Development and assessment of freshwater mussel growth-increment chronologies in the Pacific Northwest

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Introduction

In rivers and streams throughout the Pacific Northwest, water quality in terms of flow and temperature can be significantly impacted by human activities including timber harvest, flow regulation, and point source discharges. Given the implications for salmon, trout, and overall watershed health, numerous efforts headed by state and federal agencies have targeted rehabilitation. However, a limitation to these restoration efforts is uncertainty as to historical range of variability associated with "natural" stream conditions and thermal regimes, especially on multidecadal timescales. Knowledge of baseline stream conditions and long-term dynamics would greatly help in setting restoration goals and evaluating restoration success. Temperature and flow records provide some insight, but such data sets are often scarce. In Oregon, records exceeding 20 years in length, and are often very fragmented with missing years of data. Thus instrumental records, while critically important, can provide only a limited snapshot of stream conditions over time and are unsuitable for quantifying longer-term patterns of variability. Due to limited resources, continuous instrumental records are unavailable for the vast majority of water bodies in the state, as is true elsewhere in the region.

Whereas instrumental records of environmental variability are typically limited in availability, there are opportunities in many environments to reconstruct historical conditions through analyses of age and growth of long-lived organisms. Although tree-rings are the archetypal example, recent studies have demonstrated that a wide array of long-lived animals also form annual growth increments, which can be analyzed using techniques developed by dendrochronologists. To date, the majority of these studies have assessed marine species. For example, multi-decadal growth chronologies have been developed for several species of Pacific rockfish, and correlate strongly with measures of ocean circulation such as upwelling and the El Nino Southern Oscillation (Black et al. 2005, 2008a). Pacific geoduck clams and Atlantic quahogs also closely record environmental variability, capturing 60% or more of variance in sea surface temperatures and allowing for reconstructions that extend many decades prior to the start of instrumental records (Schone et al. 2004a, Strom et al. 2004, Black et al. 2008b). Resulting chronologies are of annual precision and with data quality statistically verified to be as high as that of tree-ring chronologies. Furthermore, rockfish chronologies significantly (negatively) correlate with tree ring chronologies at high elevation in the Cascade Mountains and Sierra Nevada Mountains, also corroborating accuracy and demonstrating the interrelatedness of ecosystems in the Pacific Northwest (BA Black, unpublished data).

In freshwater systems, unionid mussels may provide long-term records of their surroundings much as tree-ring data do for terrestrial systems. Like trees, freshwater mussels are long lived, form annual growth increments, and preliminary studies indicate the widths of those increments are controlled by various aspects of the aquatic environment. In Europe, growth increment chronologies from pearl mussel shells (*Margaritifera margaritifera*) have been calibrated against water and air temperatures, allowing reconstruction of temperatures over the past 200 years (Schone et al. 2004b). Pilot studies in Vancouver British Columbia and the Willamette River indicate that a similar approach may be possible in Oregon streams using the closely related western pearlshell (*M. falcata*) mussel, which can live to at least 80 years of age (B. Schoene, personal communication; B. Black and J. Dunham, unpublished). Unpublished results from work in the Columbia River basin (cited in Chatters et al. 1995) have been applied to reconstruct thermal regimes from growth chronologies of unionid mussels (*M. falcata* and *Gonidea angulata*).

Mussels could be treated as living environmental chronometers analogous to instrumentation, but with the added advantage of providing historical data from the past several decades through the present. These living recorders of the stream environment could be used as proxy of various stream parameters where instrumentation is not feasible or is too expensive to install, for a historical perspective that predates existing instrumental records, and for filling in gaps that exist in instrumental records. To explore these possibilities, we develop two freshwater mussel chronologies in western Oregon from the species *Maragritifera falcata*. Our objectives are to i) determine the feasibility of applying tree-ring techniques to build high resolution, multi-decadal chronologies that capture variability on a range (inter-annual to decadal) of timescales, ii) determine the environmental (climatic) factors that limit growth, iii) evaluate the potential of this species in reconstructions of stream flow and temperature iv) compare freshwater mussel chronologies with tree-ring chronologies to demonstrate linkages between freshwater and terrestrial ecosystems and evaluate the strengths and weaknesses of these two proxies.

Methods

In the summer of 2006 thirty live *Margaritifera falcata* were collected from two localities in the Willamette River. One collection was made in the river near Albany, Oregon directly upstream of the confluence of the Calapooia River. A second collection was taken in the Middle Fork of the Willamette River downstream of Dexter Reservior at Elijah Bristow State Park. The latter site was chosen for its proximity to USGS gage 14150000, which provided long-term data on stream discharge and temperature. Additional details of these locations will be reported later.

Mussel valves were embedded in JB Qwik Weld resin and thin-sectioned using a diamond lapidary saw. Sectioning followed the axis of minimum growth from the umbo to the ventral margin, perpendicular to surface growth increments. A total of three thin-sections approximately 0.5 mm in thickness were taken from both the left and right valve, mounted on glass slides, and polished using 2000 grit sandpaper and 0.5 um lapping film. One section from each valve was stained with Mutvei's solution in an attempt to increase the visibility of annual growth increments (Schone et al. 2005). Growth increments in the prismatic layer of the umbo were used in chronology development due to their consistently and contrast. The clearest thin-sections from the oldest individuals were

then selected for chronology development. Within each collection (Bryant Park and Middle Fork Willamette), samples were visually crossdated using the "list year" technique in which synchronous patterns were matched among samples, working back through time from the marginal growth increment formed during the known calendar year of capture toward the hinge (Yamaguchi 1991). Crossdating ensured that all growth increments had been correctly identified and assigned the correct calendar year. Transmitted light was best for viewing the growth increments, though reflected light produced superior results in a small subset of samples. We found that staining with Mutvei's solution enhanced growth increment contrast in samples from Bryant Park, but accented a greater degree of "noise" in samples from the Middle Fork of the Willamette, which were best viewed without any chemical treatment.

Once visual crossdating was complete, growth increment widths were measured using the program ImagePro Plus v. 6.0 (Media Cybernetics, Silver Spring, Maryland). Images were captured with a Leica DC300 7.2 megapixel digital camera attached to a Leica $MZ9_5$ dissection scope. For each sample, multiple overlapping pictures were taken and tiled together into a single panorama. Growth increments were then measured continuously from the margin to as close to the hinge as possible, though innermost increments were often excluded due to erosion on the valve surface. One axis was measured per valve for a total of two measurement time series per individual.

At each site, crossdating was statistically verified using the International Tree-Ring Data Bank Program Library program COFECHA, available thorough the University of Arizona Laboratory of Tree-Ring Research http://www.ltrr.arizona.edu/pub/dpl/ (Holmes 1983, Grissino-Mayer 2001). This procedure involved isolating high-frequency variability in each set of measurements via the process of detrending, and then cross-correlating the detrended measurements to verify that all samples aligned with one another. In COFECHA, detrending was accomplished by fitting each set of mussel measurements with a cubic spline set at a 50% frequency response of 22 years, a wavelength that provided optimal crossdating verification results in splitnose rockfish and Pacific geoduck (Black et al. 2005, Black et al. 2008b). Once fitted, each set of mussel measurements was divided by the values predicted by the cubic spline, thereby removing low-frequency variability, homogenizing variance, and equally weighting each set of measurements to a mean of one (Holmes, 1983; Grissino-Mayer, 2001). Each detrended set of mussel measurements was then correlated with the average of all other detrended sets of mussel measurements in the sample. In so doing, the high frequency growth pattern of each individual was compared to the high frequency growth pattern of all other individuals. Isolating only the high frequency, serially independent growth pattern prevented spuriously high correlations among individuals, and also mathematically mimicked the process of visual crossdating. Any measurement time series with unusually low correlations were double checked for errors.

After verifying crossdating, we developed a master chronology for each site by detrending the original mussel measurement time series with negative exponential functions. Detrending with negative exponential functions removed age-related growth declines while preserving any remaining low-frequency variability, much of which could have been induced by climate. At each site, all detrended series were then averaged into a master chronology using a biweight robust mean to reduce the effects of outliers (Cook 1985). All chronology development was conducted using the program ARSTAN

(developed by Ed Cook and Paul Krusic; available at http://www.ldeo.columbia.edu/res/fac/trl/public/publicSoftware.html) (Cook 1985).

Records of annual discharge and water temperature were obtained for the Middle Fork of the Willamette River and related to the mussel chronologies. In addition to mean discharge and temperature, we also determined maximum annual temperature and the number of days in which temperature exceeded ten degrees Celsius. Monthly precipitation, mean temperature, and Palmer Drought Severity Index (PDSI) were obtained from the NOAA National Climatic Data Center for Oregon Division Two. Finally, mussel chronologies were related to the Multivariate ENSO Index (MEI), the leading principal component of six marine and atmospheric variables in the tropical Pacific (Wolter and Timlin 1998). Monthly averages of climatic variables were related with mussel chronologies to investigate the periods during the year in which this species is most sensitive to environmental variability.

Results and Discussion

Strongly synchronous growth patterns occurred at each site, allowing for crossdating even with these relatively short-lived individuals. We found no "missing" rings in any of the individuals used in chronology development; however, some discarded samples were severely damaged with periods of highly irregular and potentially incomplete growth patterns. Even in the samples that were used in the final chronologies "checks" or "false rings" frequently occurred. These checks were generally limited to the prismatic layer in comparison to true increments, which continued through to the inner nacreous layer. Ultimately, crossdating provided the final test for distinguishing the most challenging checks and verified that all growth increments had been correctly identified. Of the original thirty specimens collected at each site, nine from the Middle Fork of the Willamette and eight at Bryant Park were clear enough and old enough (> 20 yrs in age) for measurement.

Statistical verification of crossdating revealed highly significant correlations among samples within each of the two collections, and at levels commonly found in many tree-ring and Pacific geoduck growth increment data sets from the region (Table 1) (Gedalof and Smith 2001, Black et al. 2008b). Also, mean sensitivity, an index of year-to-year variability, approaches 0.2, a value commonly attained by tree-ring data used in climate reconstructions (Fritts 1976). Although mean length of the measurement time series was just over twenty years in both chronologies, actual mussel ages were almost certainly greater (Table 1). Many specimens experienced erosion through the prismatic layer and into the nacreous layer, obscuring the earliest growth increments. Furthermore, two individuals from Bryant Park were well over 40 years in age, but had experienced such significant damage that they were unsuitable for use in chronology development. With additional collections, mussel chronologies could almost certainly be extended.

Final chronologies extend from 1978-2004 for Bryant Park and 1981-2005 for the Middle Fork of the Willamette. The spans reported for both chronologies included only that interval shared by a minimum of six measurement time series, the sample depth necessary to ensure EPS values greater than 0.85. In comparison to one another, the two chronologies were only weakly correlated ($r = 0.39$), indicating that though growth patterns were much more strongly conserved within each site than between sites (Figure 1). Despite these differences, both chronologies did, however, relate similarly to

instrumental records of water temperature and discharge taken from the Middle Fork of the Willamette. As for maximum water temperatures, correlations were consistently positive for both chronologies, though only that with the Middle Fork of the Willamette chronology was significant ($p < 0.05$) (Figure 2A). Relationships with mean temperature or days at which water temperature exceeded 10ºC were also positive, but weaker and less consistent than those with maximum water temperature (data not shown). Overall, these correlations were dominated by outliers and must be interpreted with caution. If the two year of greatest mussel growth (1992 and 2001) were dropped, all correlations with temperature variables fell below significant levels. By contrast, relationships with mean annual discharge were much more linear and of greater significance ($p < 0.01$) in both chronologies. These correlations with discharge were consistently negative, not only for the Middle Fork of the Willamette, but also for instrumental records at three other locations along the Willamette River: Dexter, Harrisburg, and Albany (Figure 2B). With respect to these three additional discharge records, correlations with the Middle Fork of the Willamette chronology were all significant ($p < 0.05$) while Bryant Park was significantly correlated only with the record from Dexter. Averaging the two mussel chronologies did, however, provide highly significant ($p < 0.01$) correlations with discharge records at all four sites (r = -0.68 Middle Fork Willamette, -0.54 Albany, -0.55 Harrisburg, and -0.53 Dexter). Indeed a regression between the average of both chronologies and the mean discharge at the Middle Fork of the Willamette yielded an R^2 of 0.46. An average of the two chronologies did not provide an equivalent increase in correlations with temperature records (data not shown).

Both chronologies also significantly correlated with seasonal averages of precipitation, PDSI, air temperature, and the MEI (Figure 3). Consistent with negative relationships between growth and water discharge, the mussel chronologies negatively correlated to precipitation and PDSI, indices in which high values indicate wet conditions (Figure 2). Also, as was found for water temperatures, correlations with air temperature tended to be positive, at least for the Bryant Park chronology (Figure 3). These relationships were, however, far from consistent among seasons, and the greatest correlations occurred during the winter and spring of the current year (Figure 3). For the Middle Fork of the Willamette chronology correlations were greatest with PDSI and precipitation while for Bryant Park, correlations were greatest with temperature (Figure 2). Bryant Park also showed significant relationships with temperature, but later in the year during fall (Figure 3B). Furthermore, Bryant Park was strongly related to the MEI, especially in the spring months. The R^2 in a regression between spring MEI and the Bryant Park chronology was 0.33, underscoring the degree to which growth related to an index of broad-scale ocean variability. An average of both chronologies was much more weakly related to precipitation, air temperature, PDSI, or MEI than either chronology alone (data not shown).

Ultimately, relationships with precipitation, air temperature, PDSI, and MEI must be carefully interpreted, as these variables can only influence mussel growth through indirect effects on the aquatic environment. An understanding of the potentially complex interactions among air temperature, precipitation, stream flow, and water temperature would be necessary to fully interpret these climate-growth relationships. Yet they are at least consistent with the climate-growth relationships established for direct measurements of flow and water temperature, and also indicate that the two mussel chronologies are

most sensitive to environmental variability in the winter and spring months. Finally, correlations with precipitation, air temperature, PDSI, and MEI underscore the fact that each chronology captures a somewhat unique climate signal, as is also evidenced by a more thorough analysis of the relationships between growth and discharge. For example, a stepwise regression ($p < 0.05$ to enter) reveals the Bryant Park mussel chronology accounts for 33% of the variance in discharge records, and that the Middle Fork of the Willamette chronology accounts for an additional 14%, bringing total variance explained to 47%. Mallow's Cp in the two-variable model is 3.0, and variance inflation factors are both at 1.18 in the model, indicating no significant problems with collinearity. A combination of these two differing "perspectives" yields more robust relationships with environmental variables than either chronology could provide individually.

Climate-growth relationships identified for these two western Oregon mussel chronologies contrast with those described in other studies. For example, growth increment width for *Margaritifera margaritifera* in Sweden is positively related to water temperatures in June, July, and August, with the strongest relationships in the northernmost sites, suggesting that cold summers limit growth (Schone et al. 2004b). In the Columbia River, to which the Willamette River is a tributary, mean *M. falcata* growth in the ninth and tenth years positively related to the number of days at which water temperature exceeded 10ºC, and with an R^2 of 0.89 (Chatters et al. 1995). Farther north near Vancouver, British Columbia, Canada, an *M. falcata* growth increment chronology negatively correlated to June air temperatures, and positively correlated with summer and winter precipitation, opposite to those identified in our Willamette River chronologies (Schone et al. 2007). In tree-ring studies, limiting factors, and consequently climate-growth relationships, can vary considerably within and among species and across various temporal and spatial scales (Fritts 1976, Cook and Kairiukstis 1990). For mussels, *M. margaritifera* are near the northern boundaries of their natural range, explaining their sensitivity to temperature (Schone et al. 2004b). Yet near Vancouver, a positive relationship between *M. falcata* growth increment width and precipitation is likely due to the fertilization effect from runoff in an agricultural landscape (Schone et al. 2007). The negative relationships between growth and flow in western Oregon, particularly in the winter months, may be due to damage from flooding. If even handling freshwater mussels can induce "disturbance marks" and reduce growth as has been reported for other freshwater mussel species (Haag and Commens-Carson 2008), high water events are likely to be traumatic. As evidence of damage, shell surfaces were often considerably eroded, and cross-sections contained multiple disturbance marks. A sensitivity to discharge could also explain climate-growth relationships with ENSO, which in Oregon is linked to streamflow (Beebee and Manga 2004).

Considering these climate-growth relationships, freshwater mussels in western Oregon could serve as proxies for reconstructing stream flow. The average of the two mussel chronologies accounts for 46% of the variance in Middle Fork of the Willamette discharge records. The same amount of variance is explained if the two chronologies are entered into multiple stepwise regression ($p < 0.05$ to enter), arriving at the same result but with one less degree of freedom. In comparison, a tree-ring chronology from 217 Douglas-fir in the Blue River watershed, located approximately 30 km north of the Middle Fork of the Willamette, explains 19.8% of the variance in the river discharge data. When lagged by one year, the tree-ring chronology also relates to the freshwater

mussel chronology with an R^2 of 0.28. Tree growth is positively related to PDSI, and negatively related to mussel growth, consistent with Douglas-fir's reputation as a drought sensitive species. Furthermore, this tree-ring chronology correlates more strongly with moisture status form the previous summer, explaining stronger correlations when lagged with respect to the mussel chronology. Overall, tree-ring data fail to relate as strongly to river discharge data, underscoring the strength of freshwater mussels at capturing this environmental signal. More importantly, relationships between mussel and tree growth underscore the pervasive and synchronizing effects of climate, even between marine and freshwater systems in western Oregon.

As for reconstructions of river discharge from freshwater mussels, a significant drawback is the short length of the final mussel chronologies. Also, other proxies may serve as better indicators. In particular, the Palmer Drought Severity Index, with records back to 1895, accounts for 80% of the variance in the discharge record. Adding the average freshwater mussel chronology in a stepwise multiple regression brings the total discharge variance explained to 87% (Figure 4). Thus, PDSI could serve as a very strong indicator of discharge in the Middle Fork of the Willamette over the past 100 years, with mussels explaining at least some additional variance over the past thirty.

Despite this finding, mussels can still yield valuable data regarding stream history, particularly with respect to fine-scale variability. First, PDSI or precipitation are regional variables, and would not detect local patterns. Major disturbances significant human activity could alter the stream environment in ways that could not be captured by regional precipitation or air temperature data. For example, dams, wildfires, or logging could significantly affect the freshwater ecosystem independent of broad-scale PDSI indicators. Furthermore, mussel longevity may be much greater than thirty or forty years. In other locations, *M. falcata* may live to be more than eighty years, with the potential for even greater ages, particularly farther north. Time series of such length could be crossdated with dead shells from middens or historical collections to generate much longer master chronologies. Such an approach in Sweden led to the development of a partial 217-year freshwater mussel chronology sensitive to water temperatures (Schone et al. 2005). Almost certainly such an approach could be utilized in the Pacific Northwest with the collection of older populations. Even if crossdated chronologies are impossible to construct, particularly over timescales of thousands of years, climate-growth relationships could still be used to identify long-term trends in the environment (Chatters et al. 1995).

Perhaps more importantly, the utility of mussels is not limited to climate reconstructions. Comparisons among chronologies will reveal the diversity of growth patterns and the environmental rivers of those patterns across the landscape. Networks of mussel chronologies could show gradients in environmental regimes, and the connectivity of aquatic ecosystems throughout the region. From a more ecological perspective, mussel chronologies reveal how these species respond to the environment, and provide context for interpreting how climate variability and change could effect growth and potentially survival. Population age structures in mussel populations, as determined through crossdating, could also provide information on salmonid species, on which mussels rely for dispersal. Finally, mussel chronologies serve as an overall indicator of the aquatic ecosystem, and can be compared to chronologies from other species in contrasting environments, as highlighted by their correspondence with tree-

ring chronologies in the western Cascade Mountains. Mussel chronologies could also be linked to a growing number of chronologies from marine species, demonstrating climate-driven interrelationships among highly diverse ecosystems and taxa in the Pacific Northwest. As more chronologies are developed, freshwater mussels could be applied for a number of climate and ecological-related studies throughout the region.

Literature Cited

Beebee, R. A. and M. Manga. 2004. Variation in the relationship between snowmelt runoff in Oregon and ENSO and PDO. Journal of the American Water Resources Association **40**:1011-1024.

Black, B. A., G. W. Boehlert, and M. M. Yoklavich. 2005. Using tree-ring crossdating techniques to validate annual growth increments in long-lived fishes. Canadian Journal of Fisheries and Aquatic Sciences **62**:2277-2284.

Black, B. A., G. W. Boehlert, and M. M. Yoklavich. 2008a. A tree-ring approach to establishing climate-growth relationships for yelloweye rockfish in the northeast Pacific. Fisheries Oceanography:In press.

Black, B. A., D. Gillespie, S. E. MacLellan, and C. M. Hand. 2008b. Establishing highly accurate production-age data using the tree-ring technique of crossdating: a case study for Pacific geoduck (*Panopea abrupta*). Canadian Journal of Fisheries and Aquatic Sciences:In press.

Chatters, J. C., V. L. Butler, M. J. Scott, D. M. Anderson, and D. A. Neitzel. 1995. A paleoscience approach to estimating the effects of climatic warming on salmonid fisheries of the Columbia River basin. Pages 489-496 *in* R. J. Beamish, editor. Climate change and northern fish populations. National Research Council of Canada, Ottawa.

Cook, E. and L. Kairiukstis. 1990. Methods of dendrochronology : applications in the environmental science. Kluwer Academic Publishers, Dordrecht, Netherlands ; Boston.

Cook, E. R. 1985. A Time-Series Analysis Approach to Tree-Ring Standardization. Thesis (Ph.D.). University of Arizona, Tucson, AZ.

Fritts, H. C. 1976. Tree rings and climate. Academic Press, London ; New York.

Gedalof, Z. and D. J. Smith. 2001. Dendroclimatic response of mountain hemlock (*Tsuga mertensiana*) in Pacific North America. Canadian Journal of Forest Research **31**:322-332.

Grissino-Mayer, H. D. 2001. Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. Tree-Ring Research **57**:205-221.

Haag, W. R. and A. M. Commens-Carson. 2008. Testing the assumption of annual shell ring deposition in freshwater mussels. Canadian Journal of Fisheries and Aquatic Sciences **65**:493-508.

Holmes, R. L. 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bulletin **43**:69-78.

Schone, B. R., A. D. F. Castro, J. Fiebig, S. D. Houk, W. Oschmann, and I. Kroncke. 2004a. Sea surface water temperatures over the period 1884-1983 reconstructed from oxygen isotope ratios of a bivalve mollusk shell (*Arctica islandica*, southern North Sea). Palaeogeography Palaeoclimatology Palaeoecology **212**:215-232.

Schone, B. R., E. Dunca, J. Fiebig, and M. Pfeiffer. 2005. Mutvei's solution: An ideal agent for resolving microgrowth structures of biogenic carbonates. Palaeogeography Palaeoclimatology Palaeoecology **228**:149-166.

Schone, B. R., E. Dunca, H. Mutvei, and U. Norlund. 2004b. A 217-year record of summer air temperature reconstructed from freshwater pearl mussels (M. margarifitera, Sweden) (vol 23, pg 1803, 2004). Quaternary Science Reviews **23**:2057-2057.

Schone, B. R., N. A. Page, D. L. Rodland, J. Fiebig, S. Baier, S. O. Helama, and W. Oschmann. 2007. ENSO-coupled precipitation records (1959-2004) based on shells of freshwater bivalve mollusks (Margaritifera falcata) from British Columbia. International Journal of Earth Sciences **96**:525-540.

Strom, A., R. C. Francis, N. J. Mantua, E. L. Miles, and D. L. Peterson. 2004. North Pacific climate recorded in growth rings of geoduck clams: A new tool for paleoenvironmental reconstruction. Geophysical Research Letters **31**:1-4.

Wolter, K. and M. S. Timlin. 1998. Measuring the strength of ENSO events - how does 1997/98 rank? Weather **53**:315-324.

Yamaguchi, D. K. 1991. A simple method for cross-dating increment cores from living trees. Canadian Journal of Forest Research **21**:414-416.

Table 1. Freshwater mussel chronology properties.

chronology	mussel sample size [a]	mean sensitivity [b]	interseries correlation [c]	mean series length (years)
Middle Fork Willamette	18	0.24	0.71	20.3
Bryant Park	16	0.19	0.67	24.2

[a] The number of otoliths used in developing each chronology

[b] An index of high-frequency variability

[c] The average correlation between each detrended measurement time series (using a 22-year cubic spline) and the average of all other detrended measurement time series

Figure Captions

Figure 1. Middle Fork of the Willamette and Bryant Park freshwater mussel master chronologies. Minimum sample size is six individuals.

Figure 2. Relationships between the Middle Fork of the Willamette chronology, Bryant Park chronology, and the average of the two mussel chronologies with maximum water temperature and mean discharge in the Middle Fork of the Willamette River.

Figure 3. Correlations with precipitation, air temperature, the Palmer Drought Severity Index (PDSI) and Multivariate ENSO Index (MEI) for A) the Middle Fork of the Willamette mussel chronology and B) the Bryant Park freshwater mussel chronology.

Figure 4. Reconstruction of Middle Fork of the Willamette River discharge from freshwater mussel chronologies and Palmer Drought Severity Index records.

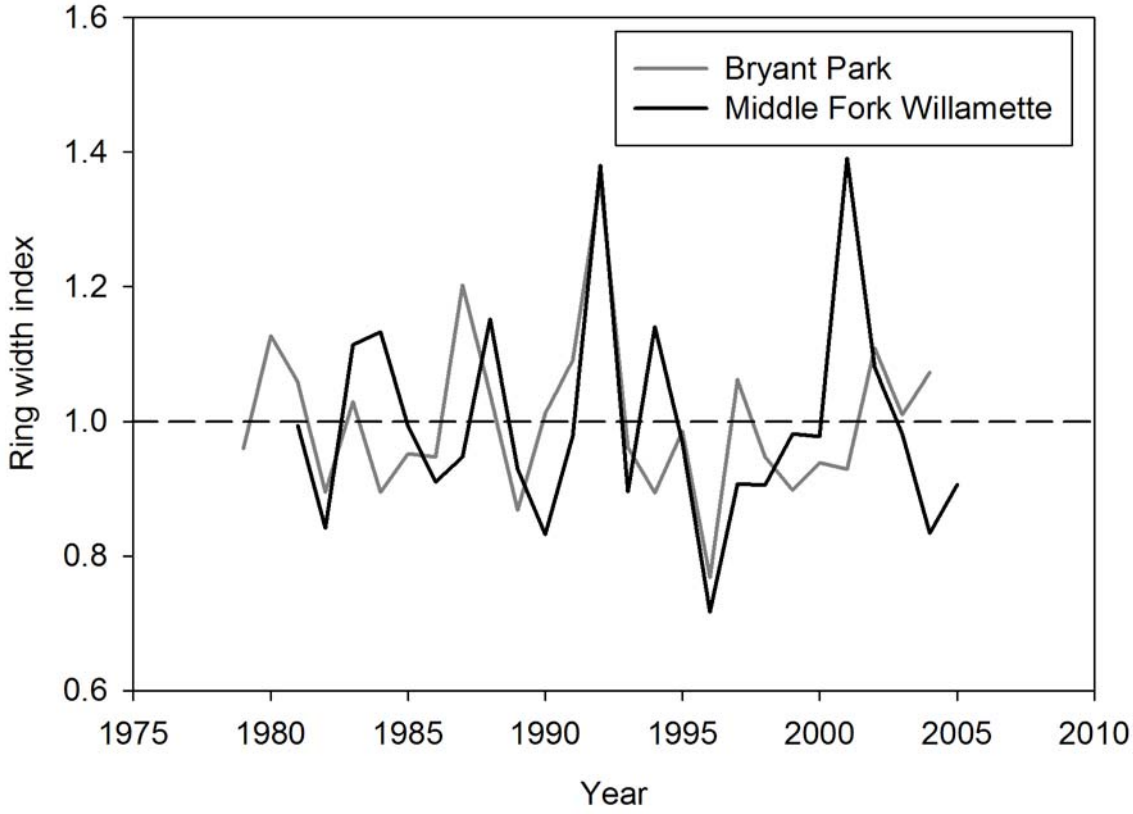
Bryant Park
Middle Fork Willamette
Ring width index
Year
1.6
1.4
1.2
1.0
0.8
0.6
1975
1980
1985
1990
1995
2000
2005
2010

Figure 1

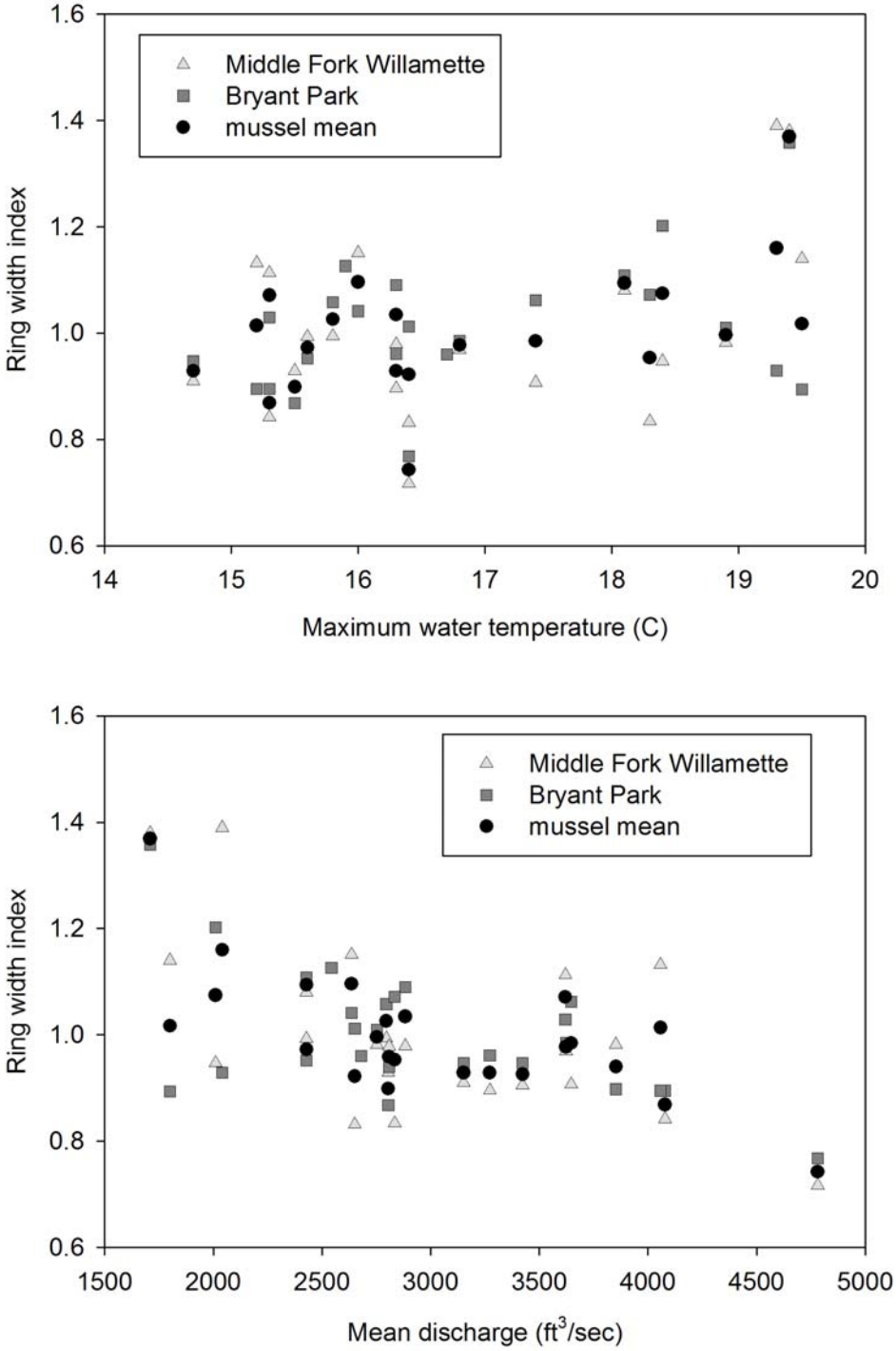
Middle Fork Willamette
Bryant Park
mussel mean
Ring width index
Maximum water temperature (C)
Middle Fork Willamette
Bryant Park
mussel mean
Ring width index
Mean discharge (ft3/sec)

Figure 2

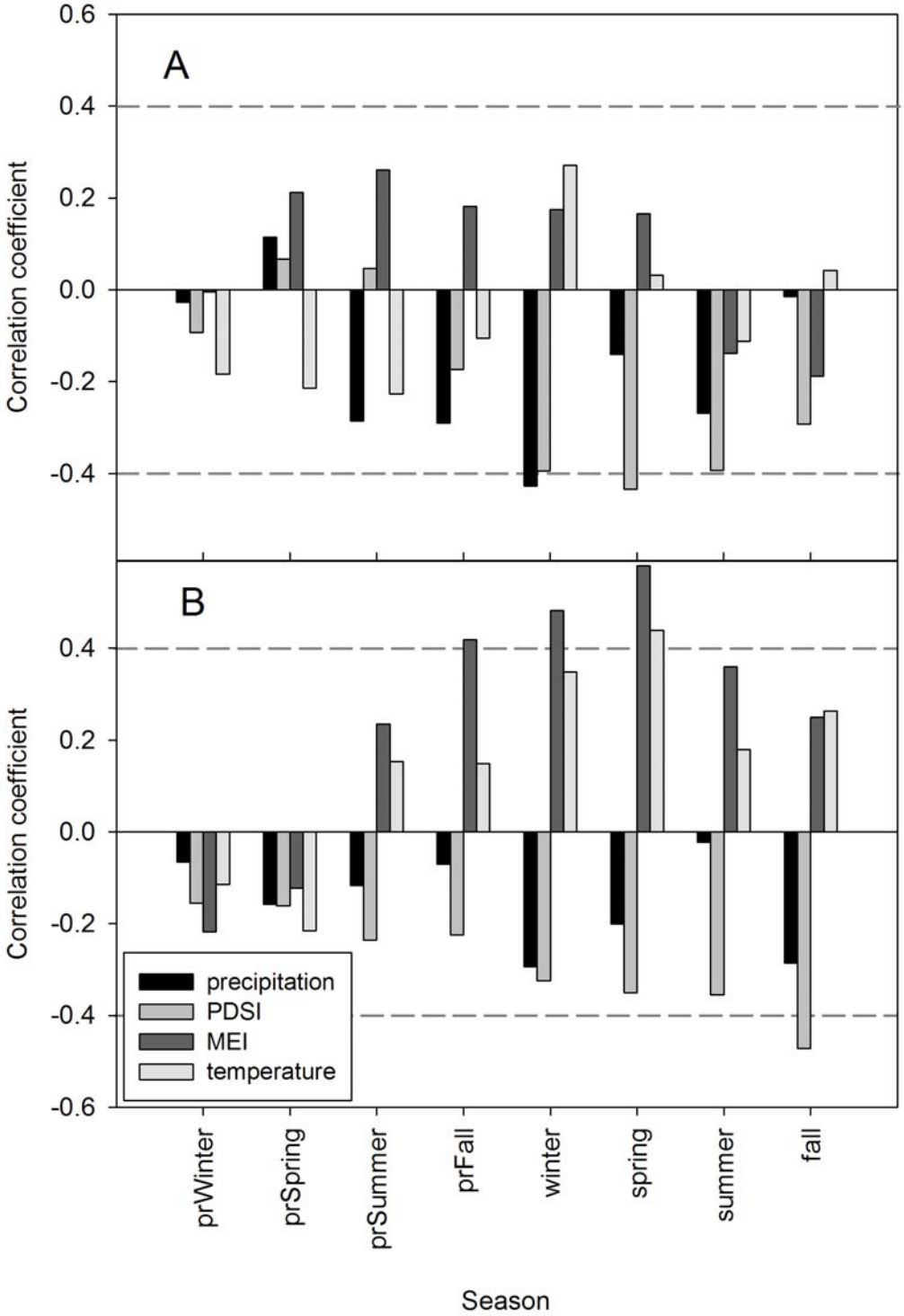
A
B
Correlation coefficient
Correlation coefficient
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
precipitation
PDSI
MEI
temperature
prWinter
prSpring
prSummer
prFall
winter
spring
summer
fall
Season

Figure 3

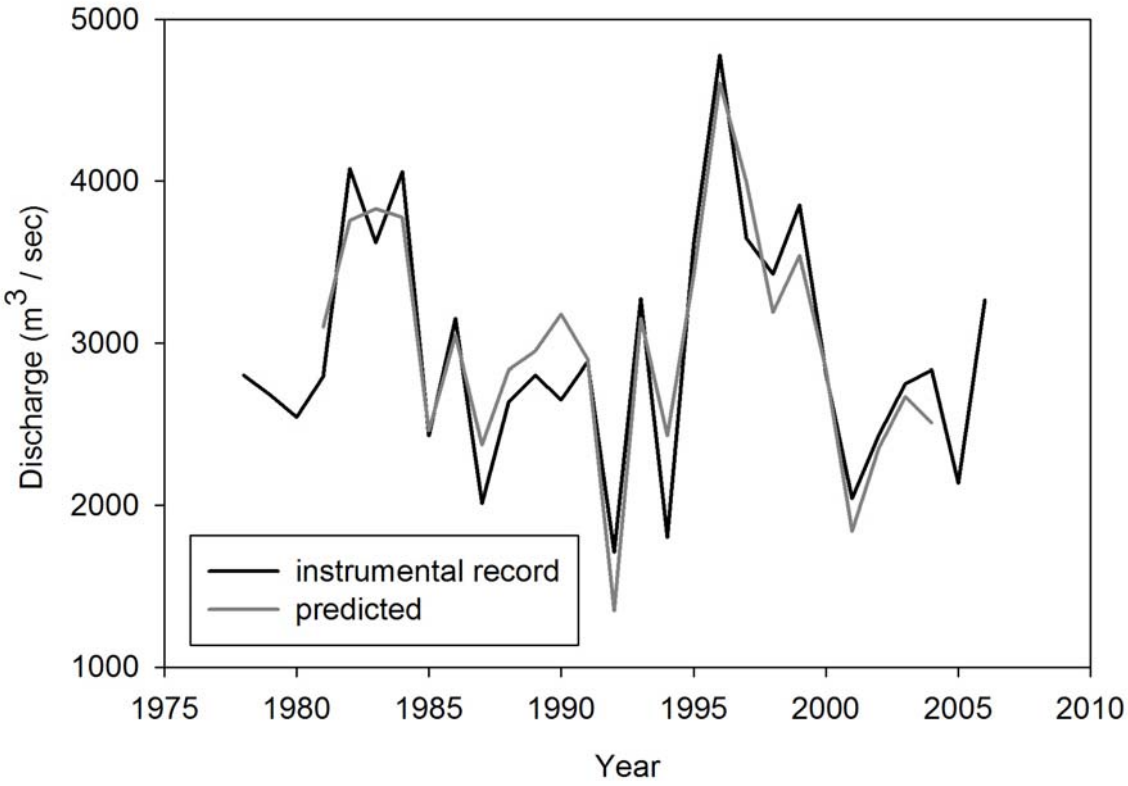
5000
4000
3000
2000
1000
Discharge (m3 / sec)
1975
1980
1985
1990
1995
2000
2005
2010
Year
instrumental record
predicted

Figure 4