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Bradford C. Chase

brad.chase@mass.gov

South Coast Marine Fisheries Field Station

Stephanie Berkman

South Coast Marine Fisheries Field Station

Michael N. Burgess

South Coast Marine Fisheries Field Station

Joseph Holbeche

Annisquam River Marine Fisheries Field Station

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Phenology and spawning migration life history of diadromous rainbow smelt (*Osmerus mordax*) at coastal rivers in Massachusetts

Bradford C. Chase[1,3], Stephanie Berkman[1], Michael N. Burgess[1], and Joseph Holbeche[2]

[1] Massachusetts Division of Marine Fisheries, South Coast Marine Fisheries Field Station, 836 South Rodney French Blvd., New Bedford, MA 02744, United States

[2] Massachusetts Division of Marine Fisheries, Annisquam River Marine Fisheries Field Station, Gloucester, MA 019302, United States

[3] Corresponding author, brad.chase@mass.gov

Abstract

Diadromous rainbow smelt are a cold-water, data-poor species with no stock assessment in their native range of the northwest Atlantic Ocean and few ongoing monitoring efforts that contribute life history or population abundance data. Smelt have apparently undergone a dramatic contraction of their range in the 20th century with the southern extent moving north from the mid-Atlantic region to Massachusetts. This change in range is considered to be related to climate warming, although causal information on their distribution, abundance and phenology is sparse. Smelt migrate from marine waters to coastal rivers during spring spawning runs. The Massachusetts Division of Marine Fisheries manages smelt populations through fishing bag limits, and time-of-year restrictions on fishing and construction activity during the spawning run. DMF monitors the spawning runs with spring in-river fyke nets to support resource management and smelt population and habitat restoration. This study reports on the phenology and life history characteristics of the smelt spawning migration during the 20-year fyke net monitoring. The smelt fyke net catch-per-unit-effort was found to be significantly declining in three of the four fyke net stations. The Parker River and Weweantic River catch have declined to a degree that raises concerns of population collapse. Unexpectedly, the Fore River fyke net catch was increasing during the 20-year data series, although not significantly. The smelt run onset and peak were occurring earlier at the Fore and Jones River with a large shift to an earlier run peak at both rivers. The vernal warming of coastal waters has been found to be most related to changes in spawning run migrations of other diadromous species. Significant warming of bottom water and earlier spring transition dates occurred during the study period at two marine stations that represent winter staging areas outside of the spawning rivers. The fyke net monitoring has demonstrated recent and rapid changes to smelt spawning run timing and population declines at three of the four sampled rivers. Changes in smelt

phenology may be most related to the warming marine waters. This information can assist marine resource managers to protect stressed and threatened smelt populations.

Keywords: diadromous, phenology, fyke nets

Introduction

Diadromous rainbow smelt (*Osmerus mordax*) occupy freshwater, estuarine, and near-coastal marine habitats throughout much of their native range, providing an important trophic niche as a small, forage species. Smelt historically ranged from Labrador, Canada south to the United States mid-Atlantic region, with populations confirmed in the Delaware River and possibly farther south into Virginia (Kendall 1926; McAllister 1963; Scott and Scott 1988). Presently, smelt populations are found from Massachusetts to Lake Melville, Labrador (Enterline et al. 2012; Sutton et al. 2024; Chase 2006), with the truncation of the southern extent in the 20th century expected to be influenced by climate warming.

Anadromous rainbow smelt migrate from marine waters to freshwater tributaries to spawn in spring. The environmental cues that initiate smelt spawning are not quantified, although a river temperature of 4 ^{o}C is referenced as an approximate threshold for the smelt spawning onset (Rupp 1959; McKenzie 1964; Lawton et al. 1990; Lischka and Magnuson 2006; and O'Brien et al. 2012). Smelt spawning habitat is limited to freshwater spawning riffles a short distance above the tidal interface. Smelt deposit demersal adhesive eggs at these riffles that incubate for 1-4 weeks before hatching depending on temperature (McKenzie 1964; Murawski et al. 1980; Chase 2006; and Chase 2009). Spawning occurs at night and is most associated with night flood tides (Rupp 1959; McKenzie 1964; Murawski et al. 1980; Enterline et al. 2020; Pearson et al. 2024). Northern smelt runs demonstrate a brief duration with a rapid spawning peak after onset (McKenzie 1964; Pouliot 2002; and Lischka and Magnuson 2006), while spawning runs in Massachusetts can last for over two months with peaks building a month after onset (Chase 2006).

Post-spawning, smelt remain in the downstream estuary or embayment area for weeks to months (Enterline et al. 2012; Pearson et al. 2024). While research on movements further offshore is limited, smelt likely inhabit cooler, deeper embayments in the summer and overwinter in near-coastal, marine waters (Buckley 1989; Clayton 1976; McKenzie 1964). Smelt are adapted to thrive in cold water temperatures as the production of glycerol and antifreeze proteins in their tissue and blood activates when water temperature reaches 5 °C or below, preventing their body from freezing (Lewis et al. 2004; Driedzic and Ewart 2004; and Driedzic and Short 2007). This physiology may provide a competitive advantage by allowing smelt to both avoid predation and actively feed at lower water temperatures that many other species avoid.

Rainbow smelt provided important recreational, commercial, and subsistence fisheries in the northern region of their range (Goode 1884; and Kendall 1926). Fried and Schulz (2006) and Enterline et al. (2012) provide synopses that indicate smelt fisheries and abundance have declined sharply at the southern extent of their range. Despite the importance of smelt fishing historically (Kendall 1926; and Woods et al. 2012), present activity in Massachusetts is limited to minor recreational fishing effort from the shoreline in the fall and winter, with a sharp reduction in winter ice in estuaries presently limiting traditional ice fisheries. The Massachusetts Division of Marine Fisheries (DMF) set a spring closure of the smelt fishery on March 15th in the 1960s to protect the spawning run. This date was changed to March 1st in the 1990s following survey observations of earlier smelt egg deposition (Chase 2006).

The influence of climate warming on population dynamics, age and growth, and migration life history has had little investigation. Although the concept of a dramatic contraction of their range is accepted, documentation on the shift and disappearance of populations is limited to connecting historical accounts to present surveys (Enterline et al. 2012; Fried and Schultz 2006). Smelt have been found to exhibit decreasing length-at-age and later age of maturity across their range, moving from southern to northern

latitudes (Enterline et al. 2012; Chase et al. 2019; O'Malley et al. 2017; and Sutton et al. 2024). This expression of the Temperature-Size Rule (Atkinson 1995) and associated plasticity in rainbow smelt life history may be important in the response of smelt populations to a rapidly warming environment (Sutton et al. 2024). Overall, the causes of smelt population declines are not well-documented, with concerns expressed over reductions in selective benefits of diadromy due to degradation of freshwater spawning habitats and the impact of climate warming on their distribution and physiological traits (Enterline et al. 2012; Chase et al. 2019; and Sutton et al. 2024).

The warming of the Gulf of Maine ocean temperatures since the late 20th century (Pershing et al. 2015; and Hare et al. 2016) has been related to changes in phenological processes, including fish migrations (Thomas et al. 2017; and Staudinger et al. 2019). Climate warming impacts on diadromous fish migrations have been demonstrated for Pacific salmon (Hodgson et al. 2006; and Keefer et al. 2008), striped bass and American shad in the Hudson River (Nack et al. 2019) and river herring in New England (Ellis and Voukoun 2009; Rosset et al. 2017; Lombardo et al. 2019; and Legett et al. 2021). In the studies involving River herring, water temperature was the most significant predictor of spawning run migration timing at both the seasonal and daily level. However, while correlations between water temperature and river herring migrations are apparent, less is known about the long-term effect of phenological changes and influences on population health and abundance. For rainbow smelt, no studies have reported changes in spawning run phenology, and details on smelt spawning migrations are limited to brief accounts that suggest substantial latitudinal differences across the smelt's range.

Information on rainbow smelt population demographics (McKenzie 1964; Clayton 1976; and Murawski and Cole 1978) is sparse: no population assessments have been conducted within their range, and no long-term population metrics are available for smelt in New England. The Massachusetts DMF conducts smelt spawning run surveys using fyke nets at four coastal rivers in Massachusetts. This survey provides

an opportunity to progress life history knowledge on smelt population demographics related to spawning run phenology (reported here), catch-per-unit effort, sex ratio, and size and age relationships (separate article). Using fyke net data collected from 2005-2024, this study assessed characteristics of rainbow smelt spring spawning migrations, including the evaluation of temporal changes, and the influence of environmental covariates on spawning run timing.

Study Area

The DMF conducted monitoring of smelt spawning habitat on the Gulf of Maine coast out of concern for declining catch and effort in the popular smelt sport fishery and documented 45 smelt locations within 30 coastal watersheds (Chase 2006 and 2009). Following this study, smelt fyke nets were set at nine smelt spawning runs to record demographic information on smelt spawning runs. Four locations have been maintained as long-term monitoring stations: Parker River, Newbury; Fore River, Braintree; Jones River, Kingston; and Weweantic River, Wareham (**Figure 1**). All four rivers are within relatively small, coastal watersheds (**Table 1**).

Figure 1. Smelt fyke net study area including fyke net stations and marine water temperature stations.

Table 1. Smelt fyke net sampling stations and summary river information (discharge = average April cubic feet per second, (cfs)); source: U.S. Geological Survey, http://waterdata.usgs.gov/state/Massachusetts.

The four fyke net stations in the present study were included in a genetic population structure analysis for Gulf of Maine diadromous smelt conducted by Kovach et al. (2013). They found differences within this limited geographic range but no river-level genetic variation. Smelt runs in Massachusetts Bay (including Fore River) were most similar genetically. The Parker River and Jones River were related to the Massachusetts Bay grouping although most of their genetic distinctiveness was associated with other

populations north of the Parker River and south of the Jones River. The Weweantic River had among the least genetic diversity among 18 smelt runs sampled in the Gulf of Maine. This was considered consistent with a declining population at the southern extent of the species range (Enterline et al. 2012; and Kovach et al. 2013).

Methods

The DMF smelt fyke net survey conducted a pilot season in 2004 and adopted standard sampling methods in 2005 with the survey continuing as an annual series. Rebar poles were pounded into the substrate at a mid-channel location downstream of known spawning habitat near the tidal interface. Custom fyke nets (total length of 3.4 m, 1.2 x 1.2 m entrance and side wings on metal frames; 6 hoops of 0.8 m diameter with two throats connecting to a terminal cod end; all mesh are 7 mm delta) were attached to the rebar poles facing downstream during the first week of March and hauled on three consecutive days after overnight sets. The sampling season ran for 11 weeks until mid-May. With each haul, all fish were collected, counted by species, total length (TL, mm) was measured, and were released alive. Weekly TL subsamples were made for common estuarine species and large catches of smelt. Smelt were classified by sex, and scale samples were collected at the Fore and Jones rivers for aging using methods described in Elzey et al. (2015).

Catch-per-Unit-Effort. Fisheries net survey data can be non-normal distributed, positively skewed, and have common zero values (Hinton and Maunder 2003). Gear catchability biases can limit survey catch data for abundance indices as can population dynamics such as variable year-class strength and maturation recruitment (Ricker 1975). We evaluated the data qualities of the smelt fyke net catches to determine the most suitable catch-per-unit-effort (CPUE) metrics and potential as indices of abundance. CPUE metrics for the fyke net catches were evaluated for hauls from March 1st to May 15th. Fyke net sets were made one week earlier starting during the last week of February in 2017; to account for

observations of early migrants as the time series progressed. The February hauls were excluded because catches were incidental and not available for the entire data series. The CPUE data were evaluated using three measures of effort (overnight set, total set hours, and night hours as defined by sunset to sunrise).

After evaluating each of these methods, it was determined that night hours were the most effective measure of effort. The hauls were set and retrieved near low tide, resulting in variability in the time that the nets were fishing during overnight sets. Spawning movements of rainbow smelt have been shown to occur primarily at night (Enterline et al. 2019); and night hours were recently applied to calculate CPUE by Turner et al. (2020) for the Fore River smelt fyke net station. We found that total hours and night hours did not differ significantly, so we selected the night hours metric as the most biologically relevant measure of effort.

Catch-per-unit-effort (CPUE) metrics were calculated for each river using smelt catch standardized to night hours. Initial exploration analyses compared the coefficient of variation (CV) across different CPUE formulations to assess data variability and guide the selection of analytical approaches for each river. We used General Linearized Model (GLM)-standardized models where applicable, as this approach is preferred by ASMFC for improving the precision of abundance by including variation in sampling conditions, such as environmental variables (ASMFC 2009). The Jones and Fore Rivers were sufficiently data rich to support GLM-standardization, while the Weweantic and Parker River catches declined markedly in recent years, resulting in the reporting of the arithmetic mean for CPUE. GLM-standardization provided significant improvements in precision over nominal indices and validated the robustness of the data collected at the Jones and Fore River. The CPUE data used for standardized indices of abundance of the smelt fyke net survey will be reported in greater detail in another article (*In prep*.).

Environmental Covariates. River water temperature measurements were made hourly from stations located upstream of the fyke net, beyond the extent of tidal influence. Marine measurements were made hourly from stations anchored to the bottom in embayments close to the fyke stations (**Figure 1**). Water temperature for rivers and marine waters was recorded with Onset WaterTemp Pro V2 loggers (accuracy ± 0.2 ^{o}C). Marine water temperatures were measured from DMF bottom logger stations at Cape Cod Bay (Manomet Station, 1988-2024) and Boston Harbor (Martins Ledge Station, 1989-2024). Marine stations prior to 2005 used Ryan Tempmentor loggers (accuracy ± 0.3 ^{o}C). Mean daily river temperatures were averaged for the smelt spawning season of March 1st to May 20th. Mean daily marine temperatures were averaged for the smelt spawning season and for January-March to provide a metric of winter ocean temperature when smelt would be expected to be staging in marine waters prior to the spring spawning run.

Tidal amplitude data was recorded from annual Eldridge Tide and Pilot Book (ISBN 978-1-883465-20-9) using the Boston Harbor data with assigned delays for the Parker, Fore, and Jones river smelt fyke station locations. The Weweantic River station used the Sippican River data. Daily moon phase was recorded from the U.S. Naval Observatory website (https://aa.usno.navy.mil/data/MoonPhases). Daily river discharge was recorded for all rivers except for the Weweantic River from U.S. Geological Survey stream flow gauge stations (https://waterdata.usgs.gov/state/massachusetts/).

Phenology. The smelt fyke catch data were evaluated to determine suitable spawning run timing metrics. During 2005-2016, fyke nets were set during the first week of March to avoid ice damage and to intercept the expected start of the smelt spawning run. Low numbers of smelt were caught during the first week of hauls in most years with a few exceptions of no catches during severe winters. Therefore, an estimate of a true onset of the spawning migration (hauls with zero catches each year) was not possible. The 5% cumulative catch was estimated each year and was adopted as a proxy for the start of the

spawning run. Starting in 2017, the fyke nets were deployed one week earlier at the end of February in response to our expectation that smelt were arriving earlier. However, relatively few smelt were caught in late February (0 - 1.6 smelt/haul among rivers). Therefore, all phenology statistics for the time series were generated from haul data starting March 1st.

The 50% cumulative catch was used as a proxy for spawning run peak. The weighted mean catch date (W_M) and the weighted-mean migration temperature (W_T; based on river water temperature on haul date) were also evaluated as indicators of peak run timing. The spawning run end was recorded as the observed last date of smelt catch. Run duration was recorded both as the difference between first and last observed smelt catch and between the 5% cumulative catch date and last observation (Ellis and Vokoun 2009). Phenology moments not captured on exact haul dates were assigned dates using linear interpolation. The Mann Kendall Trend Test was used to test for changes in all run timing metrics (R 4.6.0, Kendall package). The Mann-Kendall test is a non-parametric, rank-based test that is commonly used in environmental sciences to determine whether there is a monotonic trend in a time series. Negative *tau* values indicate negative monotonic trends. There are no underlying assumptions made about the normality of the data. The low smelt catches in the Parker River and Weweantic River prevented the assignment of phenology metrics in a majority of seasons. A seasonal CPUE of >0.5 smelt/haul was selected as the threshold for generating cumulative statistics on the smelt run onset, peak and duration.

$W_M = \Sigma(n \times d)/N$, where n is the number of smelt caught on a given day, d is the Julian date, and N is the total number of smelt caught for the season (Rossett et al. 2017).

$W_T = \Sigma(n \times t)/N$, where n is the number of smelt caught on a given day, t is the average daily river water temperature on haul date, and N is the total number of smelt caught for the season (Ellis and Vokoun 2009; Quinn and Adam 1996; and Rossett et al. 2017).

GLMS for Environmental Covariate Analysis. To evaluate the influence of environmental conditions on rainbow smelt catch, negative binomial GLMs were fit to raw smelt counts from fyke net sampling at the Fore River (2005–2024, n = 547 hauls) and Jones River (2005–2024, n = 588 hauls). The natural log of night hours was included as an offset to standardize catches to effective fishing effort. A quadratic Julian date term controlled for the unimodal seasonal pattern in smelt presence during the spring spawning run. This analysis was conducted separately from the GLM used to standardize CPUE for the annual abundance index (separate article *In prep.)*; the environmental model was designed to identify ecological drivers of catch variation rather than to produce an index of abundance.

Candidate environmental covariates included tidal amplitude, river discharge (daily average on haul date at USGS stream flow stations), tidal flood timing, and a water–ocean temperature differential calculated as site water temperature minus ocean temperature on each haul date. Flood timing was converted to a circular variable using sine and cosine transformations on the 12.42-hour M2 semidiurnal tidal period. Raw temperature variables were excluded from the final candidate set due to strong collinearity with Julian date (Pearson's r = 0.64–0.83 at both sites), as seasonal warming is inherently confounded with calendar date during the spring sampling window. The temperature differential was retained because it captures the thermal gradient between riverine and marine environments independent of the shared seasonal trend. Moon phase was excluded after initial analysis showed it was not significant at either site.

All additive combinations of the four covariate blocks were evaluated, yielding 16 candidate models per site. Models were compared using AIC, and variance inflation factors confirmed the absence of multicollinearity in all candidate models. Coefficient estimates were exponentiated to obtain rate ratios representing the multiplicative change in expected catch per one standard deviation increase in each covariate. All analyses were conducted in R (R 4.6.0, MASS and car packages).

Cumulative Catch Curves. The nominal catch (number of smelt per overnight haul) were summed by Julian date for the entire data series to produce cumulative catch curves for the spring spawning period. The Kolmogorov Smirnov test was used to determine if the cumulative frequency distributions from each river were from the same populations (two-tailed test, R 4.60, dgof package).

Environmental Correlations to Smelt Migrations. Correlations between environmental factors (river discharge, ocean temperature, and river temperature) and smelt fyke CPUE were tested with Kendall's tau correlation analysis (R 4.6.0, Kendall package). Daily ocean temperature was averaged for a winter staging period of Jan-March and the smelt spawning period of March 1st – May 20th for the two Massachusetts Bay stations. Daily river temperature was averaged for the smelt spawning period and a larval emigration period of May 1st – June 30th in the Jones and Fore rivers. Daily USGS stream flow data were averaged for March-May and for April for the Jones and Fore rivers. The average smelt fyke CPUE for night hours during the smelt spawning season was used as the dependent variable in the Kendall tau correlation analysis that evaluates the strength and direction of monotonic relationships (Castellan 1988). Secondly, smelt age keys were generated from smelt age data (R 4.60 FishMethods) package) and applied to all captured smelt to produce annual age composition of the fyke net catches. The age composition data was lagged as age-1 and age-2 fish to their year of birth and correlated with the above environmental variables, as we hypothesized that cold winter ocean temperatures were correlated with higher cohort CPUE.

Spring Transition Date. Seasonal water temperature transitions (eight consecutive days above a temperature threshold with life history significance) can influence fish migrations and ontogenetic periods of development (Friedland et al. 2015; Henderson et al. 2017; and Thomas et al. 2017). Spring transition dates have been applied as indicators of the onset of river herring migrations (Dalton et al. 2022). The water temperature threshold of 4 ^{o}C was applied as the onset of rainbow smelt spawning. We assign the first day of the year following eight consecutive days ≥ 4 ^{o}C as a thermal threshold relevant to smelt spawning migrations. The Mann Kendall Trend Test was used to test for changes in spring transition dates (R 4.6.0, Kendall package).

Migration Correlations among Rivers. Correlations of run timing and water temperature metrics between the Fore and Jones rivers were tested with Kendall's *tau* correlation analysis (R 4.6.0, Kendall package). The annual spring transition date, 5%, 50%, run duration, spawning season river temperature and weighted mean temperature for each river were tested for significant correlations.

Results

Rainbow smelt were captured at all four fyke net locations during the study period with a wide range in CPUE (**Figure 2**). All stations except the Fore River displayed a declining trend in catches, with sharp reductions in the Parker River and Weweantic River. The low catches later in the time series in the Parker River and Weweantic River, including years with zero catches, suggest a population collapse and this status limited quantitative analyses on CPUE and phenology for those rivers.

Figure 2. Nominal catch-per-overnight haul (± SE) of rainbow smelt in Massachusetts fyke nets, 2005-2024, with Mann Kendall *tau* and *p*-values reported.

Catch-Per-Unit-Effort. The smelt fyke net CPUEs for all metrics had high variability; influenced by common zero catches and run peaks with higher catches. The nominal CPUEs for overnight sets, total set hours and night set hours had the highest CVs among all treatments, all exceeding 1.0. GLM-standardization was applied to the CPUE of night set hours at the Jones and Fore River. This reduced the CVs from 1.354 and 1.405, to .241 and .228, respectively. The nominal CVS could only be reported for the Parker and Weweantic River, which were 2.586 and 3.488, respectively. The CPUE data were tested with the Mann-Kendall Trend Test to determine whether there is a monotonic trend in the timeseries. The results for each river were similar for each of the nine CPUE treatments with no contradictions in significance.

Figure 3. Generalized Linear Model results of standardized CPUE Indices of Abundance for the Fore River and Jones River.

Figure 3 Description: GLM-standardized indices of abundance at the Fore River (a) the Jones River (b). Counts were fitted to a negative binomial model to account for high variation and a large presence of zero counts. Counts were logged and offset using night hours. A day of year, day of year quadratic, and year were included as covariates. All covariates were scaled, and all date values were centered to zero.

Table 3. The Generalized Linear Model statistics for the standardized CPUE Indices of Abundance for the Jones River (A) and the Fore River (B).

The CPUE time series for the Parker, Jones, and Weweantic rivers were all significantly declining, with all three rivers showing very low catches in recent years, and the Parker and Weweantic rivers having

several years with no smelt catches. The Fore River CPUE trend is increasing, although not significantly (*tau* = 0.17, *p* = 0.315). Three of the four highest average annual CPUEs in the Fore River time series have occurred in the last 10 years.

Phenology. Most smelt catches occurred in April at all sites except for March in the Parker River (**Figure 4**). The rapid, early peak of the Parker River smelt migration at the northernmost station was not expected, nor was the later peak in April for the Weweantic River, the southernmost river. Catches in February and May were minor for all rivers. The highest presence in May was found at the Fore and Jones rivers, the stations with the longest run duration and highest CPUE. The cumulative catch distributions for smelt catch show similar curve for the Fore and Jones rivers and the earlier peak for the Parker and later peak for the Weweantic. However, all station catch curves were significantly different from each other (**Figure 5**).

Figure 4. Cumulative monthly catch-per-unit effort (nominal catch/overnight haul) for all fyke net hauls.

Figure 5. Cumulative catch curves for smelt fyke net. Nominal catch data were combined by Julian date. Catch curves are all significantly different among rivers (Kolmogorov-Smirnov test, $p < 0.001$).

Estimates of run timing statistics were possible for all survey years (N = 20) for the Fore and Jones rivers; low catches limited these statistics for the Parker River (N = 9) and Weweantic River (N = 7) (**Table 2**). The first observation of smelt catch was not a reliable metric for the onset of the smelt spawning migration. In most years, smelt were caught in low numbers at the first haul in the Fore and Jones rivers in early March. Late February sets from 2017-2024 indicated that minor movements of smelt began in February in most years in the Jones and Fore rivers. The 5% cumulative catch date was selected as a more

346 consistent and conservative metric for onset. The date of first catch provided meaningful life history
347 information for some rivers in particular years. For example, delayed onset was seen in several years in
348 which cold late winter conditions were associated with low river water temperature ≤ 1 °C.
349
350 Table 2. Smelt migration timing metrics.
351
352 Table 2. Description: Average migration metrics are only included for years in which smelt catch was 0.5
353 fish/haul. The End Date is the date when smelt were last caught. The Duration is the maximum period
354 when smelt were observed excluding February hauls.
355
356 The spawning run onset as determined by the 5% cumulative catch date was similar for all rivers except
357 the southernmost station at the Weweantic River which showed a much later and less variable start
358 (**Figure 6A**). Conversely, the northernmost run at the Parker River had the earliest spawning run peak as
359 determined by the 50% cumulative catch date (**Figure 6B**). Run duration, as determined by the difference
360 between the 5% cumulative catch date and the date of last observed smelt showed truncated spawning
361 durations for the Parker and Weweantic rivers (**Figure 6C**) with few smelt caught in May and fewer in
362 February (0 in 20 hauls in Weweantic, and 1 in 6 hauls in the Parker). Extensive spawning run durations
363 were documented for the Fore and Jones rivers, exceeding an average of 50 days for the duration
364 statistic and over two months for the total period when smelt were observed. Duration statistics for the
365 Fore and Jones rivers were tested with Mann Kendall and found no significant trends for total duration,
366 5% cumulative catch to last observations, and end date during the time series (**Figure 7**).
367
368 **Figure 6.** Box plots on smelt spawning migration duration, 5% and 50% cumulative catch.
369

Figure 7. Smelt spawning run duration statistics for the Fore and Jones rivers, 2005-2024. The season duration is from March 1st to last observation. No significant trends found with Mann Kendall Trend test (p = 0.05) for all duration metrics.

Fore River Migration Timing. Large smelt catches in the Fore River were supportive of generating annual statistics on migration timing. The Fore River spawning run grew in CPUE from late March to have an average catch peak on April 8th, and the longest average duration (66 days) among rivers. The Mann-Kendall test was applied to determine if trends were present in the start of the migration (5% cumulative catch), migration peak (50% cumulative catch) (**Figure 8**), and water temperature during run peak (W_T, weighted mean temperature) (**Figure 9)**. All three migration timing metrics had declining trends, although only the catch peak had a significant, negative monotonic trend (*tau* = -0.54, p = 0.001). The difference in the smelt catch peak from the start to the end of the time series was pronounced: the migration peak averaged 21 days earlier during the last five years of the time series than the first five years.

Figure 8. Julian date of estimated smelt run onset (5% cumulative catch) and peak (50% cumulative catch) at Massachusetts fyke nets, 2005-2024.

Figure 9. River water temperature in the Fore River and Jones River: average spawning season daily mean and Weight Mean Temperature (W_T).

Jones River Migration Timing. Smelt catches in the Jones were suitable for generating annual statistics on migration timing metrics for all study period years. Overall, the spawning run statistics tracked similar to the larger Fore River smelt run located approximately 30 km north of the Jones River. The Jones River

had the earliest average 5% cumulative catch date of March 12th among rivers and an extended average run duration of 64 days. Repeating the Mann-Kendall tests as above, all three migration metrics had significant declining trends (Figure 8 and 9). The onset averaged 10 days earlier, and the migration peak averaged 13 days earlier during the last five years of the time series than in the first five years.

Parker River Migration Timing. Limited analyses were possible for the Parker River smelt fyke net catch data due to estuarine ice impacts at the start of seasons and declining catches in the time series. Of principal importance, smelt catches plummeted in the Parker River after 2012 (**Figure 2**). Secondly, half of the seasons in the 20-year time series lost at least one week of sets at the start due to ice. The low catches and interference of ice with gear deployment limited the generation of run timing metrics to nine years, most early in the time series. Smelt were caught in most seasons during 2005-2012 in early March when the fyke nets were first deployed. The presence of ice may have biased the 5% and 50% cumulative catch estimates to be closer than actual. A review of all Parker River catch data indicates that the spawning run was active early in March and peaked in late March with minor catches after April 15th. During 2005-2012, the average annual smelt catch per haul was 15. After 2012, smelt catches declined sharply to average 0.2 smelt/haul annually with six seasons having 0-1 smelt caught (**Figure 2**).

Weweantic River Migration Timing. Limited analyses were possible for the Weweantic River smelt fyke catch due to low and declining catches in the time series. Smelt catch in the Weweantic River reached 1 smelt/haul in only four years from 2008-2024, with three of those years occurring in the first five years (**Figure 2**). Run timing metrics could only be generated during 7 of the 17 years of sampling. The Weweantic River station displayed a clear trend of later catches than the other three fyke stations with most catches occurring in April (89%), and had the latest run peak (April 9th) and shortest average run duration (33 days) among rivers. After 2012, smelt catches declined sharply to less than 1 smelt/haul

418 annually with six seasons having 0-1 smelt caught. Despite being the southernmost station in
419 Massachusetts, the Weweantic River smelt run did not have strong movements in March and displayed a
420 truncated duration relative to the other fyke stations.
421
422 **Water Temperature**. Bottom water temperature increased significantly during January-March at both
423 the marine stations in Cape Cod Bay (*tau* = 0.398, *p* = 0.001) and Boston Harbor (*tau* = 0.333, *p* = 0.004)
424 since the late 1980s (**Figure 10A**). The daily average temperature during this period for the last five years
425 of the time series was 2.1 °C and 1.5 °C warmer than the average for the first five years for Cape Cod Bay
426 and Boston Harbor, respectively. The water temperature at the marine stations also increased
427 significantly for the spring spawning season since the late 1980s and for the study period (**Figure 10B**).
428 The daily average temperature during March 1st to May 20th for the last five years of the time series was
429 1.6 °C and 2.2 °C warmer than the average for the first five years for Cape Cod Bay and Boston Harbor,
430 respectively.
431 River temperature for the Fore River and Jones Rivers smelt spawning season was also increasing (**Figure**
432 **10B**), although not significantly (Fore: *tau* = 0.311, *p* = 0.060; Jones: *tau* = 0.290, *p* = 0.080). Overall,
433 water temperature data for all marine and river stations were increasing approximately 1-2 °C during the
434 time series, with larger, significant increases in marine waters.
435
436 **Figure 10.** Marine bottom water temperature for Cape Cod Bay (CCB) and Boston Harbor (BH) stations
437 from 1988-2024 (A), and marine and river water temperature for smelt spawning season (B).
438
439 River temperature, in terms of weighted-mean temperature (W_t), could only be assessed for the Fore
440 River and Jones River (**Figures 9**) given the majority of years with low catches in the other rivers. The W_t
441 is a proxy for water temperature at the run peak. The time series mean W_t for the Fore River was 10.4 °C

and 9.7 °C for the Jones River. The W_t temperature declined in the Fore River, although not significantly (Tau = -0.265, p = 0.112). The weighted-mean temperature in the Jones River, showed high variability while significantly declining (Tau = -0.337, p = 0.041).

Spring Transition Date. The marine bottom waters in Massachusetts Bay continue cooling in January from summer peaks, with February being the coldest bottom temperatures among all months. Therefore, marine spring transition dates were selected as the 8th straight day after January 30th with temperature ≥ 4 °C, while the river temperature transition date was the absolute first 8th day period of vernal warming at this threshold. Both marine and river stations had declining or earlier transition dates for the study period (**Figure 11**). Both marine stations and river stations had declining trends or earlier arrival of the transition date for fyke net study period of 2005-2024; however, none of these trends were significant. Both marine stations were significantly declining for the time period of 1988-2024. The Boston Harbor station displayed consistent early arrival of the transition date later in the time series, including the condition during 2023 and 2024 where the bottom water temperature did not decline below 4 °C anytime during January and February.

Figure 11. Annual transition dates for the Fore River, Jones River, and the Boston Harbor (BH) and Cape Cod Bay (CCB) temperature logger stations. The transition threshold is 8 straight days ≥4 °C.

Environmental Covariates. A negative binomial GLM was prepared to evaluate the influence of environmental covariates on Fore and Jones River smelt fyke CPUE. The best-supported model at both sites included all four environmental covariate blocks in addition to the quadratic Julian date term and

carried the majority of AIC weight at each site (Fore River: 53.5%, Jones River: 95.6%). All variance inflation factors were below 2.0, confirming no multicollinearity issues among predictors. The quadratic Julian date term confirmed the expected unimodal seasonal peak in smelt catch around early April at both sites, with substantially higher predicted catches at the Fore River (approximately 185 fish per 10-hr night) compared to the Jones River (approximately 28 fish per 10-hr night). The water–ocean temperature differential was the most consistent environmental predictor, positively associated with smelt catch at both sites (Fore River RR = 1.448, $p < 0.001$; Jones River RR = 1.1.363, $p < 0.001$). This indicates higher catches occurred when river water was warmer relative to ocean temperature, suggesting that the thermal gradient between freshwater and marine environments may serve as a cue or correlate of conditions favorable for smelt presence. Tidal amplitude and river discharge were both significant predictors at each site although operating in opposite directions. Higher tidal amplitude reduced catch at the Fore River (RR = 0.860, $p < 0.01$) but increased it at the Jones River (RR = 1.273, $p < 0.01$), while higher discharge increased catch at the Fore River (RR = 1.198, $p < 0.01$) but decreased it at the Jones River (RR = 0.786, $p = 0.001$). These contrasting effects likely reflect differences in estuarine geomorphology, tidal dynamics, and potentially channel conditions at each fyke net station. Flood timing was significant at the Jones River (RR = 1.202, p = .019) indicating that there is some pattern to the movement timing of Rainbow Smelt. Flood timing was not included in the model for the Fore River as it was found to be non-significant and did not reduce the model AIC as it did for the Jones (**Table 3**).

Environmental Correlations among Rivers. No significant correlations were found in the phenology metrics of onset, peak and duration between the Fore and Jones rivers. The two water temperature metrics of W_T (*tau* = 0.332, $p = 0.043$, **Figure 9**) and average spawning season temperature (*tau* = 0.794, $p < 0.001$, **Figure 10**) were significantly correlated between the two rivers

Environmental Correlations with CPUE. No significant Kendall's *tau* correlations were found with any water temperature metrics and spring river discharge and annual CPUE in the Fore and Jones rivers. In fact, all annual correlations between CPUE and seasonal marine, river temperatures and river discharge were weak with no predictive value. The lagged CPUE data for age-1 and age-2 smelt in the Fore River also produced no significant correlations to environmental covariates. However, all four lagged age-2 CPUE correlations with marine winter season water temperature, marine spring water temperature, river spawning season, and river post-spawning season all had negative Kendall *tau* values (-0.23 to 0.29) with *p* values <0.20, indicating that higher lagged CPUE was related to cooler water temperature for year the cohort was born (**Figure 12).** In contrast, the Jones River produced highly significant correlations (*tau* = -0.47 to - 0.58; and p = 0.004 to 0.0004) of lagged age-1 and age-2 CPUE to marine winter temperature, marine spring water temperature and age-1 CPUE to spawning season river discharge (**Figure 12**).

Figure 12. Correlation of lagged smelt CPUE at the Jones River (A) and Fore River (B) with water temperature.

Discussion

Analysis on the timing of smelt spawning runs in Massachusetts provides the first evidence of phenological changes for this species. Both the Fore and Jones rivers had significant negative trends in timing of the 50% cumulative catch peaks in a 20-year period. The start of the smelt runs, as indicated by the 5% cumulative catch, were also trending earlier in both rivers, although only significantly in the Jones River. Ocean temperatures in Boston Harbor and Cape Cod Bay were significantly warming during the study period with earlier transition dates. River temperatures for the Fore and Jones rivers were also warming, although not to the extent of marine waters and not significantly. The trends for run duration were flat with no significant changes in duration length for the Fore and Jones rivers. Collectively, the

phenology metrics indicate that smelt are responding to warming marine habitat conditions with earlier arrival to freshwater spawning habitats in the spring and significantly earlier spawning peaks.

The advancement of phenological events in the wake of climate warming has been demonstrated in some ectothermic organisms dating back to the 1980s (Thackeray et al. 2010). The phenology of diadromous fish spawning run migrations has been studied most in Pacific salmon with trends of earlier migrations found for several species (Quinn and Adam 1996; Kovach et al. 2015; Manhard et al. 2017). Spring migrations of diadromous species in the Atlantic Ocean, including river herring (Alosa spp.), American shad (Alosa sapidissima), Atlantic salmon (Salmo salar), and European eel (Anguilla Anguilla), are also occurring earlier, with evidence linking the shifts to large scale climactic and local warming (Cobb 2020; Legrand et al. 2020; Eyto et al. 2022; Chang and Chen 2024). Vernal warming of nearshore marine waters is considered to be the primary selective influence on the trend of earlier emigration for juvenile salmonids. Juvenile chum (O. keta) and pink (O. gorbuscha) salmon, which like rainbow smelt, exhibit short freshwater residency periods following hatching, had the largest shift to earlier spring outmigration timing when compared to other Pacific salmon species in the same area (Wilson et al. 2023). Manhard et al. (2017) demonstrated rapid genetic change in pink salmon to favor earlier juvenile emigration: an example of recent evolution in salmon phenology in response to climate warming. Their hypothesis is that rapid, episodic adaptation to climate change could be more important than phenotypic plasticity to allow diadromous fish to successfully respond to warming environments.

Changes in river herring spawning run phenology has been shown recently in New England by relating warming water temperature to earlier migration timing (Ellis and Voukoun 2009; Rosset et al. 2017; Lombardo et al. 2019; Cobb 2020; Legett et al. 2021; and Dalton et al. 2022). River herring studies have shown that northern runs began and ended later than southern runs (Greene et al. 2009; Staudinger et al. 2019; and Leggett et al 2021). This is consistent with expected latitudinal trends in phenology that

progress from south to north. Run timing metrics for our four smelt runs vary from this expectation for diadromous fish as the northernmost Parker River smelt run had an early onset and peak and the southernmost Weweantic River run had the latest onset. However, these rivers had short run durations, sharply declining catch rates over the time series and extremely low smelt catch rates in recent years; all raising concerns over the risk of population collapse.

The warming trends found at the marine water temperature stations in Cape Cod Bay and Boston Harbor were not surprising given the awareness that the Gulf of Maine is one of the fastest warming ocean regions in the world (Hare et al. 2016). Relative to the marine warming, the river temperatures increased modestly during the study period. Questions arise over the impact of warming ocean waters beyond the demonstrated changes in phenology. Our hypothesis that cold marine waters would benefit recruitment of a cold-water species like smelt was only confirmed for lagged cohorts at the Jones River. No significant correlations were found for any environmental covariates to annual CPUE for both the Fore and Jones rivers and for lagged age-1 and age-2 CPUE at the Fore River. In contrast, the Jones River had highly significant correlations of lagged age-1 and age-2 smelt cohort strength to Cape Cod Bay winter and spring temperature. The strong correlations of cool water temperature to cohort strength in the Jones compared to the weak relationship in the Fore River (non-significant and only for age-2) raises interesting questions on the role of variable maturation of age-1 smelt (Chase et al. 2019) and population dynamics among rivers. We recommend that these rudimentary correlations are expanded in future analyses that bring in more cohorts with a longer time series and additional environmental covariates.

Several environmental covariates appear to influence the fine-scale trends in smelt spawning migrations in the Fore and Jones Rivers. The quadratic day of year model is nearly perfectly correlated to the smelt

run timing at both the Fore and Jones River across all years (Table 3). As expected, our model found that the river and ocean temperature differential had a significant positive influence on daily CPUE at both sites, indicating warming waters act as a cue for the spawning migration. River discharge was positively related to fish counts at the Fore River and negatively related to counts in the Jones River. There is evidence that anadromous brown trout (*Salmo trutta*) migration runs are positively correlated with river discharge (Svendsen et al. 2003), and that river discharge is the main factor influencing upstream migration for many anadromous salmonids (Banks 1969, Harrod et al. 2009). River discharge may interact with local differences in the two smelt rivers in terms of geomorphology, substrate composition, channel features and geographic location to influence fish migration upstream at variable discharge levels.

A synopsis of smelt spawning migrations included in Enterline et al. (2012) suggest that there are substantial latitudinal differences in migration timing and duration across the smelt's range (Enterline et al. 2012). Smelt spawning migrations decline in duration from south to north with brief spawning runs occurring in the Canadian Maritimes (McKenzie 1964; Pouliot 2002; Chase 2006; and Enterline et al. 2012). A landlock population in Wisconsin was found to have a rapid spawning run peak only four days after onset with daily changes in sex ratio as only males arrive initially followed by steady increases in female presence (Lischka and Magnuson 2006). In contrast, the present study documented extended smelt spawning durations in Massachusetts with the periods of smelt presence exceeding two months in the Fore and Jones rivers and the estimated duration (5% cumulative catch date to last observation) exceeding 50 days. The timing of spawning migrations is relevant in setting resource management restrictions on fishery and watershed construction time-of-year regulations. The regulated start of the smelt run in Massachusetts was March 15th prior to the adjustment to March 1st after evidence of earlier

583 spawning from Chase (2006). The present study found evidence of spawning movements and egg
584 deposition in February; an early onset not referenced in any prior smelt study in Massachusetts.
585
586 The truncation of the migratory period in the northernmost (Parker) and southernmost (Weweantic)
587 rivers in this study may reflect the negative relationship between phenological diversity and population
588 abundance. Loss of phenological diversity and reduced migration duration was observed in declining
589 populations of Chinook salmon and steelhead trout throughout western North America (Wilson et al.
590 2013). Phenological diversity buffers populations from rapid changes in environmental conditions, which
591 could contribute to the unknown explanation on why the Fore River smelt population, with the highest
592 CPUE and average duration, is stable or increasing, while others in the region are declining (Wilson et al.
593 2013; Kovach et al. 2013 and 2015).
594
595 There is growing awareness that climate warming is altering ranges and phenological events for
596 ectothermic species including migratory fish (Thackeray et al. 2010; and Kuczynski et al. 2017.
597 The distribution, migration and population-level changes in diadromous rainbow smelt across their
598 native range suggest a strong influence of climatic warming. Warming ocean waters are influencing the
599 timing of smelt spawning runs. Less is known about how migratory changes could manifest in population
600 level impacts to species due to changes in ontogenetic development and predator-prey mismatches as
601 species have differential responses to changing environments. Migration timing has been linked to
602 survival in Atlantic salmon, Chinook salmon, and Pink salmon, with fish experiencing higher survival rates
603 when entering the marine environment when conditions were favorable for growth (Mortensen et al.
604 2000; Antonsson et al. 2010; Manhard et al. 2017; and Berkman et al. 2021). Wilson et al. (2013) found
605 that shifts in salmon phenology are not linked to the simultaneous shifts in ocean productivity, possibly
606 resulting in greater likelihood of mismatch between resource availability and migration timing. For

607 rainbow smelt, individual growth and stock survival are likely linked to smelt larvae intercepting
608 zooplankton species they have adapted to forage on in the tidal estuary following yolk-sack absorption.
609 However, dynamics of this process are currently unknown. Concurrently, the remarkable reduction in
610 estuarine ice in recent decades in Massachusetts, which has limited mortality from ice shack fisheries,
611 yet allows predators such as seals and cormorants much improved spatial and temporal foraging access
612 to smelt migrations, further complicates our understanding. More information is needed on the causes
613 of smelt population declines, and indirect influences of climate change on trophic interactions and smelt
614 physiology have not been investigated (Kuczynski et al. 2017). Further, important potential influences
615 and climate interactions such as the eutrophication and urbanization of coastal watersheds in
616 Massachusetts on smelt reproductive recruitment should be considered as related threats.
617
618 The smelt fyke net study has limitations that should be considered when interpreting the results. The
619 fyke nets were set on Mondays and hauled the following three days. This method results in four days
620 each week with no records on smelt movements. The fyke nets could not be deployed at times with
621 estuarine ice (mainly the Parker River) and during high stream flows following large rain events. The fyke
622 nets were designed to have a span that fished a relatively small portion of the river channels. This was
623 done to avoid excessive catches of smelt and other migratory fish. Using a larger net or hauling the fykes
624 at a higher frequency would have likely produced an improved characterization of the smelt migrations
625 (particularly at the Parker and Weweantic rivers with wider river channels and fewer smelt). Despite
626 these limitations, the sampling design was maintained for 20 years with relatively few environmental
627 disruptions, allowing the determination of significant changes to run timing metrics in the Fore and
628 Jones rivers. The study is supported by a prior investigation that demonstrated suitable catch efficiency
629 in the Fore River (Turner et al. 2021
630

The outlook for rainbow smelt in coastal Massachusetts is concerning. The Parker River and Weweantic River smelt runs appear to be collapsing. Smelt have vacated mid-Atlantic and southern New England regions in recent decades (Fried and Schultz 2006; and Enterline et al. 2012). The Weweantic River is the southernmost known spawning run for rainbow smelt in their range. The Jones River spawning run is also significantly declining. Unexpectedly, the Fore River smelt run has a positive trend, although not significant, that conflicts with a clear picture of coast-wide declines in Massachusetts smelt runs and neighboring New England states in the last 20-30 years. An investigation of changes in smelt age and growth from the fyke net data series is recommended to explore this divergent pattern of smelt abundance in the Fore River. Further analysis is also needed to investigate how site-specific environmental and physical conditions might impact fyke net CPUE and relate to the important management interest of developing population indices of abundance for rainbow smelt.

Climate warming trends in the last half century are impacting fish populations and migrations. Potential large-scale effects from warming include range expansion, shifts towards poles, with associated population changes in migrations, maturation and growth rates. Our results suggest that changes are occurring in smelt populations over a relatively small spatial and temporal scales. Prior investigations on these same Massachusetts smelt runs found differences in length and age that may relate to phenotypic plasticity in maturation and growth over a modest geographical range (Chase et al. 2009 and 2019). These results and phenological studies on other diadromous fish raise questions over the ability, through plasticity or rapid adaptation, of these migratory species to respond to a warming environment and maintain the original selective advantage of diadromy.

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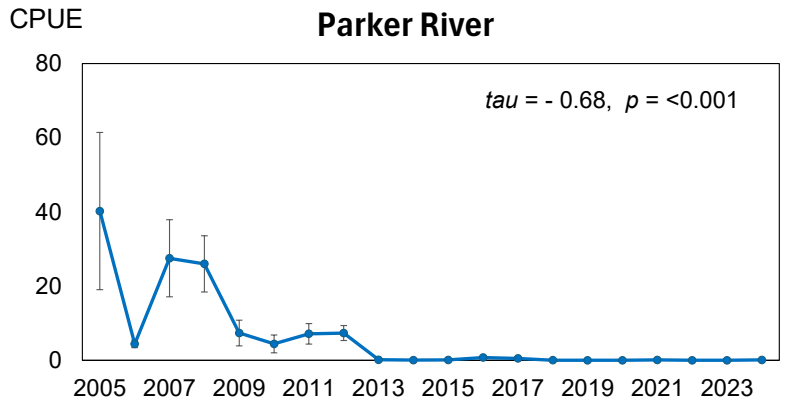
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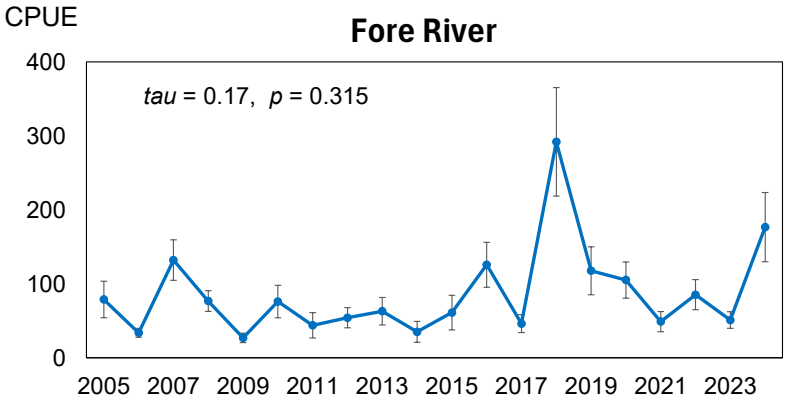
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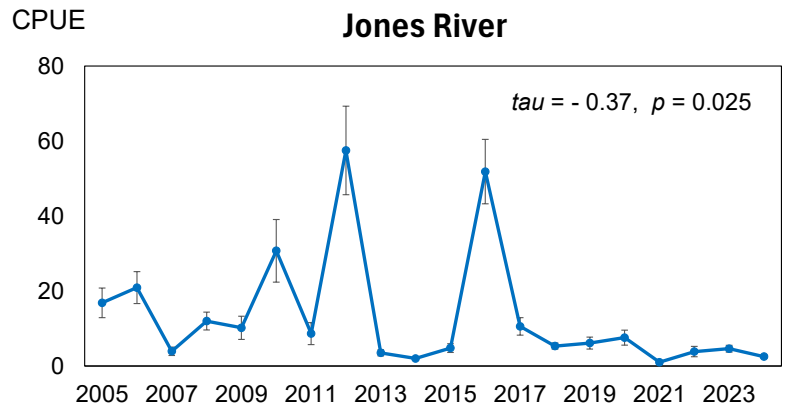
Figure 1



Figure 2


CPUE
Parker River
tau = - 0.68, p = <0.001
80
60
40
20
0
2005 2007 2009 2011 2013 2015 2017 2019 2021 2023


CPUE
Fore River
tau = 0.17, p = 0.315
400
300
200
100
0
2005 2007 2009 2011 2013 2015 2017 2019 2021 2023


CPUE
Jones River
tau = - 0.37, p = 0.025
80
60
40
20
0
2005 2007 2009 2011 2013 2015 2017 2019 2021 2023

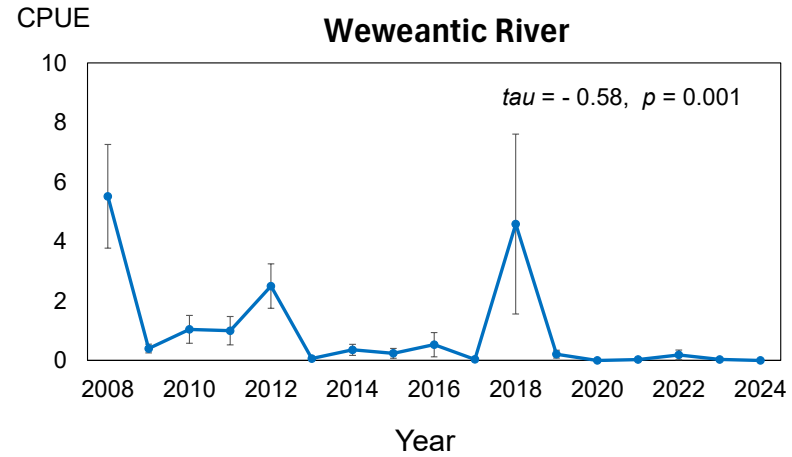

CPUE
Weweantic River
tau = - 0.58, p = 0.001
10
8
6
4
2
0
2008 2010 2012 2014 2016 2018 2020 2022 2024
Year

Figure 3

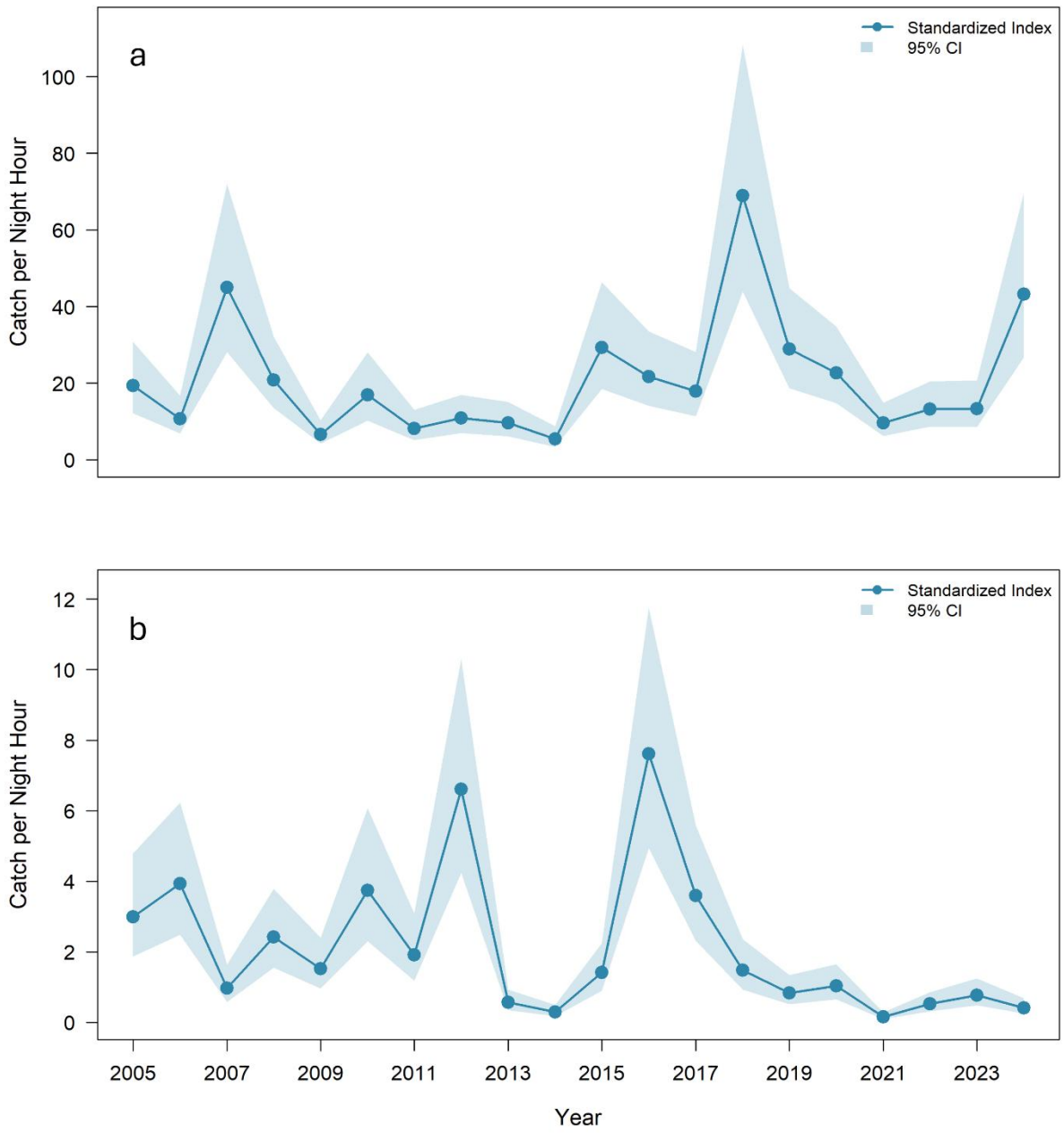

a
Standardized Index
95% CI
Catch per Night Hour
0
20
40
60
80
100
b
Standardized Index
95% CI
Catch per Night Hour
0
2
4
6
8
10
12
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
Year

Figure 4

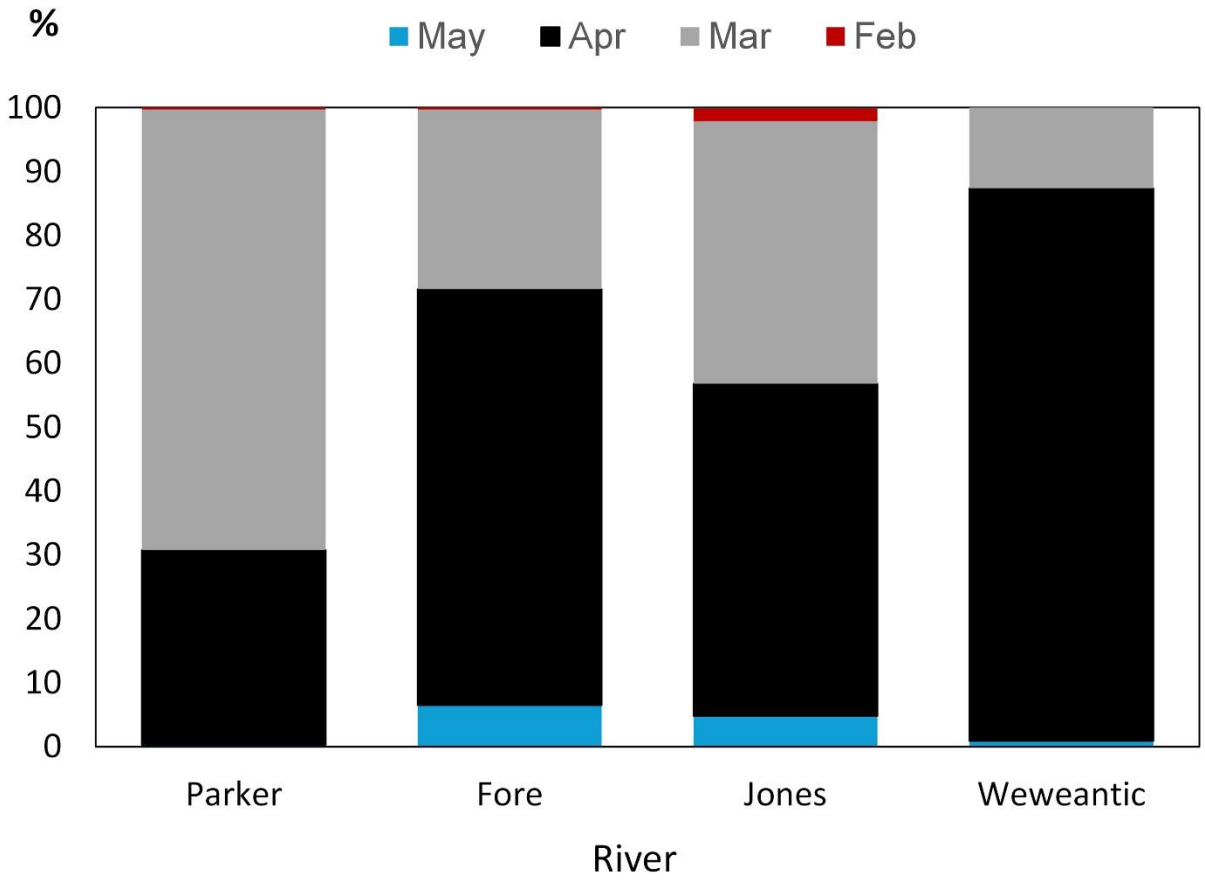

%
May
Apr
Mar
Feb
100
90
80
70
60
50
40
30
20
10
0
Parker
Fore
Jones
Weweantic
River

Figure 5

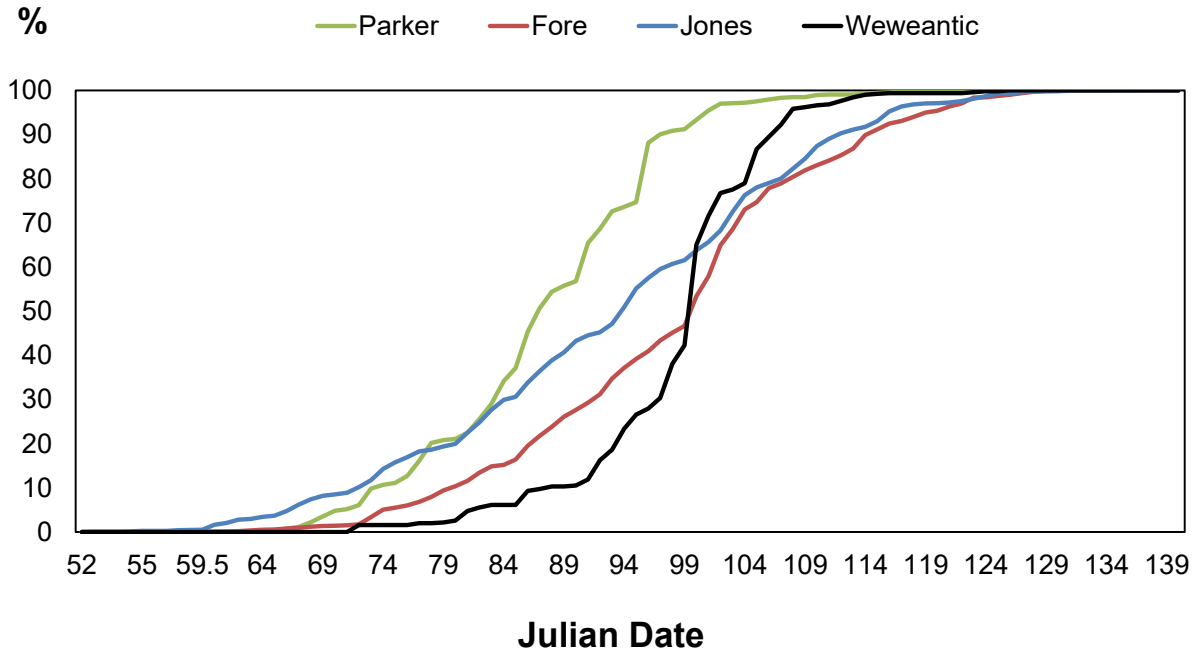

%
Parker
Fore
Jones
Weweantic
100
90
80
70
60
50
40
30
20
10
0
52
55
59.5
64
69
74
79
84
89
94
99
104
109
114
119
124
129
134
139
Julian Date

Figure 6

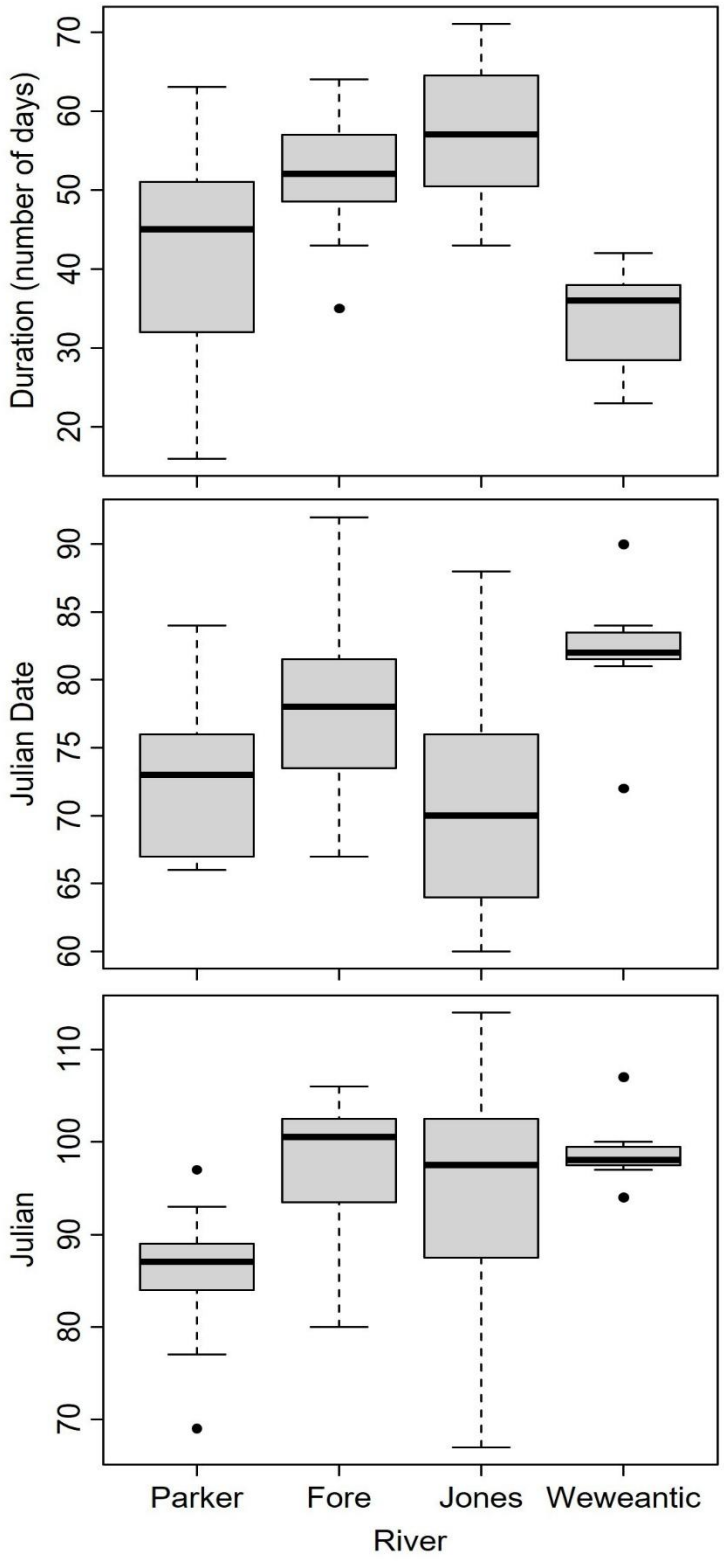

Duration (number of days)
20
30
40
50
60
70
Julian Date
60
65
70
75
80
85
90
Julian
70
80
90
100
110
Parker
Fore
Jones
Weweantic
River

Figure 7

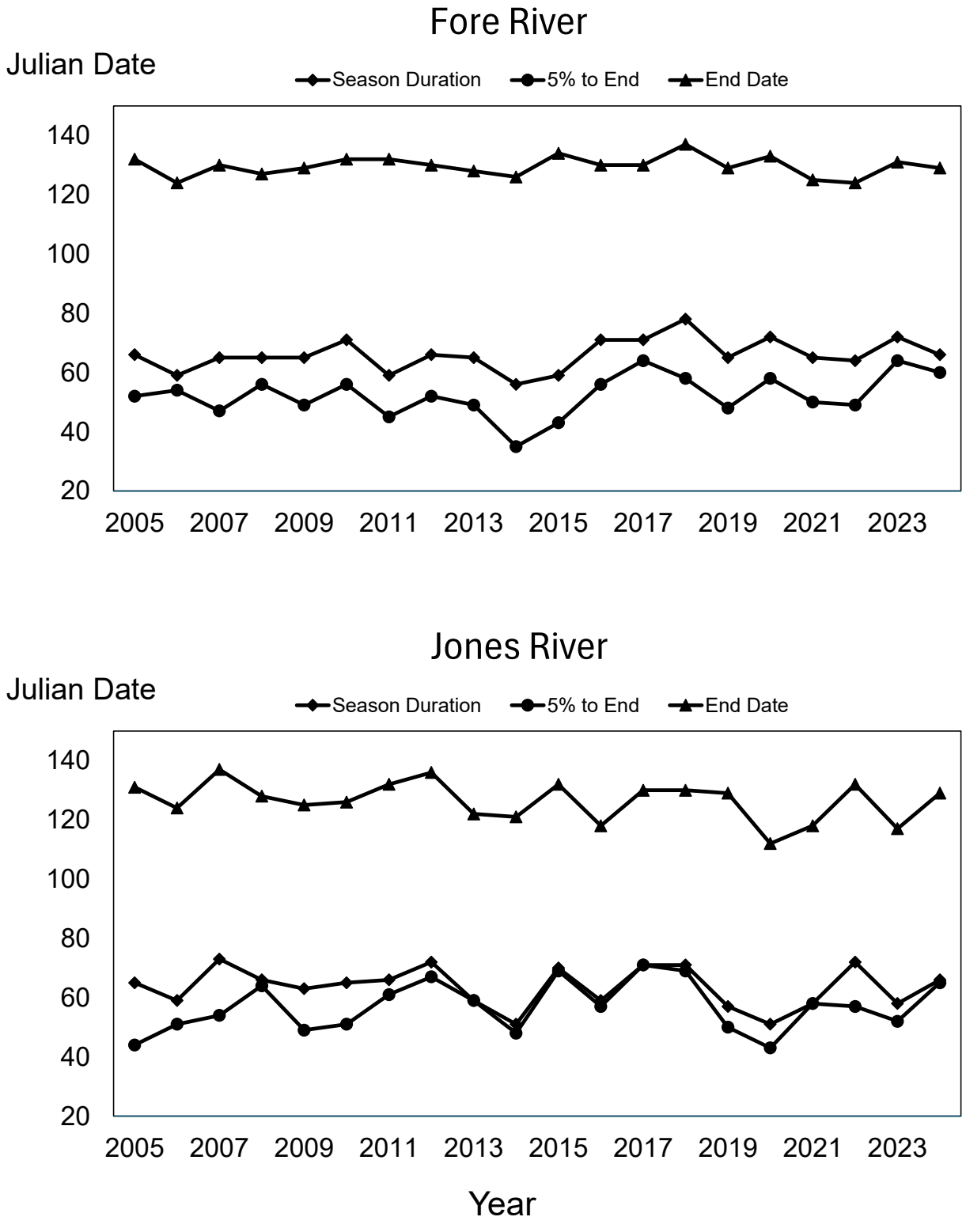
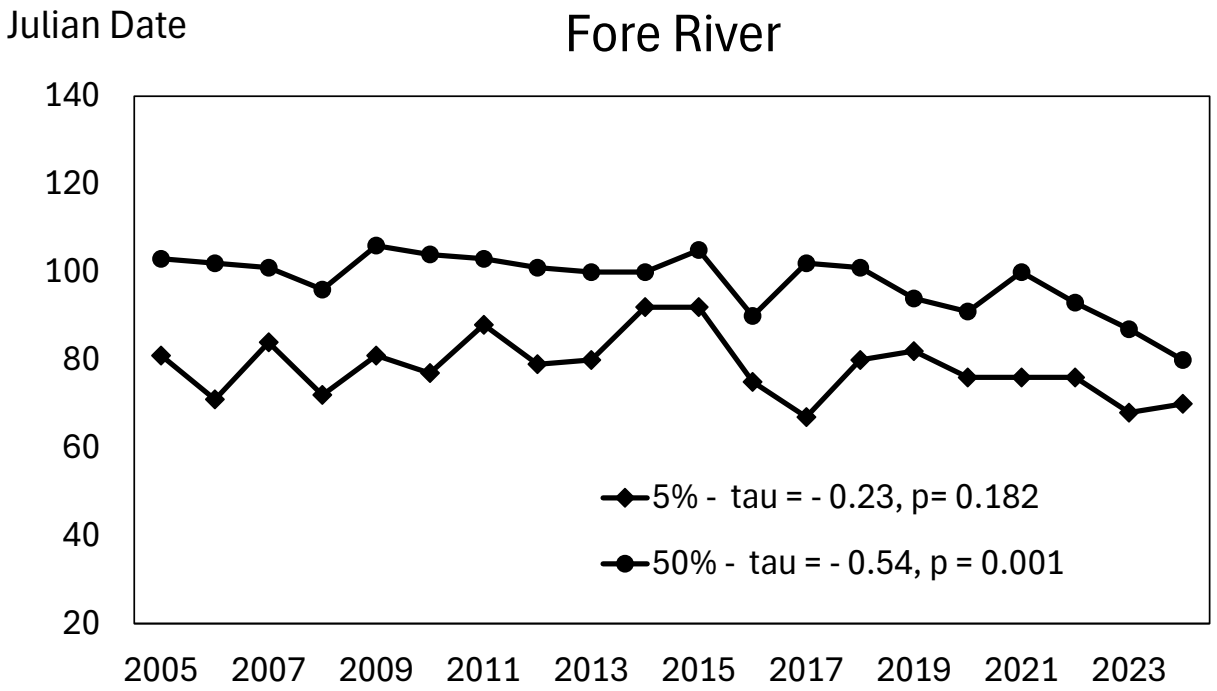

Fore River
Julian Date
Season Duration
5% to End
End Date
140
120
100
80
60
40
20
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
Jones River
Julian Date
Season Duration
5% to End
End Date
140
120
100
80
60
40
20
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
Year

Figure 8


Julian Date
Fore River
140
120
100
80
60
40
20
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
5% - tau = - 0.23, p= 0.182
50% - tau = - 0.54, p = 0.001

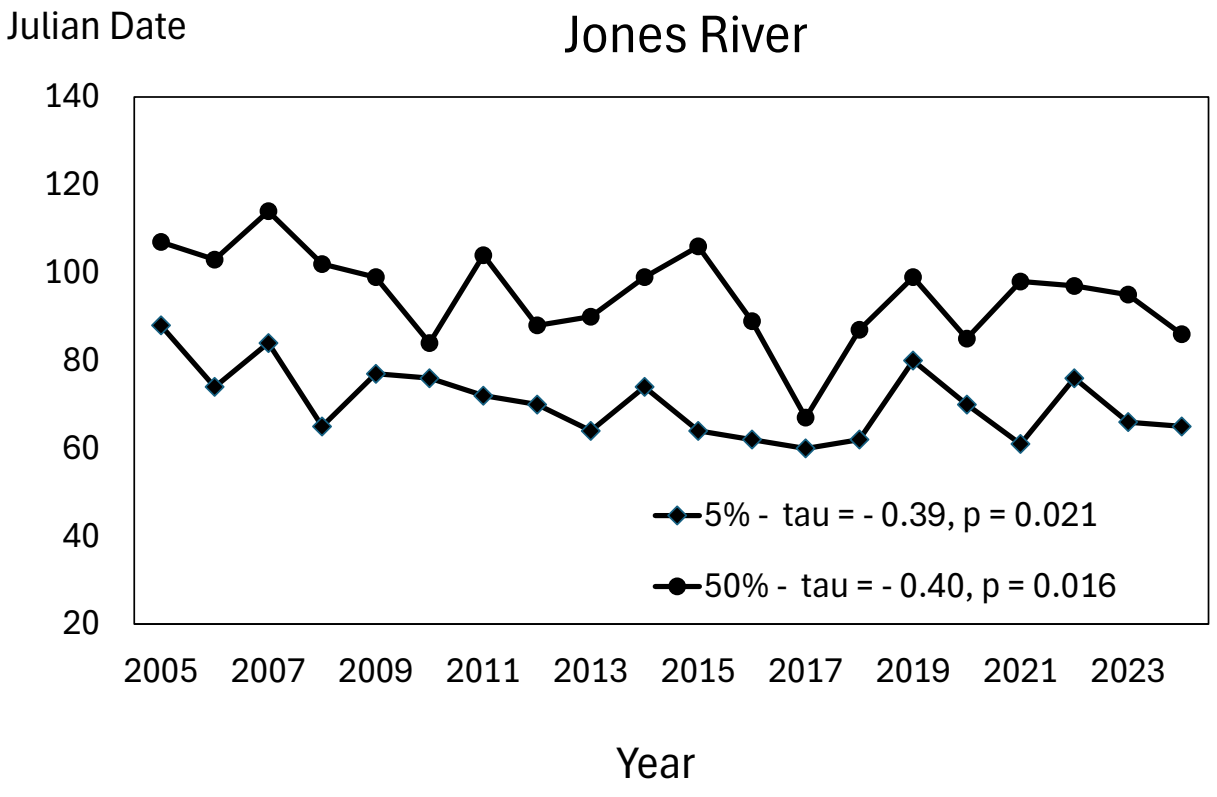
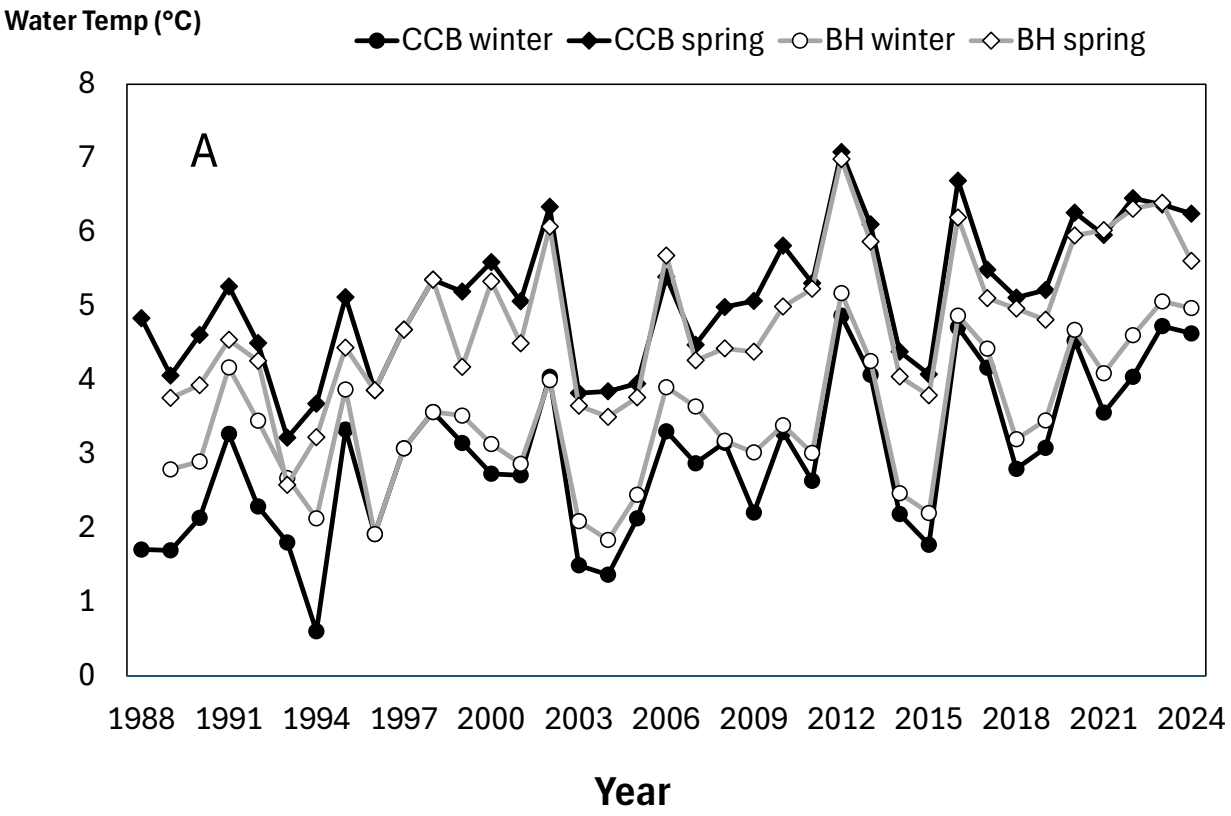

Julian Date
Jones River
140
120
100
80
60
40
20
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
5% - tau = - 0.39, p = 0.021
50% - tau = - 0.40, p = 0.016
Year

Figure 9


Water Temp (°C)
CCB winter
CCB spring
BH winter
BH spring
A
8
7
6
5
4
3
2
1
0
1988
1991
1994
1997
2000
2003
2006
2009
2012
2015
2018
2021
2024
Year

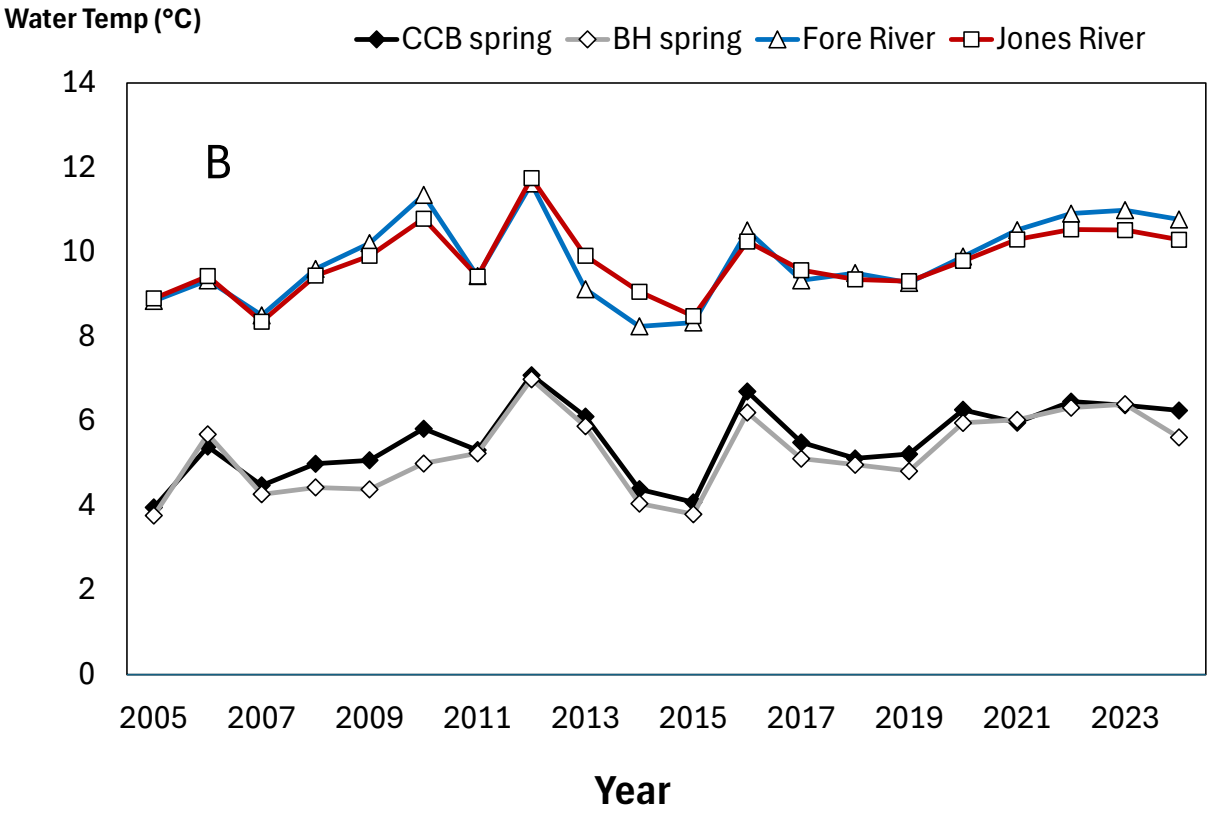
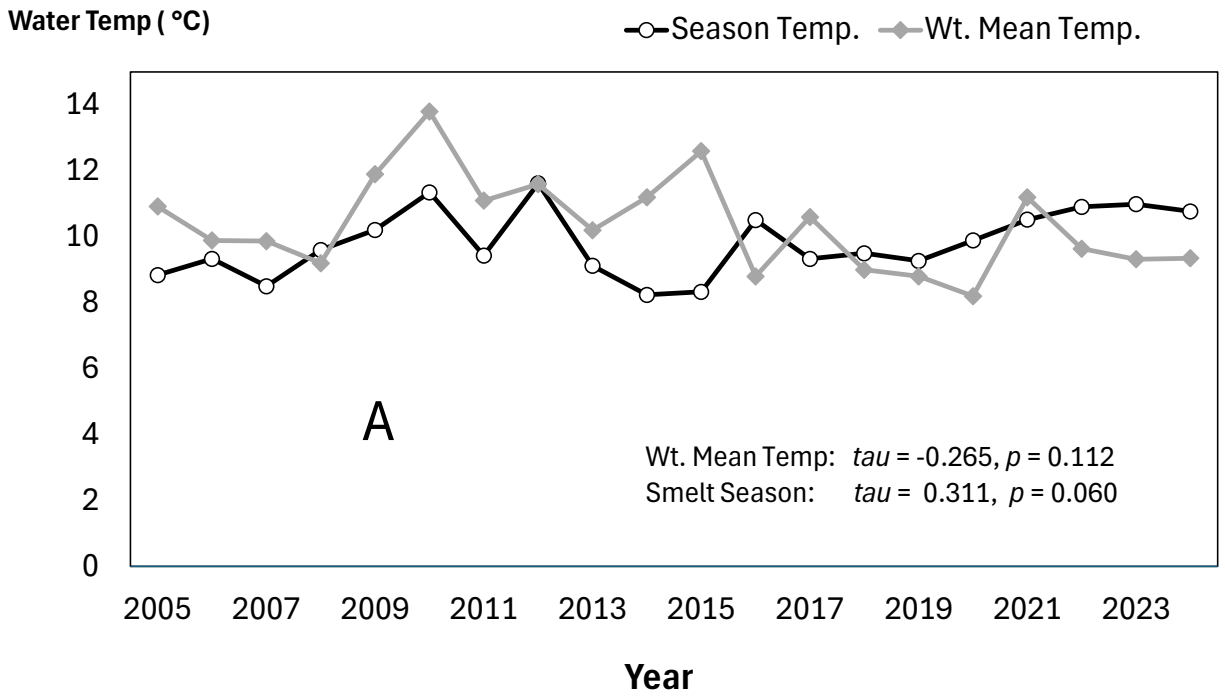

Water Temp (°C)
CCB spring
BH spring
Fore River
Jones River
B
14
12
10
8
6
4
2
0
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
Year

Figure 10


Water Temp (°C)
Season Temp.
Wt. Mean Temp.
14
12
10
8
6
4
2
0
A
Wt. Mean Temp: tau = -0.265, p = 0.112
Smelt Season: tau = 0.311, p = 0.060
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
Year

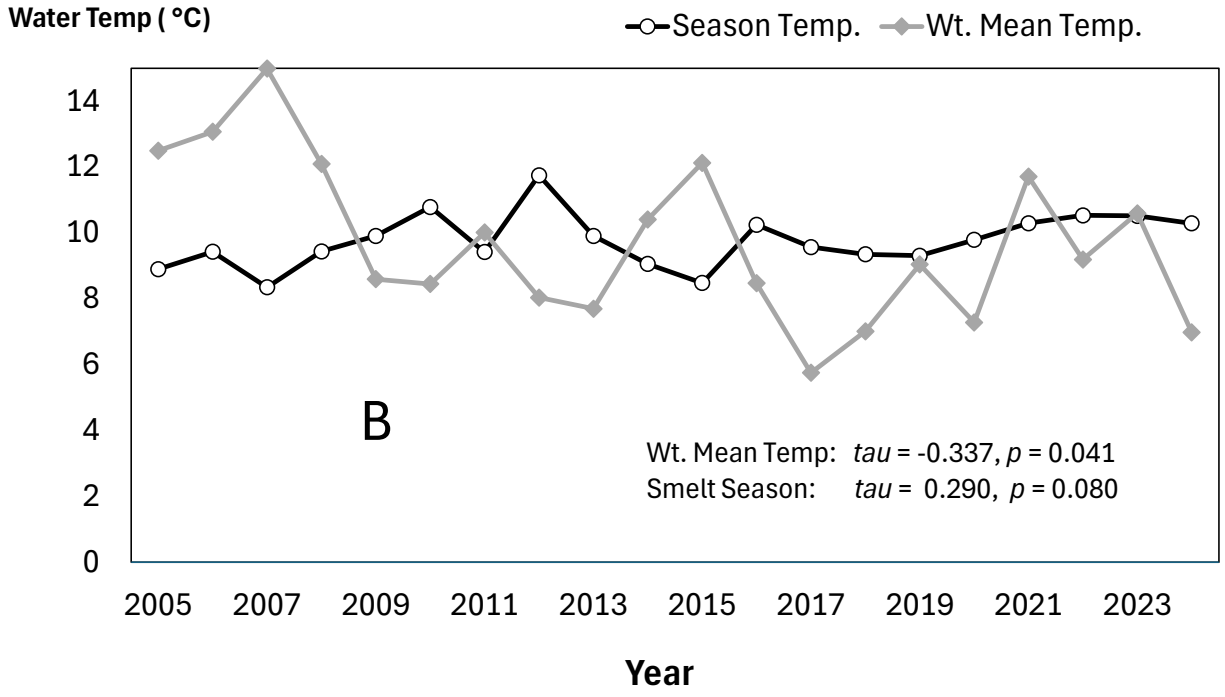

Water Temp (°C)
Season Temp.
Wt. Mean Temp.
14
12
10
8
6
4
2
0
B
Wt. Mean Temp: tau = -0.337, p = 0.041
Smelt Season: tau = 0.290, p = 0.080
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
Year

Figure 11

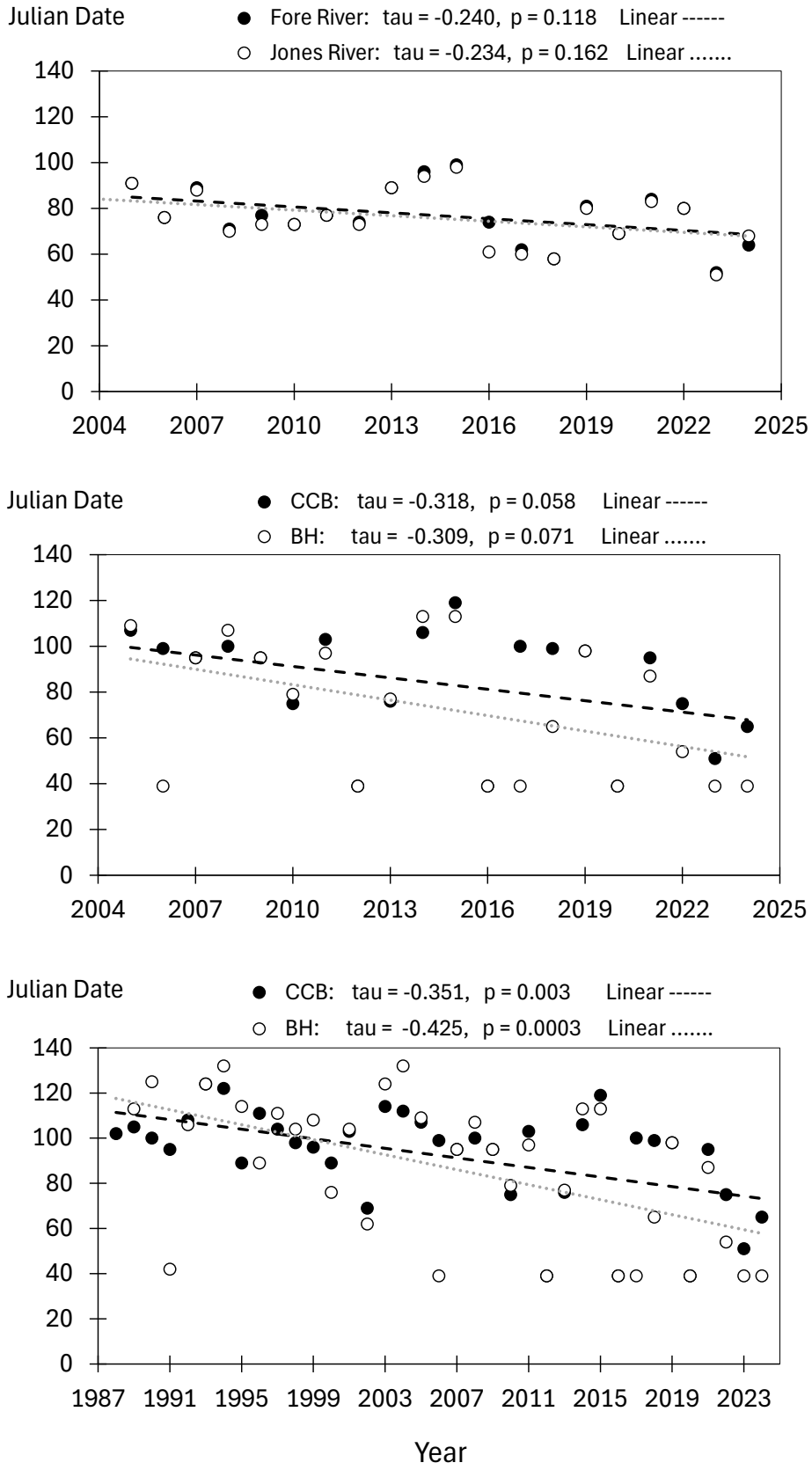

Julian Date
Fore River: tau = -0.240, p = 0.118 Linear ------
Jones River: tau = -0.234, p = 0.162 Linear .....
140
120
100
80
60
40
20
0
2004
2007
2010
2013
2016
2019
2022
2025
Julian Date
CCB: tau = -0.318, p = 0.058 Linear ------
BH: tau = -0.309, p = 0.071 Linear .....
140
120
100
80
60
40
20
0
2004
2007
2010
2013
2016
2019
2022
2025
Julian Date
CCB: tau = -0.351, p = 0.003 Linear ------
BH: tau = -0.425, p = 0.0003 Linear .....
140
120
100
80
60
40
20
0
1987
1991
1995
1999
2003
2007
2011
2015
2019
2023
Year

Figure 12

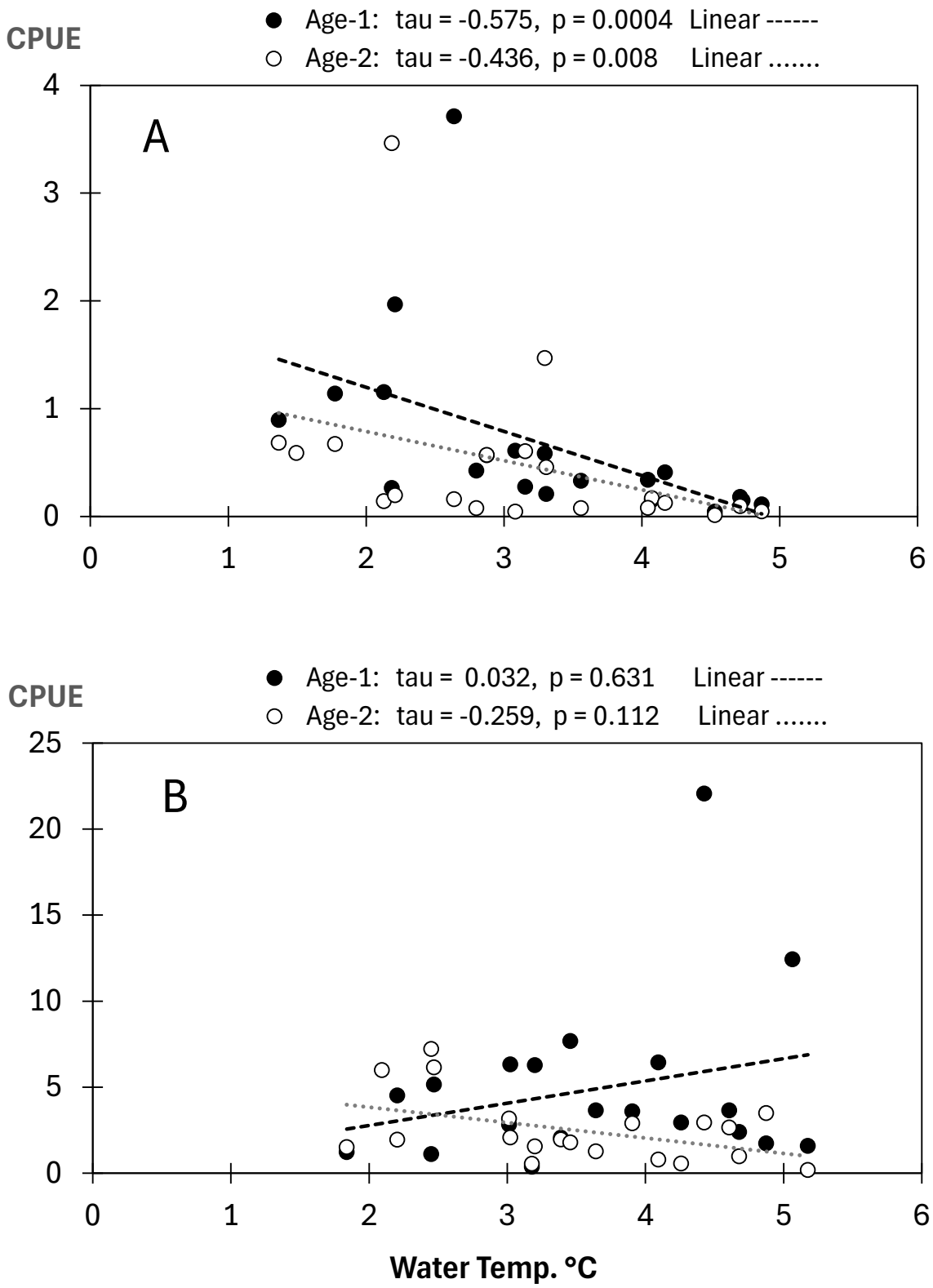

CPUE
Age-1: tau = -0.575, p = 0.0004 Linear ------
Age-2: tau = -0.436, p = 0.008 Linear .....
A
4
3
2
1
0
0
1
2
3
4
5
6
CPUE
Age-1: tau = 0.032, p = 0.631 Linear ------
Age-2: tau = -0.259, p = 0.112 Linear .....
B
25
20
15
10
5
0
0
1
2
3
4
5
6
Water Temp. °C

Table 1

River	Town	Latitude	Longitude	Watershed	Land Use ($1^o/2^o$)	Drainage Area (km^2)	Discharge (cfs)	Channel Width (m)
Weweantic	Wareham	41.7662	-70.7461	Buzzards Bay	Residential / Forest	148.2	NA	35.7
Jones	Kingston	41.9960	-70.7233	South Coastal Basin	Residential / Forest	69.3	55.4	27.3
Fore	Braintree	42.2225	-70.9732	Boston Harbor	Urban / Residential	74.7	81.4	13.7
Parker	Newbury	42.7505	-70.9282	Plum Island Sound	Residential / Forest	66.0	82.7	54.8

Table 2

River	Years (No.)	Onset Julian Date	5% Catch Julian Date	50% Catch Julian Date	End Date Julian Date	5% duration (Days)	Duration (Days)	Wt Mean Julian Date	Wt. Mean Temp (°C)	5% Catch (°C)	50% Catch (°C)	Duration (°C)
Parker	9	71	73	85	114	42	45					
Fore	20	65	78	98	130	52	66	99	10.36	5.83	10.19	9.43
Jones	20	64	71	95	127	57	64	95	9.70	5.64	9.69	9.11
Weweantic	7	81	82	99	114	33	35					

Table 3

Selected Model - Coefficients & VIF - Jones River (Table A)

Variable	Estimate	Std_Error	Z_value	P_value	Significance	Rate_Ratio	Rate_Ratio CI_Lower	Rate_Ratio CI_Upper	Percent Change	VIF	VIF_Status
Intercept	158.970	24.340	6.531	6.52E-11	***	1.096E+69	2.095E+48	5.74E+89	1.1E+71	N/A	N/A
year	-0.079	0.012	-6.501	7.99E-11	***	0.924	0.903	0.947	-7.6	1.11	OK
doy_c	-0.043	0.004	-10.527	6.46E-26	***	0.957	0.95	0.965	-4.3	1.83	OK
doy2	-0.002	0.000	-14.468	1.94E-47	***	0.998	0.997	0.998	-0.2	1.04	OK
river_discharge_scaled	-0.241	0.064	-3.77	0.000163	***	0.786	0.694	0.891	-21.4	1.09	OK
amplitude_scaled	0.241	0.075	3.204	0.00136	**	1.273	1.098	1.475	27.3	1.48	OK
flood_sin_scaled	0.184	0.078	2.344	0.0191	*	1.202	1.031	1.401	20.2	1.56	OK
flood_cos_scaled	-0.071	0.081	-0.882	0.378		0.931	0.795	1.091	-6.9	1.71	OK
temp_diff_scaled	0.310	0.084	3.687	0.000227	***	1.363	1.156	1.608	36.3	1.83	OK

Selected Model - Coefficients & VIF - Fore River (Table B)

Variable	Estimate	Std_Error	Z_value	P_value	Significance	Rate_Ratio	Rate_Ratio CI_Lower	Rate_Ratio CI_Upper	Percent Change	VIF	VIF_Status
Intercept	-50.425	21.897	-2.303	0.0213	*	0	0	0.001	-100	N/A	N/A
year	0.027	0.011	2.436	0.0149	*	1.027	1.005	1.049	2.7	1.02	OK
doy_c	-0.022	0.004	-5.804	6.48E-09	***	0.979	0.972	0.986	-2.1	1.83	OK
doy2	-0.003	0.000	-22.522	2.5E-112	***	0.997	0.996	0.997	-0.3	1.05	OK
river_discharge_scaled	0.181	0.060	3.017	0.00255	**	1.198	1.065	1.348	19.8	1.11	OK
amplitude_scaled	-0.151	0.058	-2.579	0.0099	**	0.86	0.767	0.964	-14	1.04	OK
temp_diff_scaled	0.371	0.078	4.74	2.13E-06	***	1.448	1.243	1.688	44.8	1.85	OK

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SmeltPhenologyDMFAugust2026Tables.pdf