# Oregon's Blue Carbon Ecosystems: State of the Science

A summary of the current understanding of the climate mitigation potential of Oregon's coastal and marine habitats

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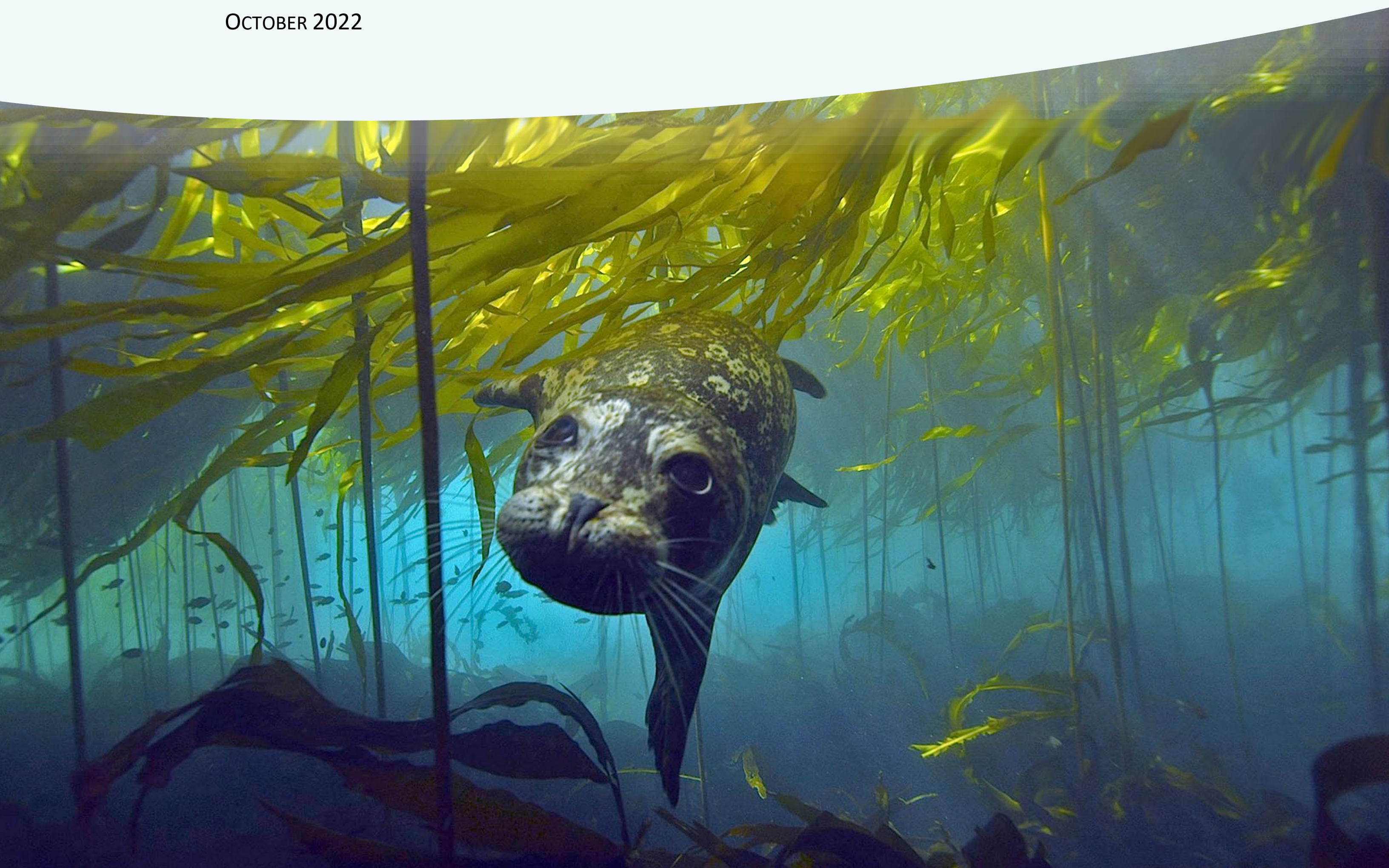

**Cover photos**: *Top*: Forest and marshland near Warrenton, Oregon. Photo by Browning (2016). *Bottom*: Harbor seal in bull kelp. Photo by Graner (2015).

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## ABBREVIATIONS

| | |
|---|---|
| C | carbon |
| $CaCO_3$ | calcium carbonate |
| CCRCN | Coastal Carbon Research Coordination Network |
| $CH_4$ | methane |
| CMECS | Coastal and Marine Ecological Classification Standard |
| $CO_2$ | carbon dioxide |
| $CO_2e$ | carbon dioxide equivalent |
| eDNA | environmental DNA |
| EPA | U.S. Environmental Protection Agency |
| GHG | greenhouse gas |
| $N_2O$ | nitrous oxide |
| NERRS | National Estuarine Research Reserve System |
| $O_2$ | dioxygen |
| PNW | Pacific Northwest |
| SE | standard error |
| U.S. | United States |
| VCS | Verified Carbon Standard |

## GLOSSARY

**Additionality** = the net climate benefit associated with an activity or project separate from what would have happened in the absence of that activity.

**Baseline** = net sequestration in the absence of any change from business-as-usual practices.

**Blue carbon** = the pools and processes affecting carbon storage within, or strongly influenced by, marine ecosystems.

**Coastal blue carbon** = in Oregon, coastal ecosystems capable of storing and sequestering carbon, including estuarine wetlands such as scrub-shrub and forested tidal wetlands, tidal marshes, submerged aquatic vegetation (e.g., seagrass and seaweed), and tidal mudflats.

**Carbon credit** = a measurable, verifiable emission reduction that results from a certified offset project that reduces or avoids greenhouse gas (GHG) emissions and/or sequesters carbon. These carbon credits can then be sold via carbon markets. Once an entity or individual buys a carbon credit, it is permanently retired so that it cannot be reused.

**Carbon flux** = the movement of carbon between carbon pools.

**Carbon pool** = a component of the climate system that has the capacity to store, accumulate, or release carbon (e.g., oceans, soils, atmosphere, and forests).

**Carbon sink** = a location or process where carbon storage outbalances carbon emission (i.e., net sequestration).

**Carbon source** = a location or process where carbon emissions outweigh carbon storage (i.e., net emission).

**Carbon stock** = the amount of carbon within a particular carbon pool.

**Durability** (or permanence) = either the expected duration of carbon storage or the risk of reversal due to anthropogenic or natural disturbances.

**Emission** = the release of various gases, either from natural or anthropogenic sources, that results in increased atmospheric GHGs (e.g., carbon dioxide [$CO_2$], methane [$CH_4$], nitrous oxide [$N_2O$]).

**Fish carbon** = the contribution of marine vertebrates (whales, bony fishes, etc.) to carbon sequestration in the ocean.

**Flux** = the movement of any material or gas from one place to another.

**GHG flux** = the emission and/or sequestration of multiple GHGs, including $CH_4$ and $N_2O$.

**Greenhouse gas** (GHG) = a gas that, when present in the atmosphere, results in net atmospheric warming. $CO_2$, $CH_4$, $N_2O$, water vapor, and ozone are the primary GHGs in the Earth's atmosphere. GHG concentrations and emissions are often listed in units of carbon dioxide equivalent ($CO_2e$).

**Mariculture** = the cultivation of products for food and other uses in saltwater (i.e., <u>mari</u>ne aqua<u>culture</u>).

**Marine blue carbon** = in Oregon, nearshore ocean ecosystems, such as subtidal kelp forests, as well as marine mammals and other open-ocean biomass like long-lived fish species.

**Natural climate solution** = ecosystem restoration, conservation, and management to reduce the amount of GHGs in the atmosphere while providing co-benefits that maintain or improve biodiversity and ecosystem services, such as coastal shoreline protection, that benefit coastal communities.

**Net flux** = the difference between the amount of a gas (e.g., $CO_2e$, $CO_2$, $CH_4$, and $N_2O$) added to the atmosphere by emissions and the amount sequestered.

**Net sequestration** = a measure of the net flux of $CO_2e$ into an ecosystem; it is the inverse of net emissions. It represents the net removals of GHGs from the atmosphere.

**Permanence** = see "durability."

**Remineralization** = the breakdown of particulate organic matter into inorganic carbon molecules (like dissolved $CO_2$).

**Sequestration** = the process of capturing carbon within carbon sinks over the long term.

A heron hunts for prey in a seagrass bed in Netarts Bay. Photo by Oregon Sea Grant (2017b).

# EXECUTIVE SUMMARY


Blue carbon refers to the carbon stored and sequestered in the soils, living vegetation, and other biotas in coastal and marine ecosystems. Managing these ecosystems provides an opportunity to mitigate climate change by reducing greenhouse gases (GHGs) emitted into the atmosphere. **To help interested stakeholders make sense of this evolving opportunity, The Nature Conservancy in Oregon compiled this document to examine the status of blue carbon science in Oregon and the Pacific Northwest (PNW).** Specifically, this report summarizes regionally relevant scientific literature to help readers understand the basics of the blue carbon cycle and GHG mitigation, and the mechanisms of carbon sequestration and storage in Oregon's coastal and marine ecosystems. **With this document, we aim to highlight what is known and what remains unknown concerning coastal and marine blue carbon in Oregon and provide recommendations for managing blue carbon ecosystems as natural climate solutions.**

While gaps remain in the evidence base needed to fully assess blue carbon opportunities in Oregon, ongoing efforts continue to fill these gaps. In particular, the work of the PNW Blue Carbon Working Group has significantly contributed to understanding blue carbon ecosystems and dynamics. In some cases, we lacked regionally specific data that would be needed for a robust evaluation of Oregon blue carbon potential. We summarize the existing blue carbon data and limitations in Table 1.

Oregon is among those coastal states with the most plentiful and best-quality blue carbon data. Regionally specific knowledge of carbon dynamics varies depending on the ecosystem type. Blue carbon data gaps for Oregon's tidal wetlands are rapidly being filled, and the remaining major data gaps related to the PNW's coastal blue carbon should largely be addressed by the end of 2023. The following additional information needs have been identified:

- Improved habitat mapping of the current and potential extent is needed for more refined estimates of carbon production and sequestration for all wetland types and land uses, in addition to submerged aquatic vegetation (seaweed, eelgrass) to identify potential blue carbon restoration areas at a local scale.
- Understanding the carbon dynamics in coastal and nearshore ecosystems can help clarify the relative role of blue carbon activities in climate mitigation.
- Better salinity mapping can aid in identifying restoration and protection opportunities.
- Climate change, sea level rise, and migration of estuarine and coastal habitats may affect blue carbon resources in the future, but how vulnerable these ecosystems are remains unresolved.
- Regional research is needed to understand carbon dynamics within kelp forest ecosystems and rates of carbon production and sequestration.
- A better understanding is needed of the magnitude of blue carbon benefits provided by marine vertebrates ("fish carbon") and the methods required to manage them as an oceanic carbon resource.
- Identifying emission reduction opportunities for shellfish and seaweed aquaculture can help clarify how industry and GHG mitigation goals could be harmonized and how production methods could reduce the impact on important co-located blue carbon ecosystems.

**While there is still considerable uncertainty about the magnitude of climate mitigation from blue carbon activities, the current science suggests that the following activities are likely to provide some climate mitigation benefits:**

- The preservation of existing estuarine and nearshore ecosystems is hugely important for maintaining biodiversity and ecosystem services, including carbon storage.
- Estuary-based conservation projects using existing carbon accounting methodologies are practical and enhance carbon sequestration in tidal wetlands and eelgrass meadows.
- Restoration of tidal flow to diked and drained wetlands generates climate benefits by reducing GHG emissions.
- Site-specific evaluations are necessary to estimate the precise magnitude of the benefit, and a blue carbon calculator is in development as a tool to facilitate these estimations.

- Evidence provides reasonable confidence that the restoration of scrub-shrub tidal wetlands provides carbon benefits, which should be emphasized in restoration plans.
- Benefits from blue carbon restoration accrue on a decadal scale depending on flux, and practitioners should expect a lag time between restoration and the generation of large carbon gains. Thus, estuary-based projects are needed sooner rather than later to see significant carbon reductions ahead of upcoming climate deadlines.

## INTRODUCTION

Addressing climate change requires a combination of approaches to reduce and remove greenhouse gas (GHG) emissions at local, regional, and global scales. *Natural climate solutions* use ecosystem restoration, conservation, and management to reduce the amount of GHGs in the atmosphere while providing co-benefits that maintain or improve biodiversity and ecosystem services, such as coastal shoreline protection, that benefit coastal communities.[1] *Blue carbon* refers to the carbon stored and sequestered in the living vegetation, soils, and other biotas in the coastal and marine ecosystems. Global estimates suggest that blue carbon restoration and conservation through limiting ecosystem degradation and conversion, restoring disturbed ecosystems, and other management strategies could potentially sequester the equivalent of 3% of annual global emissions by 2030.[2]

While global estimates provide a starting point for conversation, they lack regional specificity. For example, the global estimate does not include scrub-shrub and forested tidal wetlands, which form an important coastal ecosystem in Oregon. In Oregon, *coastal blue carbon* ecosystems include estuarine wetlands such as scrub-shrub and forested tidal wetlands, tidal marshes, submerged aquatic vegetation (e.g., seagrass and seaweed), and tidal mudflats. *Marine blue carbon* includes nearshore ocean ecosystems, such as subtidal kelp forests, as well as marine mammals and other open-ocean biomass like long-lived fish species.

Blue carbon, a term coined in 2009,[3] is an area of active research and creative thinking, and thus, blue carbon science is evolving rapidly. Many stakeholders remain uncertain about how to incorporate blue carbon into their strategies for coastal management, restoration, or climate mitigation.

To help interested stakeholders make sense of this evolving opportunity, The Nature Conservancy in Oregon compiled this document to examine the status of blue carbon science in Oregon and the Pacific Northwest (PNW). Specifically, this report summarizes regionally relevant scientific literature to help readers understand the basics of the blue carbon cycle and GHG mitigation, and the mechanisms of carbon sequestration and storage in Oregon's coastal and marine ecosystems.

**With this document, we aim to highlight what is known and what remains unknown concerning coastal and marine blue carbon in Oregon and provide recommendations for managing blue carbon ecosystems as natural climate solutions.** Given recent interest in Oregon for carbon sequestration and storage in natural and working lands,[4] we seek to provide policymakers and stakeholders with as much information as possible to assess the role of Oregon's highly productive coastal and marine ecosystems in GHG mitigation. Practitioners and policymakers should consider several criteria when evaluating the potential of blue carbon as a climate mitigation strategy.[5] There is a need to understand how management, restoration, and protection of blue carbon can alter or increase levels of GHG sequestration and storage compared to business as usual. Robust evaluation of blue carbon opportunities will require understanding (a) the rates that different coastal and marine ecosystems sequester carbon from the atmosphere, (b) the amount of carbon stored in those coastal and marine ecosystems, and (c) how they respond to management activities. In addition, it requires clear data on the current and

[1] Griscom et al., 2017
[2] Macreadie et al., 2021
[3] Lovelock & Duarte, 2019
[4] Beers et al., 2021; Senate Bill 1534 A, 2022
[5] Howard et al., 2017

historical extent of each blue carbon ecosystem, the risks to blue carbon—i.e., where and why blue carbon is vulnerable to loss—and how coastal and marine restoration impacts GHG emission and sequestration. Because coastal and marine ecosystems provide a myriad of additional benefits to nature and people, the co-benefits provided to ecosystems and coastal communities should be considered in any decisions around blue carbon opportunities.

In some cases, we lacked regionally specific data that would be needed for a robust evaluation of Oregon blue carbon ecosystem potential. Table 1 summarizes blue carbon sinks in Oregon and describes data limitations to aid in comparative decision-making.

# Blue Carbon Basics

## Blue Carbon Cycle

Carbon, which is a critical element for life on Earth, cycles between the atmosphere and Earth's surface (land and water). In the atmosphere, carbon is in the form of carbon dioxide ($CO_2$). On the Earth's surface, carbon is dissolved in the oceans, stored in the tissues of organisms (like plants and animals), buried in soils, and stored in rocks. These places that hold carbon are referred to as carbon pools. *Carbon pools* are reservoirs of carbon anywhere on Earth that have the ability to store, accumulate, or release carbon (e.g., the atmosphere, the ocean, soils, marine sediments, and living tree biomass). Carbon moves between these pools, including into and out of coastal and marine ecosystems, as part of the global carbon cycle.

The major carbon pools discussed throughout this report are above- and belowground living and dead biomass and soil or sediment carbon. In terms of climate mitigation, a *carbon sink* is any process or mechanism that removes $CO_2$ from the atmospheric carbon pool. A given pool can be a sink for atmospheric carbon if, during a given time interval, more carbon is going into it (sequestration) than going out (emission).

Coastal and marine ecosystems remove $CO_2$ from the atmosphere through photosynthesis by the plants growing in these systems (Figure 1). This is called *sequestration*. Carbon can move into and out of ecosystems through decomposition, cellular respiration, and biotic activity. The annual sequestration rate for an ecosystem refers to the quantity of $CO_2$ removed from the atmosphere annually. It is expressed as a rate (e.g., Mg $CO_2$/yr; see the callout box for unit definitions and conversions). This carbon can be stored in several pools in coastal and marine ecosystems. For example, carbon may be stored in above- and belowground living biomass or in sediments. In coastal and marine ecosystems, dead plant and animal biomass containing carbon may become buried in oxygen-poor coastal and marine sediments where biomass breaks down very slowly, allowing significant long-term carbon storage. Salinity can also play a key role in determining the rates and ratios of GHGs emitted from coastal or estuarine wetland environments.

**Units, abbreviations, and common conversions used in carbon accounting**

| Unit | Unit abbreviation | Conversions |
|---|---|---|
| Gram | g | |
| Megagram (metric ton) | Mg | 1 Mg = 1,000,000 g |
| Meter | m | |
| Hectare | ha | 1 ha = 10,000 $m^2$ |
| Carbon dioxide equivalent | $CO_2e$ | 1 Mg C = 3.67 Mg $CO_2e$ |
| Methane | $CH_4$ | 1 Mg $CH_4$ = 25 Mg $CO_2e$ |
| Nitrous oxide | $N_2O$ | 1 Mg $N_2O$ = 298 Mg $CO_2e$ |

**Table 1**. Summary of the knowledge base of climate mitigation benefits from Oregon's coastal and marine blue carbon.

| Oregon blue carbon | Knowledge base | Mechanism for sequestration, storage, or reduced emissions | Durability | Vulnerability | Potential action(s) to improve or protect climate mitigation benefits | Limitations or complications |
|---|---|---|---|---|---|---|
| Tidal wetlands | High; good evidence of sequestration capacity from existing soil carbon databases; forthcoming emission flux data; need refined scrub-shrub and forested tidal wetland mapping in OR estuaries | Soil carbon, biomass production & accretion, and salt-inhibition of methane generation; long-term storage in scrub-shrub and forested tidal wetland biomass | Long-term storage in soils, woody biomass | Due to coastal uplift experienced by many OR estuaries, most tidal wetlands can be considered somewhat resistant to currently predicted rates of sea level rise | Restoring tidal wetland functions and associated ecosystem services to former tidal wetlands historically converted to agricultural lands; conservation of least-disturbed tidal wetlands; restoration of disturbed seagrass beds | GHG emissions in low-salinity environments can offset benefits from carbon production; > 95% of forested tidal wetlands have been lost, and restoration of this wetland type is more complex than marsh restoration |
| Eelgrass | Moderate to high; good evidence of carbon storage capacity within sediments, but uncertainty remains about import and export carbon dynamics; lower sequestration capacity; need more widespread extent mapping in OR estuaries | Soil carbon, biomass production & accretion, and salt inhibition of methane generation; short-term storage in living biomass | Long-term storage in soils, little in biomass, but some connectivity to open-ocean ecosystems resulting in carbon export | Coast-wide loss of eelgrass most likely due to changes in water temperature; eelgrass loss due to dredging and other historical and more recent human activities, including commercial oyster production | Mapping current extent; restoration by replanting; eelgrass bed conservation | The majority of carbon in eelgrass bed sediments is allochthonous (imported) and cannot be counted for carbon credits |
| Seaweed & kelp forests | Low to moderate; kelp forests are highly productive, but sequestration capacity is unclear despite connectivity to oceanic and estuarine carbon sinks | Biomass production; short-term storage in living biomass; export of biomass to sediments on shelf, estuary, or deep sea | A portion may be considered stored over the long term if transported to deep sea or captured in sediments | Significant loss of kelp forest cover due to several factors, including marine heat waves, overgrazing from herbivores, and loss of keystone predators | Mapping of canopy-forming and subtidal kelp species; management of herbivores; identification of stressors; possible restoration | Kelp forest production–emission balance is complex, especially at system level; drivers of kelp loss are unclear and variable; currently no way to include seaweed carbon in carbon financing |

| | | | | | | |
|---|---|---|---|---|---|---|
| Marine vertebrates ("fish carbon") | Low; lack of rigorous studies on the carbon storage capacity of marine vertebrates; management strategies for carbon unclear | Living biomass in long-lived species; active transport of surface carbon to deep water; deadfall carbon; increased nutrient availability to phytoplankton | Only fish carbon that reaches sediments (deadfall/ particulate organic carbon) will be stored over the long term; biomass carbon can cycle on short or long timescales, depending on individuals' longevity | Long-lived fish species and whales face threats from climate change, habitat loss, fishing stressors, entanglements, and ship strikes | Fisheries management, particularly targeting long-lived species of fish; reduced whale entanglements | Carbon fluxes related to marine vertebrates are still highly uncertain; increasing "mobile carbon resources" or fish carbon may only modestly affect ultimate sequestration of carbon; challenging to create realistic policies targeting carbon benefits in transient organisms |
| Seaweed aquaculture | Low; carbon sequestration capacity variable depending on culture methods and product uses | Carbon uptake into biomass while cultured seaweeds grow; potential to seed wild seaweed and kelp; GHG mitigation when used as livestock feed additive | Fast-growing, high-carbon kelps, like bull kelp and giant kelp, may have better carbon benefits but rely on marketability | Carbon benefits generated are dependent on market conditions and development of a market for seaweed products | Expanded production to improve seaweed product profitability and carbon benefits | Seaweed farming not likely to have large carbon benefits unless large in-water farms of native seaweed are implemented; stored biomass in carbon released on consumption |
| Shellfish aquaculture | Low; carbon sequestration capacity variable depending on culture methods and product uses | Carbon storage in production and removal of calcium carbonate shells; emissions and mitigation depend on practices and downstream use of material | Durability of carbon stored within shells depends on the downstream use, resulting in net emissions in some applications | Carbon benefits generated are dependent on market conditions | Refined methodology of production to reduce carbon emissions; use of shell material to generate carbon benefit | Shellfish aquaculture may have overall net carbon emissions when accounting for the entire process; carbon benefits likely to occur only if shellfish substitute for carbon-intensive terrestrial agriculture |

*Note*. GHG = greenhouse gas; OR = Oregon.

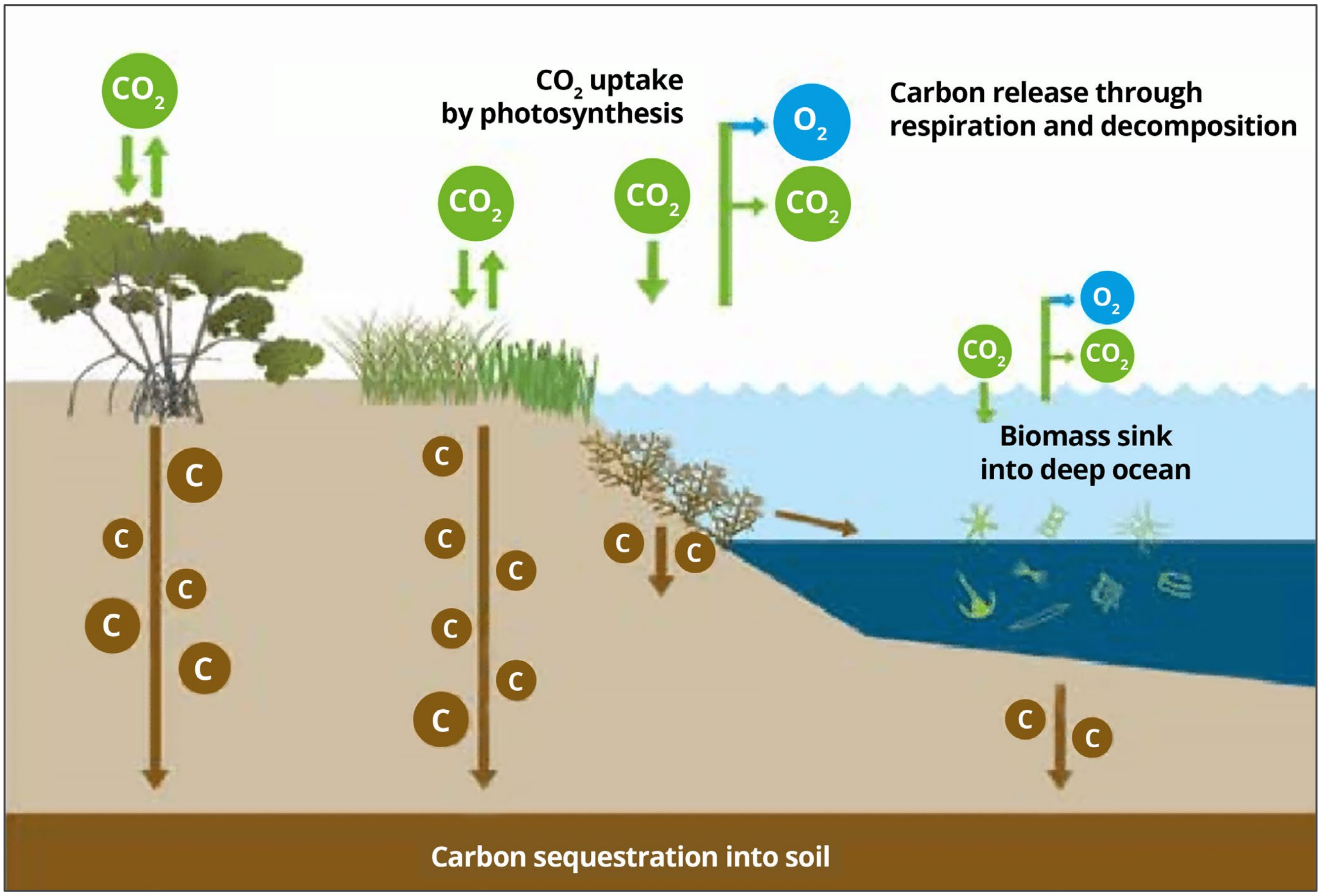


**Figure 1**. Graphic illustration of blue carbon ecosystems' carbon uptake via photosynthesis and subsequent long-term sequestration into biomass and soil, or release into the atmosphere via respiration.

*Note*. C = carbon; $CO_2$ = carbon dioxide; $O_2$ = dioxygen. From Otero & Piñeiro (2021).

The amount of carbon stored in a particular carbon pool is termed the *carbon stock* and is typically presented as the mass of carbon per unit area (e.g., g C per $m^2$). For example, in a tidal wetland, carbon stored in its sediments is referred to as the soil carbon pool, and the total amount stored in the sediments would be referred to as the tidal wetland's soil carbon stock. It should be noted that tidal wetlands can also release carbon into the atmosphere as GHGs produced by plant respiration or through the production of methane or other gases from soils.

## Terminology of Climate Change Mitigation

Climate change is caused by multiple GHGs (i.e., $CO_2$, methane, nitrous oxide) emitted during the production and use of energy, materials, and land. For simplicity, the emission and sequestration of GHGs are conventionally reported in carbon dioxide equivalents ($CO_2e$; see the callout box). Climate change mitigation refers to efforts to reduce or eliminate GHG emissions and/or to remove GHGs from the atmosphere to prevent worsening climate change. The State of Oregon aims to achieve GHG emission levels that are 45% below 1990 levels by 2035 and at least 80% below 1990 levels by 2050. Most of this climate change mitigation will require reducing or eliminating the use of fossil fuels. In addition to fossil fuel reduction, the Oregon Global Warming Commission has set a goal to further reduce emissions by increasing the sequestration and storage capacity of natural and working lands—including blue carbon ecosystems.

Coastal and marine ecosystems already sequester large amounts of $CO_2$ and emit some GHGs as part of normal ecosystem processes. Degraded ecosystems may emit more GHGs. An important concept in climate change mitigation is *additionality*, which is used to distinguish the net climate benefit associated with an activity or project from what would have happened in the absence of that activity (Figure 2). Additionality can be expressed as the net GHG emissions saving or sequestration increase in excess of that which would have occurred anyway (i.e., compared to a baseline or business-as-usual scenario).

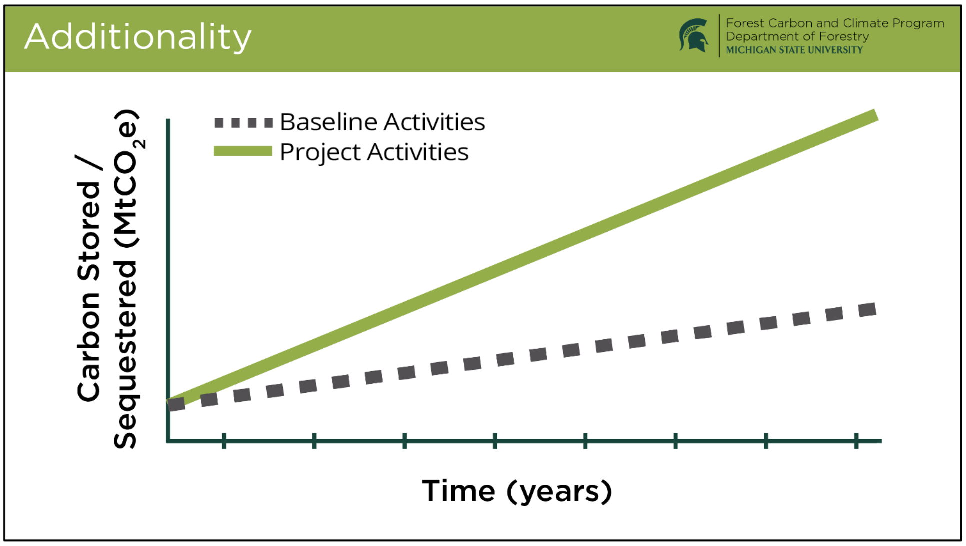


**Figure 2**. Additionality represents the GHG removals or reductions that occur in addition to what would otherwise occur in a business-as-usual scenario.

*Note*. $CO_2e$ = carbon dioxide equivalent. From Michigan State University (n.d.).

The movement of any material or gas from one place to another, or *flux*, is part of understanding blue carbon. Flux is a common term in climate science. A negative flux typically indicates sequestration, while a positive flux typically indicates emission, although there is variation in how the term is defined and displayed. *Carbon flux* refers to the transfer of carbon from one pool to another, while *GHG flux* refers to the emission and/or sequestration of multiple GHGs, including methane and nitrous oxide. *Net flux* is the difference between the amount of a gas (e.g., $CO_2e$, $CO_2$, $CH_4$, and $N_2O$) added to the atmosphere by emissions and the amount sequestered. *Net sequestration,* or net flux, by these ecosystems, in the absence of any change from business-as-usual practices, is referred to as the *baseline*. Activities that increase blue carbon sequestration and storage or that decrease GHG emissions from coastal and marine ecosystems relative to the current baseline can contribute to climate change mitigation.

*Durability* is another important concept in climate change mitigation (also referred to as *permanence* in some carbon accounting frameworks). Durability refers to the tendency of carbon to become and remain stored over long durations. Verra, which operates the Verified Carbon Standard (VCS), defines permanence as the likelihood of maintaining carbon sequestered in a project area over a period of 100 years. The durability of carbon pools in natural systems depends on both the expected persistence of living biomass and how much of the accumulated biomass is transferred to long-term sinks, like deep-sea sediments or undisturbed tidal wetland soils. The majority of blue carbon research, and corresponding activities, has focused on understanding, protecting, and restoring carbon sinks (e.g., tidal wetlands, seagrass meadows) and the carbon sequestration and storage processes associated with them. The carbon stored in these soils is considered to have high durability—that is, it is expected to be stored for long periods and is at low risk of reversal.

Long-term carbon storage via sequestration is a fundamental mechanism to decrease atmospheric carbon and mitigate climate change. However, increasing short-term blue carbon storage in other pools (e.g., marine fauna and macroalgae biomass) may also have climate benefits as biotic activity captures carbon and shifts it from the atmosphere to blue carbon pools. The role of these short-term blue carbon pools is less well known, and their contribution to climate mitigation depends on the magnitude of export from these short-term carbon pools to long-term carbon pools. Given the need for near-term actions to constrain the climate crisis, efforts to mitigate climate change using blue carbon need to balance the carbon durability, sequestration rate, cost-effectiveness, and management cost.

# Oregon's Coastal Blue Carbon

The climate mitigation potential of Oregon's blue carbon ecosystems depends on multiple interacting variables, including the current extent and magnitude of current carbon stocks and sequestration potential, durability of existing and future carbon stores, vulnerability to degradation, and opportunities for conservation, restoration, and changed management to provide a climate benefit.

Table 1 and the following sections summarize the best available, regionally relevant information about Oregon blue carbon. In some cases, local (e.g., PNW) research is lacking, so we have synthesized the best available information and identified areas of uncertainty, limitations in data interpretation, and/or where more research is needed to fully characterize the blue carbon potential of Oregon's coastal and nearshore ecosystems.

## Tidal Wetlands

### Overview and Extent

Oregon's tidal wetlands are highly productive estuarine ecosystems that are regularly tidally inundated. These wetlands are composed of deep-rooted perennials and categorized based on dominant vegetation cover: emergent marshes and scrub-shrub and forested tidal wetlands (collectively referred to as tidal swamps). Historically, tidal wetlands covered approximately 113,000 acres of Oregon's coast, 54% of which was emergent wetland. The extent of wetlands has been reduced to 41,000 acres due to diking as well as vegetation and land use conversion.[6] Losses of tidal wetlands in Oregon's 15 largest estuaries vary from 0% (Beaver Creek and Netarts Bay) to as much as 86% (Coquille River), and more than 95% of highly carbon-dense forested tidal wetlands have been lost, much of which cannot be easily restored due to soil subsidence.[7]

### Carbon Stocks and Sequestration

As tidal wetland vegetation photosynthesizes, it draws $CO_2$ from the atmosphere and converts it into biomass (organic carbon). As biomass dies, a portion of the dead biomass is stored, or sequestered, in tidal wetland soils through a process called vertical accretion, which is the progressive buildup of tidal wetland soils resulting from tidally driven sediment trapping and incorporating dead leaves, branches, stems, and roots into the soil. In tidal wetlands, 80%–99% of the total ecosystem carbon is stored in wetland soils,[8] which highlights the importance of the soil carbon pool and accretion over time in maintaining carbon in these ecosystems.

### Magnitude and Durability

Organic carbon stocks and carbon sequestration within tidal wetland ecosystems tend to increase along an elevation gradient, with the highest stocks found in forested tidal wetlands.[9] Soil carbon ranges from 140 to 284 Mg C/ha between low and high marshes, respectively[10] (Table 2). In forested tidal wetlands dominated by Sitka spruce, a significant portion of carbon is stored within aboveground woody biomass, and the total ecosystem carbon stocks (1063.7 ± 37.5 Mg C/ha) are on par with tropical mangroves and Oregon old-growth forests.[11]

Researchers install a soil corer in the Alsea Bay high marsh to study blue carbon burial in Oregon's tidal wetlands. Photo by Oregon Sea Grant (2017a).

[6] Beers et al., 2021
[7] Brophy, 2019
[8] Kauffman et al., 2020
[9] Gailis et al., 2021; Kauffman et al., 2020; Peck et al., 2020
[10] Gailis et al, 2021
[11] Kauffman et al., 2020

**Table 2**. Regionally relevant studies reporting blue carbon ecosystem soil carbon stocks.

| Blue carbon ecosystem | Carbon stock (Mg C/ha; mean ± SE) | Study region | Study extent | Depth | Source |
|---|---|---|---|---|---|
| eelgrass | 80 ± 7.3 | PNW | WA, OR, CA | 100 cm | Kauffman et al., 2020 |
| eelgrass | 65.12 | PNW | BC, WA, OR | 100 cm | Prentice et al., 2020 |
| eelgrass | 110 ± 11.8 | CA | CA | 100 cm | Ward et al., 2021 |
| eelgrass | 69.4 | U.S. West Coast | Alaska to Mexico | 100 cm* | Röhr et al., 2018 |
| tidal flat (unvegetated) | 98.3 | PNW | WA | 100 cm* | Poppe & Rybczyk, 2021 |
| salt marsh | 235 ± 17.7 | CA | CA | 100 cm | Ward et al. 2021 |
| salt marsh (natural) | 198.3 ± 14.7 | PNW | WA | 100 cm* | Poppe & Rybczyk, 2021 |
| salt marsh (restored) | 147.7 ± 7.3 | PNW | WA | 100 cm* | Poppe & Rybczyk, 2021 |
| salt marsh (natural) | 341.2 ± 36.9 | PNW | Tillamook, OR | 100 cm* | Brophy et al., 2018 |
| salt marsh (restored) | 374 ± 18.0 | PNW | Tillamook, OR | 100 cm* | Brophy et al., 2018 |
| salt marsh (low marsh) | 190.6 ± 11.1 | PNW | WA, OR, CA | 100 cm | Kauffman et al., 2020 |
| salt marsh (low marsh) | 140 ± 60 | PNW | BC | 100 cm* | Gailis et al., 2021 |
| salt marsh (high marsh) | 261.8 ± 16.5 | PNW | WA, OR, CA | 100 cm | Kauffman et al., 2020 |
| salt marsh (high marsh) | 284 ± 140 | PNW | BC | 100 cm* | Gailis et al., 2021 |
| scrub-shrub | 506 | PNW | OR | 100 cm* | Brophy et al., 2018 |
| tidal forest | 338.6 ± 15.5 | PNW | WA, OR, CA | 100 cm | Kauffman et al., 2020 |

*Note*. * = extrapolated.

*Note*. Carbon stocks for blue carbon ecosystems were extracted from the referenced studies and standardized to 1 m sediment depth. The carbon stocks do not include aboveground biomass for each ecosystem. BC = British Columbia, Canada; C = carbon; CA = California; OR = Oregon; PNW = Pacific Northwest; SE = standard error; U.S. = United States; WA = Washington.

Tidal wetland soil carbon stocks appear to be durable carbon sinks overall, but the stored carbon's durability depends on its location within the ecosystem. Living biomass, particularly in aboveground herbaceous foliage, is a small and short-term carbon pool compared to carbon stores within sediments serving as a long-term carbon sink. Woody vegetation stores significant amounts of carbon, and scrub-shrub wetlands appear to sequester carbon at a high rate.[12] Even unvegetated tidal flats within estuaries store carbon,[13] although the rate of flux is not well understood.

## Vulnerability to Loss

Tidal wetlands may be at risk of drowning due to rising sea levels if the rate of rising water outpaces local rates of sediment and vertical accretion. "Marsh drowning" results in tidal wetlands' slow conversion to lower elevation (relative to mean sea level) wetland types and, ultimately, to unvegetated intertidal

[12] According to ongoing work by the PNW Blue Carbon Working Group.

[13] Poppe & Rybczyk, 2021

and then subtidal flats. Progressive loss of sediment stabilization as sea level rises can accelerate tidal wetland drowning. Fortunately, due to tectonic uplift along most of the Oregon coast, it appears that blue carbon sequestration and storage processes within Oregon wetlands are largely resilient to sea level rise, except for those in the central Oregon coast where uplift rates are lower and wetland sediment and vertical accretion rates do not keep pace with the current rate of rising waters.[14]

### Opportunities, Limitations, and Uncertainties

Restoration of tidal wetlands, a conservation activity with a long history in Oregon, has restored historically lost carbon sequestration and storage functions to Oregon's blue carbon ecosystems. Ongoing tidal wetland restoration work now increasingly incorporates carbon sequestration and storage functions into the calculation of project co-benefits (i.e., ecosystem services). Scientists are working with policymakers and restoration practitioners to develop tools to facilitate the quantification of blue carbon benefits for tidal wetland restoration projects in Oregon and the PNW. The rate of carbon accumulation depends on local site characteristics and hydrology, and much of the accumulated soil carbon within recently restored sites is imported by sediment deposition instead of in situ production.[15] Restoration of scrub-shrub and forested tidal wetlands is of particular interest due to their ability to store significant amounts of carbon.[16]

In addition to restoring carbon sequestration and storage functions, tidal wetland restoration can reduce GHG emissions from former tidal wetlands converted to agricultural lands. In Oregon, both draining and impounding tidal wetlands have been practiced for a wide range of purposes, including agriculture and development. Blocking or restricting tidal flows (e.g., by installing dikes and tide gates or other infrastructure) leads to decreased salinity and degradation of the tidal wetland ecosystem. Methane emissions are partially controlled by salinity in tidal wetlands, with methane generation nearly completely inhibited at salinities greater than 18 ppt (the salinity of pure seawater is 35 ppt).[17] Thus, these degraded, less saline wetlands produce more methane emissions. Similarly, draining tidal wetlands allows air to penetrate previously inundated soils and promotes aerobic microbial respiration of the stored carbon stocks, thereby emitting $CO_2$. Reintroducing tidal flow can reduce both methane and $CO_2$ emissions from these degraded areas.[18] Restored tidal marshes (formerly diked pastures) in the Tillamook estuary had faster accretion rates and similar carbon stocks to reference sites, suggesting that restoration of tidal wetlands has high climate mitigation potential.[19]

A recent study comparing GHG fluxes from reference, disturbed, and restored coastal wetlands in Tillamook Bay and Coos Bay, Oregon, found that there can be large variability in methane emissions from oligohaline and mesohaline (i.e., brackish) systems.[20] The same study confirmed that disturbed sites had higher $CO_2e$ emissions than restored sites. The data from this study were limited to a single water year, so there is a need for longer-term monitoring of GHG flux data across restored tidal wetlands ranging in salinity. Nonetheless, restoration of mesohaline and oligohaline coastal wetlands may result in a time lag between the initial restoration and when the restored site consistently functions as a reliable carbon sink (i.e., where $CO_2e$ sequestration is higher than $CO_2e$ emissions).

For tidal wetlands to have a net climate benefit, the rate of carbon sequestration must outweigh GHG emissions. Net flux can vary widely across sites, and reliable estimates have not yet been published that capture a range of conditions. However, ongoing regional work will soon add more data about net ecosystem flux across the least-disturbed, restored, and disturbed coastal wetlands in the PNW. Coastal wetland restoration projects, where possible, should include site-specific before and after emissions monitoring emissions over 10–20 years.[21]

## Eelgrass Meadows

### Overview and Extent

Seagrass meadows in Oregon estuaries are primarily made up of eelgrass (*Zostera marina*), a flowering vascular plant adapted to temperate waters across

[14] Peck et al., 2020
[15] Poppe & Rybczyk, 2021
[16] Beers et al., 2021; Brophy, 2019
[17] Poffenbarger et al., 2011
[18] Kroeger et al., 2017
[19] Brophy et al., 2018
[20] Schultz, 2019
[21] Rosentreter et al., 2021

the northern hemisphere. Despite its widespread distribution and occurrence along Oregon's coast, the documentation of eelgrass extent is incomplete; the best estimate of maximum extent is greater than 3,600 acres.[22] Surfgrass in the genus *Phyllospadix* is another common seagrass on Oregon's outer coast. However, its contribution to blue carbon is less understood, and its overall coverage or extent is unknown.

### Carbon Stocks and Sequestration

Carbon storage and sequestration within eelgrass meadows occur through biomass production in aboveground leafy blades and belowground rhizomatous roots that stabilize carbon-rich soils. Eelgrass meadows in the PNW have lower carbon stocks and sequestration rates relative to salt marshes, scrub-shrub, and forested tidal wetlands.[23] Importantly, it appears that there is a substantial degree of connectivity between eelgrass meadows and terrestrial and marine carbon sources. Estimates suggest that the majority of soil carbon stocks within eelgrass meadows are imported from external sources (e.g., terrestrial vegetation and coastal kelp), and about a quarter of carbon is produced in situ.[24] Phytoplankton and macroalgae are major contributors to sediment carbon within eelgrass meadows,[25] and canopy-forming kelps may contribute one-third of the organic carbon within sediments.[26]

### Magnitude and Durability

The magnitude of carbon stocks and sequestration varies depending on seagrass meadow size, age, and substrate characteristics, and hydrologic conditions affect the magnitude of carbon stocks.[27] The total ecosystem carbon stock within the PNW eelgrass meadows is 217.1 ± 60.3 Mg C/ha, 99% of which is stored in soils (80 ± 7.3 Mg C/ha in top 1 m; Table 2).[28] The scientific community lacks consistently replicated methodologies, making comparison among studies difficult. Sediment cores range from 20 cm to 3 m. Where possible, this report compares values standardized to 1 m. Mean carbon stocks range from 13.4 to 110.8 Mg C/ha, depending on meadow age.[29] The average sequestration rate ranges from 0.11 to 0.25 Mg C/ha/yr (0.4 to 0.9 Mg $CO_2$e C/ha/yr; Table 3).[30]

### Vulnerability to Loss

Oregon's estuaries are likely to experience periodic marine heat waves, causing eelgrass loss from temperature stress, especially in relatively shallow bays (e.g., Netarts Bay). The effect of these heat-wave events varies among PNW estuaries due to local hydrologic characteristics, and there is evidence that the relatively deep, upwelling-influenced estuaries (e.g., Yaquina Bay and Coos Bay) may serve as eelgrass refuges on Oregon's coast during heat-stress events.[31] Invasive species may impact ecosystem processes like carbon sequestration; however, the extent to which invasive species (e.g., *Zostera japonica*) change the blue carbon contribution of native eelgrass ecosystems has not been well studied.

Seagrass in Netarts Bay, exposed while the tide is out. Photo by Oregon Sea Grant (2017c).

### Opportunities, Limitations, and Uncertainties

While evidence suggests that eelgrass meadows serve as a local carbon sink, substantial amounts of biomass can also be exported to the nearshore. The connectivity to oceanic environments results in subsequent carbon *remineralization* (i.e., the breakdown of organic matter, resulting in the release of dissolved $CO_2$), limiting its long-term carbon emission reduction potential.[32] Regardless, preventing the loss of existing seagrass meadows can prevent emissions of the current aboveground biomass and soil carbon stocks. Given the wide variation in potential carbon storage and sequestration, site-specific data that can help determine local variation in

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[22] See Table 2 in Beers et al., 2021
[23] Kauffman et al., 2020; Peck et al., 2020; Prentice et al., 2020
[24] Prentice et al., 2019
[25] Röhr et al., 2018
[26] Prentice et al., 2019
[27] Postlethwaite et al., 2018; Prentice et al., 2019; Röhr et al., 2018; Ward et al., 2021
[28] Kauffman et al., 2020
[29] Postlethwaite et al., 2018; Ward et al., 2021
[30] Postlethwaite et al., 2018; Prentice et al., 2020
[31] Magel et al., 2022
[32] Ward et al., 2021

seagrass meadow carbon stocks and flux are needed to determine the contribution of seagrasses to Oregon's estuarine blue carbon pools.[33]

In addition to retaining existing eelgrass, restoration may provide an opportunity for blue carbon sequestration. Seagrass restoration projects have demonstrated positive climate benefits, which increase over time, although it can take a decade for restored meadows to be equivalent to natural meadows.[34] However, eelgrass needs to be mapped for Oregon estuaries. The lack of knowledge on the historical extent of seagrasses in the PNW makes identifying restoration opportunities challenging.[35] Restoration has obvious conservation benefits for a multitude of species as well.

**Table 3**. Measured rates of carbon sequestration from PNW blue carbon ecosystems.

| Blue carbon ecosystem | Avg. sequestration rate (Mg $CO_2$e/ha/yr) | Gasoline-powered vehicles equivalent per hectare | Gallons of gasoline equivalent per hectare | Source |
|---|---|---|---|---|
| eelgrass | 0.9 | 0.2 | 102 | Prentice et al., 2020 |
| eelgrass | 0.4 ± 0.2 | 0.1 | 45 | Postlethwaite et al., 2018 |
| salt marsh (high marsh) | 2.8 ± 1.3 | 0.6 | 315 | Peck et al., 2020 |
| salt marsh (high marsh) | 7.3 ± 4.8 | 1.6 | 821 | Gailis et al., 2021 |
| salt marsh (low marsh) | 2.8 ± 1.4 | 0.6 | 315 | Gailis et al., 2021 |
| salt marsh (natural) | 3.1 ± 0.7 | 0.7 | 351 | Brophy et al., 2018 |
| salt marsh (natural) | 4.5 ± 1.1 | 1.0 | 506 | Poppe & Rybczyk, 2021 |
| salt marsh (restored) | 5.5 ± 2.8 | 1.2 | 619 | Brophy et al., 2018 |
| salt marsh (restored) | 8.5 ± 1.7 | 1.8 | 956 | Poppe & Rybczyk, 2021 |
| scrub-shrub | 4.4 ± 1.1 | 0.9 | 495 | Peck et al., 2020 |

*Note*. Greenhouse gas equivalencies sourced from the U.S. Environmental Protection Agency (EPA), assuming 4.640 metric tons of $CO_2$e emitted per passenger vehicle per year (with an average fuel economy of 22 mpg and 11,500 miles driven per year) and $8.887 \times 10^{-3}$ metric tons $CO_2$e emitted per gallon of gasoline.[36] $CO_2$e = carbon dioxide equivalent.

# Oregon's Marine Blue Carbon

## Seaweed

### Overview and Extent

Marine seaweeds, or macroalgae, comprise a category encompassing a diverse set of species occupying Oregon's rocky nearshore reefs. Bull kelp *(Nereocystis leutkeana*) is Oregon's major canopy-forming kelp species, whereas a diversity of red, green, and brown algae makes up the understory. The form and size of macroalgal species may affect the fate of the carbon produced. Large, robust macroalgae (e.g., kelp) are more resistant to grazing and decomposition and are more likely to contribute to carbon sequestration than smaller, more delicate species.[37] Kelp forests and

[33] Postlethwaite et al., 2018; Prentice et al., 2020

[34] Oreska et al., 2020

[35] Prentice et al., 2020

[36] EPA, 2022

[37] Krause-Jensen et al., 2018

seaweed are highly productive nearshore ecosystems on Oregon's coast and support a diversity of life and the health of ocean species.

The coverage of nearshore seaweeds varies on seasonal and yearly timescales. Annual kelp species can grow up to 2 ft (0.61 m) per day in the early summer.[38] This production of seaweed biomass results in large turnover as winter storms dislodge it from the seafloor. Understory kelp species may live on multiyear timescales. Datasets of seaweed and kelp extent are lacking, the historical cover of seaweeds is unknown, and current mapping is very limited. Canopy-forming kelp species may be mapped by remote sensing,[39] but understory species are particularly difficult because they require in-water studies with divers or remotely operated vehicles.

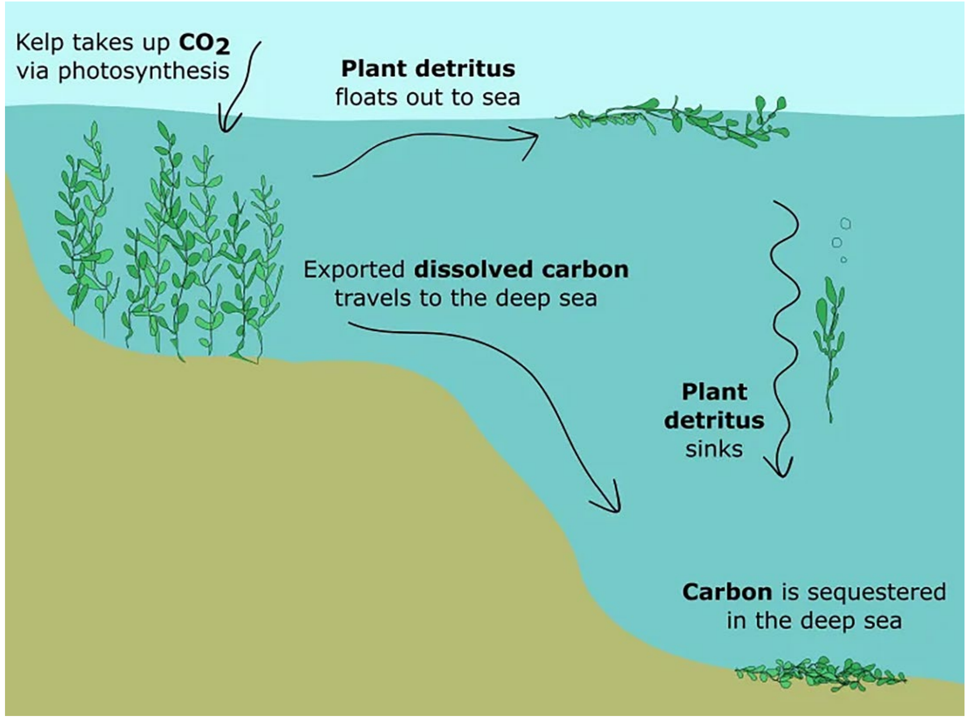


**Figure 3**. Seaweed carbon production and export in the nearshore ocean.
*Note*. $CO_2$ = carbon dioxide. From Hurlimann (2019).

## Carbon Stocks and Sequestration

Kelp forests are important producers of carbon in the coastal ocean, and researchers or other stakeholders may be missing significant amounts of carbon production by not including macroalgae-dominated ecosystems in blue carbon accounting.[40] Although kelp forests do not store much carbon in nearby sediments, there is strong connectivity between kelp beds and the deep sea, where carbon is unlikely to return to the atmosphere.[41] The sequestration of seaweed-derived carbon relies on transporting macroalgal biomass to sediments—particularly in the deep sea (Figure 3). Nearshore seaweed beds produce and export carbon-rich biomass year-round, although the magnitude varies depending on season and local conditions.[42] Herbivores, including urchins, shred large pieces of drift kelp into slow-sinking particles more likely to be transported offshore to reach deep-sea sediments—although the herbivores can be damaging to kelp forests when overabundant.[43] In fact, a sufficient supply of detrital seaweed is important to balance overgrazing by kelp forests' herbivores.[44]

## Magnitude and Durability

Generally, estimates of seaweed carbon production and sequestration rates are uncertain, and this is also the case in Oregon, where maps of seaweed and kelp distribution are lacking. Evidence suggests that seaweed-derived carbon is captured in sediment carbon sinks, but its contribution is difficult to estimate due to the lack of direct estimates of seaweed carbon burial rates.[45] One estimate calculated an average sequestration rate of 0.39 Mg C/ha/yr from

[38] Hutto et al., 2021
[39] Cavanaugh et al., 2021
[40] Filbee-Dexter & Wernberg, 2020
[41] Ortega et al., 2019; Queirós et al., 2019
[42] Queirós et al., 2019; Watanabe et al., 2020
[43] Filbee-Dexter et al., 2020; Wernberg & Filbee-Dexter, 2018
[44] Rennick et al., 2022
[45] Krause-Jensen et al., 2018

seaweeds on Australian reefs.[46] However, these estimates are likely highly variable and system dependent, so regional estimates of seaweed carbon sequestration are needed.

### Vulnerability to Loss

Warmer, more acidic oceans resulting from global climate change are expected to lead to changes within macroalgal communities, including decreased kelp forest cover.[47] Coastal kelp forest ecosystems are vulnerable to climate-driven collapse, as seen in Northern California, where greater than 90% of bull kelp was lost within one year, resulting in widespread loss of ecosystem services, including biodiversity, economic opportunities, cultural resources, and carbon pools.[48]

### Opportunities, Limitations, and Uncertainties

Seaweeds are a significant producer of marine carbon sequestered within sediments outside the habitat or exported to the deep sea. Currently, there is no robust method to account for the contributions of macroalgal habitats to marine carbon stocks, so macroalgae is left out of blue carbon strategies. The development of tools to accurately identify carbon sources—including environmental DNA (eDNA)[49]—within sediment carbon, as well as accurate macroalgal carbon burial rates, is necessary to incorporate seaweed-generated carbon into blue carbon strategies.[50] However, kelp forests are complex. At the ecosystem level, kelp forest production and export may vary due to organic inputs that shift the balance from net production to net emission.[51]

Human activities can modify the productivity of seaweed communities and their role in sedimentation, either by modifying macroalgal community structure or by impacting soft-sediment ecosystems through physical disturbance or modification of biologic communities that mediate carbon fluxes between benthic and pelagic ecosystems. These represent avoided conversion/avoided impact pathways for maintaining blue carbon (i.e., managing coastal nutrient supplies, limiting bottom fisheries, extraction, and seabed mining).[52]

Many unanswered questions remain about the role of macroalgae in Oregon's blue carbon strategies. Comprehensive datasets of nearshore seaweed extent on the Oregon coast do not exist, which is a major impediment to estimating the potential contribution of seaweed to blue carbon production and sequestration. Oregon's kelp forests face an uncertain future as nearby reefs in Northern California experience major losses, and long-term datasets of kelp extent in Oregon are sparse.[53] The variability of kelp forest extent creates challenges for predicting future needs. Restoration likely has a positive climate impact in addition to a multitude of co-benefits. However, due to the uncertainty and variability in direct carbon sequestration, seaweed carbon accounting is difficult and is unlikely to be a reliable strategy on its own to offset emissions.

## Marine Vertebrates

Blue carbon science has focused on the primary productivity of coastal and nearshore ecosystems, often based on carbon credit schemes that use place-based carbon accounting. However, large pools of overlooked carbon exist—including within the biomass of marine fauna—that could be incorporated into management practices for the purpose of climate action. This is sometimes described as *fish carbon* rather than blue carbon because of the distinct mechanism and mobility of carbon storage within living animal biomass compared to place-based blue carbon ecosystems that accumulate stable soil carbon (Figure 4). When it comes to nearshore carbon, emphasis should be broadened to include a discussion of fish carbon in addition to primary production.

Baleen whales and certain long-lived bony fishes may be considered mobile carbon resources as their tissues can store carbon in the short term. Global whaling has reduced the numbers of baleen whales to less than one-quarter of historical population sizes. The recovery of global whale populations

[46] Filbee-Dexter & Wernberg, 2020
[47] Raven, 2018
[48] Rogers-Bennett & Catton, 2019
[49] Ortega et al., 2019
[50] Krause-Jensen et al., 2018
[51] Gallagher et al., 2022
[52] Queirós et al., 2019
[53] Hamilton et al., 2020

could sequester an additional 145,000 Mg C/yr.[54] Although there will certainly be some cycling of carbon back into the environment, there is the potential to transfer carbon to the deep-sea blue carbon stocks through deadfalls, where carbon-rich carcasses sink to the seafloor. The estimation of available carbon depends on the identification of target species for management. Fish-mediated carbon export may significantly contribute to carbon export in the ocean, which facilitates long-term sequestration, but it is not well studied and left out of biogeochemical models.[55]

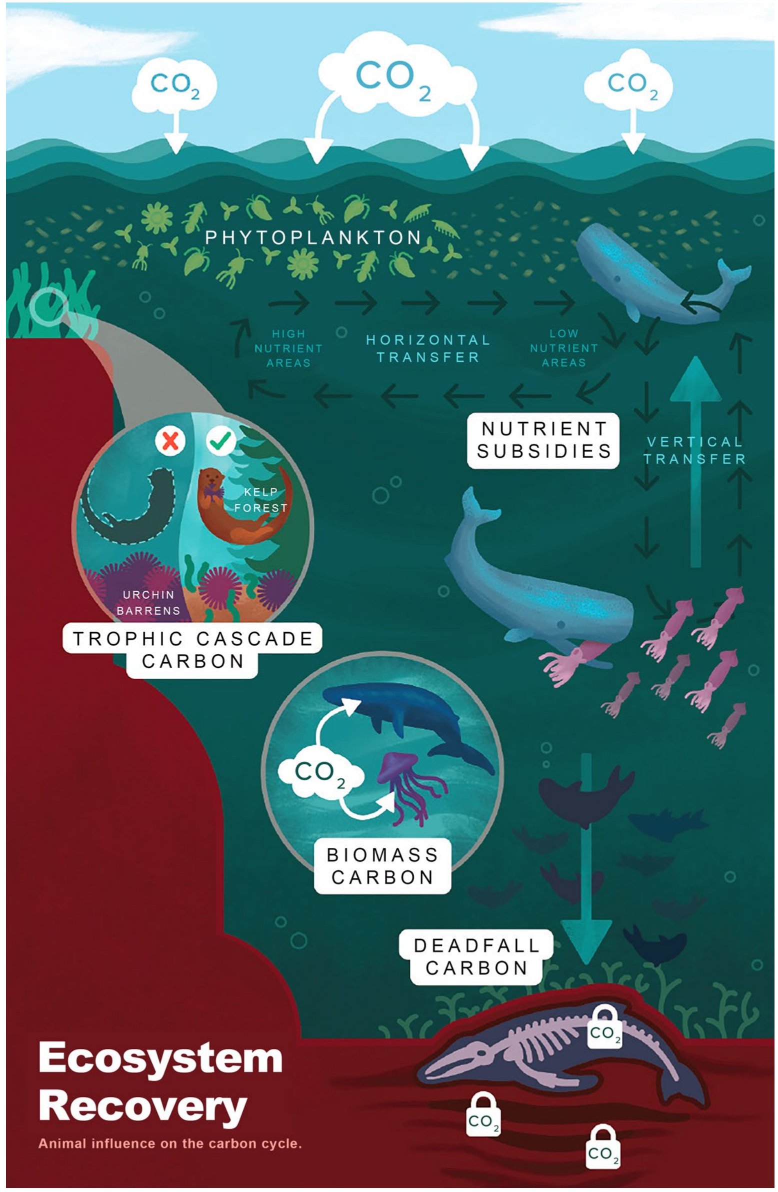


**Figure 4**. Animal influence on the marine carbon cycle.

*Note*. $CO_2$ = carbon dioxide. From the National Academies of Sciences, Engineering, and Medicine (2022, p. 156).

Additionally, marine fauna may positively affect blue carbon through indirect actions. For example, there is evidence that the presence of sea otters—a species that was extirpated from the Oregon coast in the 19th century—in kelp forest ecosystems has a significant indirect impact on net primary production.[56] Whales may fertilize phytoplankton blooms—and subsequent carbon production—by releasing nutrient-rich fecal matter at the ocean's surface.[57] In order to quantify the contribution of certain organic carbon sources, particularly for imported (allochthonous) carbon, methodologies need to be evaluated for their applicability to carbon provenance within soils of blue carbon ecosystems. This evaluation is particularly important for carbon sourced from seaweed and plankton, which are hard to quantify otherwise.[58]

Managing marine fauna as a carbon resource is complicated and without clear precedent. Whales and fish are mobile, not constrained to a particular location. Whales may migrate hundreds to thousands of miles, crossing a mosaic of management jurisdictions. Therefore, policies and programs targeting marine faunal carbon will likely be ineffective without coordination among regional partners. Identifying candidate resident species, which may be more easily managed by focusing on Oregon's jurisdictional waters, would be a necessary first step in including the biomass carbon from marine fauna in any state-level policy and management decisions. Importantly, managing marine faunal pools for carbon would include activities that may intersect with fisheries, and socioeconomic impacts are currently unknown.

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[54] Pershing et al., 2010
[55] Davison et al., 2013
[56] Wilmers et al., 2012
[57] Lutz & Martin, 2014
[58] Geraldi et al., 2019

## Marine Aquaculture

### Seaweed Aquaculture

Seaweed aquaculture (sometimes called *mariculture*, referring to the cultivation of marine species) has been proposed as another opportunity for climate mitigation on the Oregon coast. Seaweed is globally cultivated for food and other products (e.g., agar, iodine, biofuels, fertilizers)[59] and may be cultured within tanks on shore or in water on anchored lines. Current seaweed production in Oregon is minimal and in the very early stages of market production.

An aquaculture researcher at Oregon State University shows off the patented strain of Pacific dulse that he developed. Photo by Oregon Sea Grant (2015).

Seaweed production is gaining more attention in the PNW for its potential climate benefits. Fast-growing kelp species like giant kelp (*Macrocystis pyrifera*) and bull kelp may be more cost-effective due to high growth rates and carbon content.[60] Realistically, seaweed farming may play a relatively small role in mitigating GHG emissions and should be considered only one of many tools and strategies.

As an agricultural product, farmed seaweed does not appear to have direct, long-term carbon sequestration benefits overall. Its direct sequestration capacity appears low due to limited production and dependence on markets and policy. Importantly, seaweed farming may have indirect benefits by replacing carbon-intensive products with a seaweed product that has lower land use and carbon emissions than traditional agriculture. Total emissions from seaweed production (including upstream, onsite, and downstream emissions) range from 11.4 to 28.2 kg $CO_2$e per ton produced, depending on farming practices, and transportation increases maximum emissions by an order of magnitude (231 kg $CO_2$e per ton harvested). Notably, GHG emissions from seaweed production make up a small fraction of emissions associated with fed finfish aquaculture (e.g., salmonids in shore-based or floating net pens), which range from 1,380 to 44,400 kg $CO_2$e per ton produced, excluding transport.[61]

The thoughtful culture of native seaweed (i.e., restorative aquaculture) may have multiple environmental benefits, including improving water quality, reducing excess nutrients, buffering ocean acidification, seeding natural populations, and potentially sequestering carbon.[62] Combining the cultivation of kelp downstream of shellfish farms may elevate blue carbon benefits by increasing light availability for photosynthesis and reducing the epiphytic load that leads to early harvesting or complications in packaging and marketing.[63]

Seaweed aquaculture needs substantial additional research exploring biodiversity and climate benefits. Potential negative consequences include poor location and management of seaweed farms, which may negatively impact wild ecosystems and local hydrodynamics and may have seaweed disease impacts.[64]

### Shellfish Aquaculture

Questions surround whether cultivating shellfish (e.g., oysters, mussels, clams) has carbon sequestration benefits from calcium carbonate ($CaCO_3$) shell production. In seawater, the chemical formation of calcium carbonate shells is a net source of atmospheric $CO_2$ in a closed system as one molecule of carbon is released as $CO_2$ for each one that goes into forming the calcium carbonate shell. This effect is

[59] Jones et al., 2022
[60] Froehlich et al., 2019
[61] Jones et al., 2022
[62] The Nature Conservancy, 2021
[63] Hargrave et al., 2021
[64] Froehlich et al., 2019

more pronounced in colder waters.[65] However, cultivated shellfish are cultured in water and then removed from the system and used for other purposes. The net carbon effect of shellfish products depends on the use. Calcium carbonate shells produced from culturing bivalve shellfish are an abundant, cheap, sustainable resource that could be used in industry and construction. Some uses may have carbon sequestration benefits and reduce the need for energy-intensive mining (e.g., aggregate for mortar mix), while other uses would lead to the release of stored carbon (e.g., poultry supplement, agricultural lime).[66]

Although shellfish aquaculture may sometimes have a net climate benefit, the overall effect appears to be marginal. More studies are needed to direct the industry forward with regard to climate and the use of industry byproducts. Emissions from shellfish production range from −5 to 1,870 kg $CO_2$e per ton produced, depending on the production method, and transportation increases the maximum emissions to 2,740 kg $CO_2$e per ton. Because shell formation usually is a net source of $CO_2$, including those emissions in accounting increases the mean emissions estimate by 219%.[67] There are additional potential climate impacts from shellfish production if co-located with seagrass meadows, although some practices, such as raised culture beds, may reduce disturbance. Industry emissions and associated impacts on other blue carbon ecosystems need to be evaluated for Oregon.

## Blue Carbon Next Steps

Oregon is among the coastal states with the most plentiful and best-quality blue carbon data.[68] Regionally specific knowledge varies depending on the ecosystem, and carbon dynamics are relatively well understood in some and poorly understood in others. Additional needs related to broader information gathering include improved mapping and inventories. There are several areas to move ahead with blue carbon work on the Oregon coast, as discussed below.

### Filling the Information Gaps/Research Needs

Blue carbon data gaps for Oregon's tidal wetlands are rapidly being filled, and the remaining major data gaps related to coastal blue carbon in the PNW should largely be addressed by the end of 2023. Results from a collaborative research project underway to analyze gas flux data at 33 project sites in Oregon and Washington are expected to be available in the next year. These efforts to measure carbon stocks, gas fluxes, and carbon sequestration rates within natural and disturbed tidal wetland types will advance the understanding of blue carbon dynamics in the region.

Improved mapping of the current and potential extent of specific blue carbon ecosystem habitats is needed for more refined estimates of carbon production and sequestration. This need applies to all wetland types and land uses, in addition to submerged aquatic vegetation (seaweed, eelgrass), to identify potential blue carbon restoration areas at a local scale. It has previously been identified as a data need for Oregon.[69] The Coastal and Marine Ecological Classification Standard (CMECS) maps have widespread coverage of tidal wetlands at the state and regional scale. But eelgrass mapping needs to be expanded, and the accuracy of scrub-shrub and forested tidal wetland extent needs to be improved. There is an ongoing collaborative effort to pilot a method to refine these CMECS maps of blue carbon potential and identify restoration sites within the Coos and Yaquina estuaries, with special attention paid to scrub-shrub and forested tidal wetlands. This work will need to be scaled up coast-wide to streamline blue carbon project identification in Oregon. In addition, monitoring changes in blue carbon over time will require regularly updating these spatial datasets.

Filling information gaps related to mapping refinements, maximum eelgrass extent, inventories of restoration and restoration opportunities, and blue carbon prioritization maps will aid in prioritizing and implementing activities to enhance and maintain blue carbon. Additionally, understanding the carbon dynamics within estuaries and between estuaries

[65] Morris & Humphreys, 2019
[66] Jones et al., 2022
[67] Jones et al., 2022
[68] Holmquist et al., 2021
[69] Beers et al., 2021

and nearshore ecosystems can help clarify the relative role of blue carbon activities in climate mitigation. Because salinity is a major driver of GHG flux in blue carbon ecosystems, better salinity mapping can aid in identifying restoration and protection opportunities. Climate change, sea level rise, and the migration of estuarine and coastal habitats may affect blue carbon resources in the future, but how vulnerable these ecosystems are remains unresolved. As such, specific strategies to minimize the risk to the blue carbon in these ecosystems from climate change, sea level rise, and habitat migration are not fully known.

Regional blue carbon data are available through a database developed by the PNW Blue Carbon Working Group in coordination with the Smithsonian Institution's Coastal Carbon Research Coordination Network (CCRCN). The database makes data available online through CCRCN's Coastal Carbon Atlas.[70] A subset of the regional blue carbon data will be available through the National Estuarine Research Reserve System's (NERRS's) centralized Database Management Office.[71] These data provide opportunities to facilitate the analysis of regional blue carbon data to address questions from planners, policymakers, and restoration practitioners. The information summarized from database information may help fill knowledge gaps related to the "recovery time" of carbon after ecosystem restoration. Also, it may help identify how long it takes for GHG emissions accrued during restoration to be "paid off" by carbon sequestration and storage in restored blue carbon ecosystems.

A recent congressional investment will fund the Oregon Kelp Alliance to perform kelp forest surveys and develop a kelp restoration plan for Oregon's nearshore ocean.[72] Exploratory studies are needed to understand carbon fluxes within nearshore seaweed beds and whether kelp forest restoration—through planting, urchin-culling, or sea star recovery—is possible on Oregon's coast and the magnitude of additional carbon storage. Managing oceanic carbon is still in its early stages and requires managers' creativity to incorporate carbon practices into fisheries and wildlife management.

Seaweed and shellfish aquaculture require further study to understand the cases that may provide a net climate benefit, including opportunities for co-culturing seaweed and shellfish production. Also, research is needed on how aquaculture may impact associated blue carbon ecosystems within estuaries. Furthermore, there is a need to better understand the balance of emissions and sequestration based on current shellfish aquaculture practices implemented in Oregon, including the effect of downstream uses of shell material. The budding seaweed aquaculture industry in Oregon should have guidance on (a) identifying best practices to develop sustainably (including opportunities for restorative seaweed aquaculture), (b) market analysis for carbon-friendly aquaculture products, and (c) a development timeline.

## High Potential Areas

While considerable uncertainty still exists on the magnitude of climate mitigation from blue carbon activities, the current science suggests that the following activities are likely to provide some climate mitigation benefits.

- The preservation of existing estuarine and nearshore ecosystems is hugely important for maintaining biodiversity and ecosystem services, including carbon storage.
- Estuary-based conservation projects using existing carbon accounting methodologies are practical and enhance carbon sequestration in tidal wetlands and eelgrass meadows.[73]
- Restoration of tidal flow to diked and drained wetlands generates climate benefits by reducing GHG emissions.
- Site-specific evaluations are necessary to estimate the precise magnitude of the benefit, and a blue carbon calculator is in development as a tool to facilitate these estimations.
- Evidence provides reasonable confidence that the restoration of scrub-shrub tidal wetlands

[70] https://ccrcn.shinyapps.io/CoastalCarbonAtlas/
[71] https://nerrssciencecollaborative.org/project/Cornu16
[72] Merkley (n.d.).
[73] Christianson et al., 2022; Crooks et al., 2014

provides carbon benefits, which should be emphasized in restoration plans.

- Benefits from blue carbon restoration accrue on a decadal scale depending on flux, and practitioners should expect a lag time between restoration and the generation of large carbon gains. Thus, estuary-based projects are needed sooner rather than later to see significant carbon reductions ahead of upcoming climate deadlines.

## Blue Carbon Offset Projects

Conservation, restoration, and ecosystem management activities that lead to climate mitigation via blue carbon may include projects developed as part of carbon offset markets—that is, carbon credits resulting from the project are sold or transferred as carbon credits. *Carbon credits* are measurable, verifiable emission reductions that result from certified offset projects that reduce or avoid GHG emissions or sequester carbon. These carbon credits can then be sold via carbon markets. Once an entity or individual buys a carbon credit, it is permanently retired so that it cannot be reused.

Blue carbon projects do not need to be enrolled in a carbon offset program to generate climate mitigation benefits but do need to be enrolled if the project developer intends to sell the resulting carbon to organizations or individuals trying to reduce their own GHG emissions through carbon accounting. Carbon offset projects must adhere to a rigorous set of criteria to pass verification by third-party agencies and a review by a panel of experts in a leading carbon offset standard like Verra or Gold Standard. Not all blue carbon activities that lead to climate benefits can be enrolled in carbon offset programs because they lack verified methodologies.

Salmon River estuary. Photo by Beebe (2008).

The VCS Program,[74] which is managed by Verra and is the largest voluntary GHG program, currently has approved methodologies for tidal wetland and seagrass conservation and restoration. Methodologies set out detailed procedures for quantifying a project's real GHG benefits and provide guidance to help project developers determine project boundaries, set baselines, assess additionality, and ultimately quantify the GHG emissions that were reduced or removed due to project implementation. The VCS Methodology for Tidal Wetland and Seagrass Restoration is the most likely to be used for PNW blue carbon projects. It includes a range of accounting methods to quantify GHGs, including default values, emission factors, published values, models, proxies, and field-collected data. In most cases, some field sampling and monitoring of soil carbon and GHG emissions will be necessary since published models and proxies are lacking.

Developing carbon projects requires many carefully tracked technical, financial, and legal components. A feasibility assessment is highly recommended to determine if any potential projects meet the eligibility criteria, to assess the availability of data and other resources, and to evaluate associated costs. Crooks et al.[75] completed a blue carbon feasibility assessment for the PNW. At the time, the researchers concluded that restoration of tidal freshwater forests offered net GHG removals but that for projects less than 100 ha, the costs would outweigh the revenue generated by carbon offsets. They further concluded that the lack of GHG emission data was a large data gap for the PNW region. Measuring GHG fluxes and projecting the baseline scenario is the most technically complex part of blue carbon projects, and the ongoing work by regional blue carbon experts to fill this data gap will be critical.[76]

[74] https://verra.org/project/vcs-program/

[75] Crooks et al., 2020
[76] Emmer et al., 2015

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