makers, project QA manager, subcontractors)					
Organization chart shows lines of authority and reporting responsibilities					
Project QA manager position indicates independence from unit collecting/using data					
A5. Problem Definition/Background					
Clearly states problem to be resolved, decision to be made, or hypothesis to be tested					
Identifies restoration project goals					

QAPP Review Checklist for Ecological Restoration Projects

QAPP Title ______________________

Grant/Contract/Project # ______________________

Date of Review ______________________

Key: IA=Included and acceptable; IU=Included and unacceptable; NI=Not included; NA=Not applicable

Topic	IA	IU	NI	NA	Comments
A6. Project/Task Description					
Provides historical and background information					
Identifies restoration project objectives					
Describes any required regulatory permits (e.g., NEPA, NHPA)					
Includes maps(s) of project area					
Provides work schedule					
A7. Quality Objectives and Criteria for Measurement Data					
Lists and describes each planned measurement					
Identifies sampling objectives					
States measurement units for recording results (e.g., centimeters [cm], species codes, plant cover classes)					
Explains how quality is described (DQIs) for each planned measurement (e.g., precision for measurements of length of a sample, % accuracy for identification of a species, % agreement between duplicate measurements of plant cover classes, % of data valid for completeness)					
States acceptance criteria for these data (e.g., ±2 cm in length, ±1 plant cover class 90% of the time, 95% agreement on species identifications, 95% completeness)					
Describes how and when these performance criteria will be evaluated (i.e., QC field checks)					

QAPP Review Checklist for Ecological Restoration Projects					
QAPP Title					
Grant/Contract/Project #					
Date of Review					
Key: IA=Included and acceptable; IU=Included and unacceptable; NI=Not included; NA=Not applicable					
Topic	**IA**	**IU**	**NI**	**NA**	**Comments**
A8. Special Training Requirements/Certifications					
Identifies special licenses, training, crew competency requirements, and/or certification (e.g., herbicide application, prescribed burn, taxonomic classification, GPS use) prior to data/sample collection					
Discusses how training records will be documented and where records will be kept					
A9. Documents and Records					
Itemizes the information and records that will be included in the data report (e.g., field logs, results of QC checks, problems encountered)					
States retention time and location for records and reports					
B1. Sampling/Measurement Design					
Identifies locations, frequency, and timing of field observations and measurements and/or sampling and the rationale					
Identifies selection of backup/alternate sampling locations					
B2. Field Data Collection and Sampling Method Requirements					
Lists the data collection methods for each field measurement and/or sample (e.g., field crew observations and/or measurements, data from field instruments, GPS, photographs, sound recordings)					
Lists field sample collection equipment and on-site supply lists; including, labeling, sample preservation, maximum holding times, etc.					

QAPP Review Checklist for Ecological Restoration Projects					
QAPP Title ______________________					
Grant/Contract/Project # ______________________					
Date of Review ______________________					
Key: IA=Included and acceptable; IU=Included and unacceptable; NI=Not included; NA=Not applicable					

Topic	**IA**	**IU**	**NI**	**NA**	**Comments**
Identifies individuals responsible for corrective action					
B3. Sample Handling and Custody Requirements					
Describes sample handling and control requirements (e.g., use of cooler, use of bubble wrap, labeling, chain of custody [if required] for voucher specimens)					
B4. Laboratory Analytical Methods Requirements					
Describes arrangements for laboratory analyses (e.g., methods as attachments to QAPP, performance criteria, analysis and results turnaround time, person responsible for oversight)					
B5. Quality Control Requirements					
For field observations and measurements, describes QC checks (i.e., precision, hot, cold, blind, or calibration checks)					
For field samples, describes QC samples (e.g., field blanks, spikes, reference samples, and replicates or split samples)					
For laboratory analyses, describes QC checks (e.g., laboratory blanks, spikes, calibration controls, and replicates or split samples)					
B6. Instrument/Equipment Testing, Inspection, and Maintenance Requirements					
Identifies acceptance testing of sampling and measurement systems					
Describes equipment needing maintenance and frequency for such maintenance					
Notes responsible individuals					

QAPP Review Checklist for Ecological Restoration Projects					
QAPP Title					
Grant/Contract/Project #					
Date of Review					
Key: IA=Included and acceptable; IU=Included and unacceptable; NI=Not included; NA=Not applicable					
Topic	**IA**	**IU**	**NI**	**NA**	**Comments**
B7. Instrument Calibration and Frequency					
Identifies equipment needing calibration and frequency for such calibration					
B8. Inspection/Acceptance for Supplies					
Identifies acceptance criteria for restoration supplies (e.g., applied chemicals, native species viability)					
B9. Non-Direct Measurements					
Identifies type of data needed from non-direct measurement sources (e.g., computer databases and literature files), along with acceptance criteria for their use					
Describes any limitations of such data					
B10. Data Management					
Describes data management scheme from generation or acquisition to final use or storage					
Describes methods for minimizing errors in the recording, transcribing, entering of data into electronic files, archiving of data, and storing of data sheets or field files					
Describes data handling equipment (e.g., computer hardware and software) and procedures used to process and compile data (e.g., management of GPS data and photo files)					
Includes references to forms or checklists (e.g., field forms, analytical bench sheets, chain-of-custody forms)					

QAPP Review Checklist for Ecological Restoration Projects					
QAPP Title ____________________					
Grant/Contract/Project # ____________________					
Date of Review ____________________					
Key: IA=Included and acceptable; IU=Included and unacceptable; NI=Not included; NA=Not applicable					

Topic	**IA**	**IU**	**NI**	**NA**	**Comments**
C1. Assessment and Response Actions					
Describes planned assessments, their timing and frequency, and evaluation and use of results					
C2. Reports to Management					
Notes individuals responsible for preparing reports and report recipients					
Identifies the frequency, content, and distribution of reports per requirements established in the funding agency's agreement or other project documentation					
D1. Data Review, Verification, and Validation Planning					
Describes planned data review procedures					
States criteria for accepting, rejecting, or qualifying data					
D2. Verification and Validation Methods					
Describes process for data verification and validation					
Identifies process for handling data discrepancies and errors					
D3. Reconciliation with User Requirements					
Describes process for determining if overall project objectives have been met and reporting limitations on use of data					

GLOSSARY

NOTE: The definitions provided below are intended specifically to apply for the purposes of this document, and do not necessarily reflect definitions used by other documents or organizations.

Acceptance Criteria – See "Data Quality Acceptance Criteria."

Accuracy – The degree to which a measured or observer-determined value agrees with a known or reference value; includes a combination of random error (precision) and systematic error (bias).

Adaptive Management – A structured and sequential learning process (decision-support) that increases knowledge and reduces uncertainty, iteratively leading to more effective ecological restoration (Clark County 2016; Sutter 2018).

Ancillary Variable – Information collected during data gathering that are considered "ancillary" to the "primary" variables identified in project objective, sampling objective, and hypothesis statements. A variable initially determined ancillary may later be reclassified as a primary variable pending the importance of its effect on explaining the variability of the system and achievement of project objectives. More generally, ancillary variables include those helpful in evaluating data quality and interpreting monitoring results, but are not directly used to determine if sampling objectives were achieved. Examples include information about who collected the data and when, weather conditions at the time of data collection, the orientation, position, or settings of instrumentation or equipment used when evaluating a primary variable, and other information that may be related to the primary variables of interest collected with the intention of controlling- or accounting- for co-variability during data analysis procedures.

Baseline Inventory – A description of current biotic and abiotic elements of a site prior to restoration, including its structural, functional and compositional attributes and current conditions (SER 2004). A baseline inventory is implemented at the commencement of the restoration planning stage prior to the implementation of restoration activities (or treatment) and is replicated across any included reference or control sites (i.e., reference models) to inform planning including restoration goals, and treatment prescriptions and to quantify site attributes necessary to conduct baseline comparisons with targeted change (i.e., effect-size) concurrent to or after restoration activities have been concluded (McDonald et al. 2016) Sometimes referred to as "baseline condition sampling."

Bias – The systematic or persistent distortion of a data collection process resulting in error in one direction.

Blind Check – A type of field QC check used to quantitatively evaluate method implementation. These QC checks are conducted by a separate QA crew that independently measures or observes all (or a subset) of the sampling unit or variables that have been previously assessed by a routine field crew as part of their ongoing QC activities. A blind check serves as an objective and systematic assessment to determine whether data collection activities are being implemented as planned and are suitable to achieve data quality acceptance criteria. During these checks, the QA crew does not have access to the completed routine crew data.

Calibration – Comparison of a method standard, instrument, or an observation with a standard or instrument of higher accuracy, or an observation by an expert to detect and quantify inaccuracies and to report or eliminate those inaccuracies by making appropriate adjustments.

Calibration Check – QC checks that involve routine field crew members measuring or observing stable variables that have been previously determined by an expert. These checks can be performed on one or more variables independent of a sampling unit or plot, staged under controlled conditions, or using established calibration plots within or representative of the project area that have been fully characterized by a QA crew. Results are used to evaluate the data collection abilities of routine field crew members and can support determination of achievable sampling objectives and data quality acceptance criteria.

Calibration Plot – A sample point or plot within or representative of the project area that has been fully characterized by a QA crew for the purpose of evaluating the field readiness of routine crew members and their ability to achieve data quality acceptance criteria.

Censored Values – Data that are reported as less than or greater than a certain value. Censored values can represent measurement results that are below a measurement sensitivity threshold (detection limit) or above a measurement range.

Chain-of-Custody (COC) – An unbroken trail of accountability that ensures the physical security of samples, data, and records.

Cold Check – A type of field QC check used to qualitatively evaluate method implementation. These QC checks are conducted by a separate QA crew that independently measures or observes all (or a subset) of the sampling unit or variables that have been previously assessed by a routine field crew as part of either their training efforts or an ongoing QC program. Cold checks are objective and systematic assessments that determine whether data collection activities are being implemented as planned and are suitable to achieve data quality acceptance criteria. The routine field crew may or may not be present at the time of a cold check. During these checks, the QA crew has access to the completed routine crew data.

Comparability – Confidence that data can be compared to or combined with other data collected for similar purposes.

Completeness – A measure of the amount of valid data obtained from a data collection system compared to the amount that was expected to be obtained under correct, normal conditions.

Compliance Check – A verification technique used during data review to identify data that deviate from study requirements; the technique includes checks to determine if results conform to (1) specified reporting formats and units, and (2) procedural requirements and QC acceptance criteria for data quality indicators.

Compliance Rate Objective – The expected frequency of compliance in meeting an error tolerance specification.

Consistency Checks – A collection of data validation techniques used during data review that address (1) how well related variables within the dataset compare internally (internal consistency), (2) how well the data for a given variable compares to similar but external data for that variable (external consistency), and (3) how well the data compare to predictions of natural inherent relationships of the measured variables (ecological consistency).

Cost of Quality – A methodology for quantifying the total cost of QA/QC activities and deficiencies in the quality of a product or service. The methodology recognizes the cost of NOT creating a quality product or service, or the cost of creating a poor quality product or services. If work has to be re-done to address problems or issues with quality, the cost will increase (i.e., the cost of quality increases when a poor quality product is initially produced).

Data Analysis – The mathematical and statistical process of using collected data to describe results, answer questions, and support decision making and determine whether restoration project objectives were met. Data analysis may include: mathematical manipulations involved with data reduction (e.g., the aggregation of data representing multiple variables into a single indicator or index value), calculations of descriptive statistics, or the application of established statistical methods necessary evaluate model assumptions or to conduct hypothesis testing (e.g., ANOVA or GLM, or principal components analysis).

Data Assessment – A continuation of the data review process that involves addressing data quality flags, assessing data quality indicators (DQIs) across measured and calculated variables, and reconciling the quality assessment of data with project assumptions and stated sampling objectives.

Data Certification – Ensures a secure validated database (or dataset) has been completed, documented, and certified (if applicable) and that the data within the database are suitable for final usability assessments in preparation for analysis, reporting, distribution, and archiving.

Data Management —A formal, structured process that promotes data quality, availability and preservation of data for analyses, informed decision making, and data reuse. This process requires planning, documentation, and effective implementation of day-to-day workflow and procedures to facilitate the security, integrity and reliability of data collected to support project goals and objectives.

Data Management Plan (DMP) – A guiding document that combines policy-based requirements, procedural guidelines, and standard operating procedures to facilitate the effective management of project data for each component of the data management lifecycle. The plan describes strategies that can create an efficient and effective flow of data from its original source to the final, archived database.

Data Management System (DMS) —The computer environment, including system hardware and software, used to electronically manage the data. A DMS is used to help improve management and data review functionality, data security (including protection against data corruption and loss), and overall project performance and efficiency, and generally includes: (1) a computer and/or server workspace that is accessible to all approved project participants, (2) effective and clear policies on read/write permissions, and (3) well-defined procedures and locations for storing files and data.

Data Quality Acceptance Criteria – Qualitative and quantitative criteria used to evaluate and control various phases (e.g., sampling, transportation, preparation, analysis) of the measurement process to ensure the total measurement uncertainty is within the range prescribed by the sampling objectives; data quality acceptance criteria specify the level of quality needed for each measurement or observation and data quality indicators (e.g., precision, bias, accuracy, representativeness, comparability, completeness, detectability) that can be used to determine if this level of quality has been achieved. Data quality acceptance criteria are usually established during the project planning phase and usually include a tolerance objective and a compliance rate objective. Sometimes referred to by other names, such as "measurement quality objectives."

Data Quality Act – Passed by the U.S. Congress in as a two-sentence rider to a 2001 appropriations bill. The Act instructed the U.S. Office of Management and Budget (OMB) to issue guidelines that (1) "Provide policy and procedural guidance to federal agencies for ensuring and maximizing the quality, objectivity, utility, and integrity of information including statistical information disseminated by Federal agencies" and (2) "Establish administrative mechanisms allowing affected persons to seek and obtain correction of information maintained and disseminated by the agency that does not comply with the guidelines." Also referred to as the "Information Quality Act."

Data Quality Indicator (DQI) – A quantitative statistic or qualitative descriptor used to interpret the degree to which data are acceptable or useful. Commonly accepted DQIs are precision, bias, accuracy, representativeness, comparability, completeness, and sensitivity (EPA 2002; Taylor 1987). In ecological restoration projects that also rely on observational measurements, the term "detectability" is recommended because it encompasses both sensitivity and specificity.

Data Validation – See "Validation."

Data Verification – See "Verification."

Detectability – A measure of the sensitivity and specificity of the sampling design, measurement procedures, instrumentation and/or data collection personnel in detecting true differences in a target variable at ambient levels or when the measurement or observation of a target variable is dependent upon detecting the true occurrence of a rare, cryptic or secretive organism. Also see "Measurement Sensitivity" and "Measurement Specificity."

Double Data Entry – A process designed to minimize data entry errors; it involves manual entry of the same dataset (e.g., from data reporting forms) by two different individuals, automated comparison of the two datasets, and correction of any discrepancies based on re-examination of the original data source. Also referred to by other terms such as "dual data entry" and "two-pass verification."

Ecological Restoration – The process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed. It is an intentional activity that initiates or accelerates ecosystem recovery with respect to its health (functional processes), integrity (species composition and community structure), and sustainability (resistance to disturbance and resilience), (Clewell et al. 2005).

Environmental Data – Any measurements or information that describe environmental processes, location, or conditions; ecological or health effects and consequences; or the performance of environmental technology. EPA defines environmental data as both primary data (i.e., information collected directly from measurements) and secondary/existing data (i.e., data that were collected for other purposes or obtained from other sources, including literature, industry surveys, models, data bases, and information systems) (EPA 2002).

Environmental Information – The American Society of Quality defines this term using the same definition provided above for "Environmental Data" (ASQ 2014).

Existing Data – Any data that were not directly and specifically generated to support the purpose or decision at hand. Other commonly used terms to describe existing data include "acquired data," "data from other sources," "historical data," "secondary source data" and "tertiary source data."

False Negative – See "Type 2 Error."

False Positive – See "Type 1 Error."

Field Audit – See "Hot Check."

Graded Approach – Process of applying **management controls** to an activity according to the intended use of the results and the degree of confidence needed in the quality of the results (ASQ 2014). In other words, the level of QA/QC performed should be commensurate with such factors as the project objectives, project importance, risks associated with decision errors, resources, and schedules.

Hot Check – A type of field QC check used to objectively and systematically determine if data collection activities are being implemented as planned. Often referred to as "field audits" or "technical systems audits," hot checks are used as part of training or during data collection to examine crew performance and the efficacy of the standard operating procedures used in real time. During these checks, the QA crew is present on the plot along with the trainee/routine crew. The QA crew observes the routine crew activities, examines the data collected, and provides immediate feedback regarding crew/trainee performance and SOP efficacy. These checks are also used to evaluate data quality, particularly for transitory variables.

Information Quality Act – See "Data Quality Act."

Laboratory Qualifier – Code applied to the data by the contract analytical laboratory to indicate a verifiable or potential data deficiency or bias.

Management Controls – A system of management functions to plan, implement, check and evaluate activities for conformity to management and performance objectives (ASQ 2014).

Measurement Error – The difference between a measured or observed value and the true value, and is caused by the individual, instrument or process used to make the measurements or observations, and from a study-design perspective, also includes all error introduced during data transcriptions and reductions.

Measurement Quality Objectives – See "Data Quality Acceptance Criteria."

Measurement Sensitivity – Also called the true positive rate, is the proportion of positives correctly determined as positive (e.g., the observer correctly detects the true presence of species X or a targeted ecological condition such as the true proportion of water samples that are impacted by a disturbance). The measurement sensitivity threshold is also referred to as the detection limit.

Measurement Specificity – Represents the proportion of accurately determined true negatives, or the proportion of negatives or absences that are correctly identified as negatives or absences (Gitzen 2012; Drew et al. 2010).

Metadata – Consists of data (information) that "defines and describes other data" (ISO/IEC 11179). Metadata provides information on what users need in order to accurately interpret and use a dataset and is generally: (1) descriptive, (2) structured using a standardized textual format (e.g., TXT, XML), and (3) embedded or maintained separately from the applicable project dataset.

Monitoring – The systematic and usually repetitive collection of information, typically used to track the status of a variable or system (Atkinson et al. 2004).

Peer Review – The review of a draft product for quality by specialists in the same field of scientific study who were not involved in producing the draft publication. Used to ensure the quality of published information meets the standards of the scientific and technical community.

Performance Evaluation – A type of audit in which the quantitative data generated in a measurement system are obtained independently and compared with routinely obtained data to evaluate the proficiency of an instrument, observer or crew, analyst, or laboratory.

Precision – The degree of agreement among repeated measurements or observations of the same attribute under the same or very similar conditions.

Precision Check – A type of field QC check used to quantitatively evaluate method implementation and provide an unbiased estimate of precision. Members of the routine field crew use precision checks to independently assess a subset of the sampling unit. These QC checks are conducted by one or more field crews or crew members to measure or observe the same target variables for the same sample unit or at the same location. Estimates of within-crew precision can be made if a crew repeats measurement of target variables for a site where that same crew had previously collected data. Estimates of between-crew precision can be made if two or more crews collect data at the same site. Precision checks are often used when it is not feasible to have a separate QA crew. Because these checks are conducted without the benefit of data collected by experts for comparison, results of these checks cannot be used to estimate the accuracy or bias of the collected data.

Primary Variable – A variable used to determine if objectives are achieved. Contrast with "ancillary variables," which describe who collected the data and when, weather conditions at the time of collection, and other information that can be used to help evaluate data quality and interpret results.

Quality – The degree to which a set of inherent (existing) characteristics fulfils requirements. ISO 9000 Under the Data Quality Act, the U.S. Office of Management and Budget elaborated on this by saying that the quality of information is based on the following three characteristics: (1) Objectivity: The information itself must be accurate, reliable, and unbiased and the manner in which the information is presented must be accurate, clear, complete, and unbiased; (2) Utility: The information must be useful for the intended users; and (3) Integrity: The information may not be compromised through corruption or falsification, either by accident, or by unauthorized access or revision.

Quality Assurance (QA) – Part of quality management focused on providing confidence that quality requirements will be fulfilled (ISO 2015a). Quality assurance may include management activities involving planning, implementation, assessment, reporting, and quality improvement to ensure that a process, item, or service is of the type and quality needed and expected by the customer (EPA 2000b). Note that QA is generally process-oriented and focused on preventing defects.

Quality Assurance Project Plan (QAPP) – A document describing in comprehensive detail the necessary QA/QC and other technical activities that need to be implemented to ensure that the results of the work performed will satisfy the stated performance or acceptance criteria (EPA 2002; ASQ 2014).

Quality Control (QC) – Part of quality management focused on fulfilling quality requirements (ISO 2015a). Quality control includes technical activities that measure the attributes and performance of a process, item, or service against defined standards to verify that they meet the stated requirements established by the customer (ASQ 2014; EPA 2000b). Note that QC is generally product-oriented and focused on identifying defects and confirming requirements were met.

Quality Documentation – Generic term used to describe any form of planning documentation that describes the QA/QC strategies for all phases of a project lifecycle. Examples include, but are not limited to Quality Manuals, Quality Plans, Quality Management Plans, Quality Assurance Project Plans, Quality Assurance Program Plans, and Quality Control Plans.

Quality Indicators – Measurable attributes that are used to evaluate the quality of a particular outcome or decision.

Quality Improvement – Coordinated activities to direct and control an organization with regard to quality (ISO 2015a). Note: Quality improvement is a management program for improving the quality of operations. Such management programs generally entail a formal mechanism for encouraging worker recommendations with timely management evaluation and feedback or implementation (ASQ 2014).

Quality Management – That aspect of the overall management system of the organization that determines and implements the quality policy. Quality management typically includes strategic planning, allocation of resources, and other systematic activities (e.g., planning, implementation, and assessment) pertaining to the quality system (ASQ 2014).

Quality Management System (QMS) – A structured and documented management system describing the policies, objectives, principles, organizational authority, responsibilities, accountability, and implementation plan of an organization for ensuring quality in its work processes, products (items), and services. The QMS provides the framework or "blueprint" for planning, implementing, documenting, and assessing work performed by the organization and for carrying out QA and QC activities that will help ensure that final products and services meet or exceed the organization's objectives and expectations. (ASQ 2014). A "Quality Management System" is also sometimes referred to as a "Quality System."

Range Check – A data validation technique used during data review to identify data that are (1) scientifically impossible or illogical, (2) outside the normal range anticipated for the variable, or (3) within an anticipated range, but at such high or low extremes of the range that they warrant additional scrutiny.

Record – A completed document that provides objective evidence of an item or process. Records may also include photographs, drawings, magnetic tape, and other data recording media.

Reference Tables – Also known as reference lists, look-up tables, or mapping tables. Reference tables are used as the basis for conducting compliance, range and consistency checks during data review activities. These tables may be static, dynamic, universal, or project-specific, depending on the variable.

Representativeness – The degree to which data represent the characteristic of a population being assessed.

Restoration Project Goals – Used to describe the desired future conditions or ideal states that an ecological restoration effort will attempt to achieve. Such goals should be descriptive and convey a purpose that includes the attribute of interest and the action required to effect change in that attribute. They should define the general direction for a project but should not define specific desired future conditions in measureable terms.

Restoration Project Objectives – Specific, measureable, achievable, results-oriented, and time-sensitive (SMART) statements that build on the restoration project goals by describing desired changes in condition in delineated areas at a project site. These desired changes can be stated either as a targeted change that results in a change in a baseline condition (i.e., an observed trend or improvement) or results in an achievement of a targeted threshold.

Sampling Error – The difference between the characteristics identified in a sample of a population (observed or measured values) and the actual characteristics of the entire population (true values).

Sampling Objectives – Qualitative and quantitative statements that clarify study objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions. Sampling objectives support the restoration project objectives and are used to determine a sampling design for the monitoring program and identify quality requirements for data that will be collected in the program. Well defined sampling objectives specify (1) the degree of change that must be detected in order to define project success, and (2) the degree of certainty needed when stating that the change has been detected.

Sensitivity – See "Measurement Sensitivity."

Specificity – See "Measurement Specificity."

Stable Variable – A variable or ecological phenomena that can be measured repeatedly over a fixed time period and expected to produce the same result for each measurement.

Standard Operating Procedure – Detailed instructions that are designed and implemented to ensure the uniformity and consistency of a specific activity or set of activities.

Tolerance Objective – The expected range for repeated observations or repeatability.

Transitory Variable – A variable or ecological phenomena that is likely to change between repeated measurements or observations over a fixed time period, and cannot be measured (or observed) repeatedly and expected to produce the same result. These variables can be affected by time, stochastic or random effects, and disturbance due to the presence of an observer and/or the sampling procedures employed.

Type 1 Error – Incorrectly concluding that a change occurred when it did not; also known as a False Positive or a False Change, and represented by the Greek letter alpha (α).

Type 2 Error – Failing to recognize that a change occurred; also known as a False Negative or a Missed Change, and represented by the Greek letter beta (β).

Validation – Confirmation, through provision of objective evidence that the requirements for a specific intended use or application have been fulfilled (ISO 2015a; ASQ 2014). For ecological restoration data, this includes ensuring that the data are scientifically valid, and that they support broader project and sampling objectives. In other words, data validation asks, "Does it make sense?"

Verification – Confirmation, through provision of objective evidence that specified requirements have been fulfilled (ISO 2015a; ASQ 2014). For ecological restoration data, this includes verification that specified procedures (SOPs) were followed, data generated or gathered during the project met specified data quality requirements (e.g., data quality indicators met the acceptance criteria established for each sampling objective), data entry and data calculations were performed correctly, and that data integrity has been protected. In other words, data verification asks, "Did they do it right?"