Timing of Walleye Spawning as an Indicator of Climate Change

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Keywords: walleye, spawning, temperature, climate change, ice-out, *Sander vitreus*

Abstract

We obtained historical walleye (*Sander vitreus*) egg-take records for 12 spawning locations from the Minnesota Department of Natural Resources to determine if the timing of walleye spawning could be used as an indicator of climate change. We used ice-out data instead of temperature for our analyses because walleye often spawn soon after ice-out, and ice-out has been previously related to climate change. We used linear regressions to determine the relationship between the start of spawning and ice-out date and to determine if there were long-term trends in ice-out and spawning over time. Linear regressions of the date of first walleye egg-take versus ice-out date showed that for each day ice-out gets earlier, walleye spawning begins 0.5 to 1 day earlier. All but 2 regressions had slopes significantly less than 1, and slopes at the 2 exceptions were equal to 1. Regressions of first egg-take and ice-out date versus year showed trends toward earlier spawning and earlier ice-out. For regressions of first egg-take versus year, significant negative slopes ($P<0.1$) were observed in 5 out of 14 regressions with negative slopes, and there were 2 positive slopes that were not significant. For regressions of ice-out date versus year, 25 of 26 regressions were negative; there were 9 significant negative slopes ($P<0.1$) and no significant positive slopes. Overall, ice-out and walleye spawning are getting earlier in Minnesota, and the timing of walleye spawning may be a good biological indicator of climate change.

Introduction

As interest in climate change increases, there is a growing concern for its effects on the distribution and reproduction of species as well as an increasing need for biological indicators of climate change. Defining multiple parameters as indicators of climate change allows us to compare trends that can be used to predict future changes or reconstruct past changes in climate and allows us to choose cost-effective methods to monitor effects of climate change. Past research has documented climate trends by analyzing hydrologic parameters such as freeze and ice-out dates (Robertson et al. 1992; Magnusson et al. 1997; Jensen et al. 2007), climatic variables such as temperature and precipitation (Karl et al. 1996; IPCC 2001), and biological parameters such as changes in algal assemblages (Smol and Cumming 2000), diatom community structure (Kilham et al. 1996), and species distributions (Larocque et al. 2001; Chu et al 2005; Balanya et al. 2006). Indicators such as these help to answer questions from researchers, policy-makers, and the public about future climate projections, the effects of climate change on species and ecosystems, and anthropogenic forces that may be driving climate change.

The purpose of our study was to identify a biological indicator of climate change from an aquatic species that is an important commercial and recreational resource. Biological indicators are important because they provide us with a response that is a function of some stimulus over time instead of just a snapshot that may record a single extreme event (such as one random day with record high temperatures). By choosing walleye (*Sander vitreus*), a species important both commercially and recreationally, we were able to obtain long-term records to determine if the timing of walleye spawning was related to ice-out, and to identify any long-term trends in walleye spawning and ice-out data.

Walleye have been a popular sport and commercial fish in Minnesota for more than 100 years (Minnesota Department of Natural Resources 1997). Walleye egg-take for hatcheries started in the late 1800s, and by 1923 seven walleye hatcheries and collection sites were established (Minnesota Department of Natural Resources 1996). Fish trapping sites are used to capture walleye for egg collection. Walleye spawning typically occurs soon after ice-out when ambient water temperatures are between 4-11°C (Scott and Crossman 1973; Wolfert et al. 1975; Becker 1983), and is partly dependent on these conditions and photoperiod to induce gonadal and hormonal changes that prepare the fish for spawning (Hokanson 1977; Malison and Held 1996; Malison et al. 2004). Thus some climate variable(s) likely influence the timing of the spawning run.

Air temperature (e.g., mean monthly or maximum daily) has been used frequently in previous studies to examine the effects of climate change on various organisms. Air temperature has a strong relationship with life history traits of several species of birds (Winkel and Hudde 1997; Dunn and Winkler 1999; Both et al. 2005) and some amphibians (Reading 1998; Blaustein et al. 2001). For example, Dunn and Winkler (1999) discovered a strong negative relationship between the egg-laying date of tree swallows and spring temperatures, and Reading (1998) showed that the arrival of the common toad (*Bufo bufo*) to their breeding pond was strongly correlated with mean daily temperatures preceding the toads' arrival. Earlier studies of fishes have shown that climate change has significant relationships with species range shifts (Chu et al. 2005), recruitment (Shuter et al. 2002), fecundity (Sundby and Nakken 2008), and abundance (Kallemeyn 1987; Wingate and Secor 2008), but few have documented climate change effects on the timing of spawning in fishes.

For our study we decided to focus on the relationship between the timing of walleye spawning and ice-out instead of air temperature. Ice-out is generally described as the time when a lake is free of all ice. We used ice-out because walleye spawning generally occurs soon after ice-out (Scott and Crossman 1973; Becker 1983) and because previous research has documented changes toward earlier ice-out, which may be evidence of climate change (Magnuson et al. 1997; Magnuson et al. 2000; Jensen et al. 2007). We also chose to use ice-out data because it is broadly available geographically and historically (more than 100 years of data in some cases) whereas air and water temperature data are not. Moreover, Robertson et al. (1992) suggest that the climate signal is amplified by using ice cover as a response. Based on their analyses, a 1°C change in air temperature should result in a 5.1 (±0.4) day change in mean ice-out dates. Other research suggests that the timing of ice-out may be a good indicator of climate change because it is strongly correlated with air temperatures (Palecki and Barry 1986; Johnson and Stefan 2006). Previous studies suggest that the period 1970-onward is a distinct period of warming with increases in temperature occurring at a rate that is nearly double that of the previous period (IPCC, 2001; Walther et al. 2002). In agreement, a shift toward earlier ice-out in North America was documented during that same time period (Robertson et al. 1992; Johnson and Stefan 2006).

In this paper we determine the relationship between the timing of walleye spawning and ice-out, and we determine if there are trends in walleye spawning and ice-out over time in Minnesota lakes. If the timing of walleye spawning is related to ice-out, it may provide a convenient biological indicator to aid in future management plans for aquatic resources and in future climate change studies.

Methods

We obtained walleye (*Sander vitreus*) spawning records from the Minnesota Department of Natural Resources (MN DNR), and acquired Minnesota ice-out records from the Minnesota Ice Cover Database, the Minnesota Historical Society, and the Cook Herald News. For three of our spawning locations, we used ice-out data (measured as the number of days ice-out occurred after January 1st) from the same lake where walleye spawning data were collected (Table 1). Two spawning sites were in streams that flowed directly into the ice-out lakes, one site was in a system indirectly connected to the ice-out lake, and six sites were in water bodies not connected to the ice-out lakes but within 17 to 48 km. For Lake Sallie we evaluated two different ice-out datasets, Lake Sallie and Detroit Lake (connected to Lake Sallie) because the Detroit Lake ice-out record had 8 more sampled years than the Lake Sallie ice-out record. Statistical analyses were performed using R version 2.5.1, except Microsoft Excel was used to calculate some correlations. All statistical results were judged significant at the $P<0.05$ level unless otherwise stated. ArcGIS 9 (ESRI 2004) was used to map walleye spawning and ice-out locations and to measure the distance between spawning and ice-out data collection sites.

Walleye Spawning Records

Walleye spawning records collected by the MN DNR contained information on egg-take (number of eggs stripped from ripe walleye females) and individual fish counts obtained from twelve walleye egg collection operations conducted by various Minnesota hatcheries from 1938 to 2007 (Table 1). The timing of the walleye spawning runs could be described by the beginning of spawning, peak of spawning, or the end of spawning. From 1987 to 2007, the data recorded included number of walleye captured by sex and reproductive state of females (green, ripe, or spent), along with egg-take on each date. Prior to 1987, data on individual walleyes were generally not recorded and only data on egg-take were available. Because egg collection quotas were common among hatcheries and tended to halt egg collections before the actual end of walleye spawning, we decided to focus on the dates for beginning and peak of spawning only. We wanted to know if we could use these dates interchangeably or if one response was a better indicator of the timing of spawning runs. We also needed to determine whether males or ripe females would most accurately describe the timing of these walleye spawning runs and if the selected response was correlated with egg-take records so that data prior to 1987 could be used. We chose to use ripe females rather than green or spent females because these fish were ready to spawn.

We first determined if the arrival of ripe females or males was best associated with the timing of the spawning run, and if the timing was best described by the date of first or peak capture. We computed correlations between capture dates and sampling year for males and for ripe females at each location and between locations to determine if males and ripe females could be used interchangeably, and to see if there may have been variability due to different locations. We found that on average, correlations were higher for ripe females than males for both peak and first capture dates. We then used a one-way ANOVA to determine if capture dates for males and ripe females were different. There were significant differences between dates of male and ripe female capture for the peak of spawning ($P<0.001$) and for the start of spawning ($P<0.05$). On average, the first sighting of males was one day earlier than that of ripe females, and peak male capture occurred three days earlier than peak ripe female capture. For ripe females, correlations between capture date and year for the beginning and peak of spawning ranged from -1 to 0.99, so some variability may be explained by differences in location. For males, correlations between capture date and year for dates of first capture ranged from -1 to 0.99 and from -0.40 to 0.92 for dates of peak capture. Because Fitzimons *et al.* (1995) found that the initiation of spawning was associated with ripe females, and because we found that dates of capture for males and ripe females were significantly different (ANOVA), we decided to use ripe females instead of males, or the combination of males and ripe females. Moreover, because egg-take is directly from ripe females, we expected a stronger relationship between dates of ripe female capture and egg-take.

We then needed to determine if peak capture dates or dates of first capture better described the timing of the spawning run. Coefficient of determination (R^2) values from regressions of the peak of spawning versus the start of spawning for ripe females ranged from 0.16 to 0.94, and all but two locations, Otter Tail River and Rice Lake, were significantly different from zero. On average, peak capture of ripe female occurred 2 to 8 days later than first occurrence of ripe females. When correlations were computed separately across locations for the start of spawning and for the peak of spawning, correlations were larger on average for the start of spawning versus year than for the peak of spawning versus year. After considering effects of quotas on peak capture dates of ripe females (and egg-take) and the strong relationship between first capture dates versus year compared to dates of peak capture, we decided to use the date of first capture of ripe females for analyses.

To determine if egg-take (which greatly extended the data set) could be used instead of ripe females, we computed correlations between dates of first egg collection and dates of first ripe female sightings at all locations. They were highly correlated, with correlations (r) ranging from 0.78 to 0.99, and Rice Lake and Otter Tail River were the only locations with correlations less than 0.97. This allowed us to greatly extend our datasets by using egg-take data instead of data on adult walleyes that were typically not available prior to 1987.

Spawning and Ice-out Regressions and Time Series

We regressed the dates for the beginning of walleye spawning against ice-out dates for all 12 locations to determine if there was a relationship between the two variables. For these regressions April 1st was designated as day 1 to make intercepts easier to interpret. The slopes and intercepts were compared across latitudes to determine if there were obvious spatial trends, and were also compared using the “lmList” function in R (Pinhero and Bates, 2000) to create a list of slopes and intercepts as objects with 95% confidence intervals. T-tests were used to test the null hypothesis at each location that the slope was equal to one. To test for serial dependence in the datasets (Oehlert, 2000), the “acf” function in R was used to plot residuals from the regressions of walleye spawning versus ice-out date. We used a Bonferroni correction to control the family-wise error rate.

To determine if there were long-term trends in the timing of walleye spawning, we computed regressions of the beginning of walleye spawning (first egg-take) versus year for each location. Because Pike and Pine Rivers both had about a twenty year gap in data, regressions were also computed for these locations that restricted the analyses to those years after 1970. We used the “pbinom” function in R to test the probability of getting our observed number of negative slopes.

To determine if there were long-term trends in ice-out, we computed the regressions of ice-out dates versus year for all locations. Regressions were computed using full ice-out datasets at each location and using ice-out data that were matched to the sampling years represented in the spawning datasets. More than half of the ice-out locations had records that started around 1970 or later. To determine if significant trends were present for that period, the datasets with longer-term records (prior to 1970) were restricted to the years 1970 onward. We then used the "pbinom" function in R to test the probability of getting our observed number of negative slopes.

The "lowess" function in R, an algorithm based on the Ratfor original by W.S. Cleveland (1981), was used to compute a LOWESS smooth (SPAN=2/3) for each time series (spawning and ice-out). These were then compared to the linear regressions by computing the G-test statistic for lack of fit in R (Weisberg, 2005) to determine if the LOWESS smooth improved the fit. All time series datasets were tested for autocorrelation using the "acf" function in R, and a Bonferroni correction was used to control family-wise error rate.

Results

Relationship Between Spawning and Ice-out

The timing of walleye spawning runs was highly correlated with the timing of ice-out, and there was no evidence of autocorrelation. Slopes from linear regressions of first egg-take versus ice-out date were significant at all locations, and all R^2 values were greater than 0.30 (Figure 1). After a Bonferroni correction, 10 of 13 regressions were significant; only Bucks Mill, Otter Tail River, and Rice Lake were not significant. The relationships described by linear regression suggested that walleye spawning gets half a day to one day earlier for each day that ice-out gets earlier (Figure 1). Comparison of slopes and 95% confidence intervals indicated that all but 2 locations had slopes less than 1 (Figure 2), and t-tests (H_0: Slope=1) revealed that slopes were significantly different from 1 at all locations except Lake Koronis and the St. Louis River. We found no obvious trends across Minnesota latitudes to explain the differences in slope.

Spawning and Ice-out Time Series

The regressions of walleye spawning versus year revealed significant negative slopes at Otter Tail River and at Lake Koronis (Figure 3). Marginally significant ($P<0.1$) negative slopes were observed at Lake Sallie and for the restricted Pine River and Pike River datasets (Table 2). After a Bonferroni correction, Lake Koronis was the only location where the regression of egg-take versus year was significant ($P<0.0063$). Positive slopes were observed at Rice Lake and Bucks Mill, but these were not significant even without a Bonferroni correction; the other 14 slopes were negative. The probability of getting 14 negative slopes out of 16 was 0.0018. The LOWESS function improved the fit of the data ($P<0.05$) compared to linear regression at only Pike River, Pine River, and Rice Lake, which implied that data were well represented by the fit of the linear regressions at most locations.

For ice-out regressions there were 25 negative slopes and 1 positive slope (Table 3). Even if there were no significant relationships between ice-out date and year, the probability of getting 25 negative slopes out of 26 regressions was <0.0001. Significant negative slopes were observed at Lake Koronis, for the Lake Koronis time series restricted to Lake Koronis walleye sampling years, and for McDonald Lake restricted to Otter Tail River walleye sampling years (Figure 4, Table 3). A marginally significant ($P<0.1$) negative slope was observed at Detroit Lake using the full dataset, at McDonald Lake when the dataset was restricted to walleye sampling years at Dead River, and at Lake Sallie restricted to the Lake Sallie walleye sampling range (Table 3). For long-term time series where datasets could be restricted to years 1970 onward (5 out of 13 locations), a significant negative slope was observed at Rice Lake, and marginally significant ($P<0.1$) negative slopes were observed at Lake Koronis and Leech Lake (Table 3). No slopes were significant with the Bonferroni correction ($P<0.0038$). Linear regressions described the ice-out datasets better than LOWESS fits at most locations. Lack of fit G-test statistics to test if the LOWESS improved the fit compared to linear regressions were only significant ($P<0.05$) for Lake Vermilion (full dataset) and for the Lake Vermilion dataset that was restricted to the range of years represented in the Pike River egg-take dataset.

Discussion

There was a significant positive relationship between the start of walleye spawning and ice-out at all locations. Even with the Bonferroni correction, 10 of 13 regressions were significant. Walleye spawning occurred 0.5 to 1 day earlier for every day ice-out occurred earlier. Two locations had a slope equal to one: the Saint Louis River and Lake Koronis. The other 10 locations had slopes of about 0.5. Although it is typically reported that spawning occurs soon after ice-out (see Scott and Crossman 1973; Wolfert et al. 1975; Becker 1983), our results indicate that in many cases spawning may be initiated before ice-out. This may be a result of using the first occurrence of ripe females as an indicator of the start of spawning and because the peak occurrence of ripe females occurred 2 to 8 days after the first sighting of ripe females. Neither spawning habitat (river versus lake spawning), nor location (location of egg-take site or distance to corresponding ice-out location) could explain the two groups of slopes (0.5 and 1), which may mean that other lake characteristics are affecting slopes. Photoperiod and prior thermal history also determine timing of spawning (see Hokanson 1977; Malison and Held 1996; Malison et al. 2004) and likely constrain the dates of spawning.

Previous studies have shown a strong relationship between ice-out and air temperature (Palecki and Barry 1986; Robertson et al. 1992; Johnson and Stefan 2006), and temperature has significant relationships with life history traits of fishes (Bohlin et al. 1993; Shuter et al. 2002;

Sundby and Nakken 2008). In a study of the effects of temperature and climate change on year-class production of fishes in the Great Lakes Basin, Casselman (2002) noted that although the time of spawning in lake trout (*Salvelinus namaycush*) had been relatively consistent over time, an increase in fall temperatures at spawning time had a negative impact on year-class strength. Casselman observed a similar negative relationship between July-August temperatures and year-class strength for northern pike (*Esox lucius*), but observed the opposite for smallmouth bass (*Micropterus dolomieu*). Moreover, Sundby and Nakken (2008) observed that increasing temperatures induced a northward shift of spawning areas and an increase in fecundity for Arcto-Norwegian cod. Studies of walleye have shown that temperature affects the production and yield of walleye (Christie and Regier 1988; Schupp 2002) and that the timing of walleye spawning depends on water temperature and location (Scott and Crossman 1973; Hokanson 1977; Becker 1983), but the exact relationship between the timing of walleye spawning and temperature has not been well documented. Because our results show that there is a strong relationship between the timing of walleye spawning and ice-out, and ice-out has extensive evidence for its use as an indicator of climate change (e.g., Magnuson et al. 2000; Johnson and Stefan 2006), we believe the timing of walleye spawning is a useful biological indicator of climate change.

Regressions of walleye spawning versus year showed 14 negative slopes and 2 positive slopes; there were 5 significant negative slopes ($P<0.1$) and no significant positive slopes, which indicates that walleye spawning is getting significantly earlier at some locations in Minnesota, but not all. If we applied a Bonferroni correction, only 1 (Lake Koronis) of 16 regressions would be significant. However, the probability of getting 14 negative slopes out of 16 regressions was very low (0.0018). Walleye spawning regressions with more than 30 years of data comprised 80% of significant negative slopes. Four of the 5 significant regressions were for lakes where spawning records started in 1970 or later. Otter Tail River was the only significant relationship with records prior to 1970. We were unable to detect any spatial trends that would explain variability in relationships among locations.

For ice-out, our results were consistent with previous studies that documented ice-out occurring earlier over time (Schindler et al. 1990; Robertson et al. 1992; Magnuson et al. 2000; Johnson and Stefan 2006). For example, 25 of 26 regressions were negative; there were 9 significant negative slopes ($P<0.1$) and no significant positive slopes. Although a Bonferroni correction would result in no significant regressions, the probability of getting 25 negative slopes out of 26 regressions was very low (<0.0001). Ice-out regressions with more than 30 years of data comprised 75% of significant negative slopes. Six of the 9 significant regressions were for locations where ice-out records started in 1970 or later; Lake Koronis, McDonald Lake restricted to Dead River walleye sampling years, and McDonald Lake restricted to Otter Tail River walleye sampling years were the only significant relationships with records prior to 1970. Some literature (IPCC, 2001; Walther et al. 2002) suggests that 1970-forward is a period of distinct warming occurring at rates nearly double those of previous years. There was some indication of accelerating ice-out in our datasets.

Our results suggest that the timing of walleye spawning could be used as a biological indicator of climate change because it has a strong relationship with ice-out. Both walleye spawning and ice-out in Minnesota seem to be occurring earlier over time. Although all slopes were not negative and those that are negative were not all significant, both variables (spawning and ice-out) show mostly negative trends over time. Moreover, the very low likelihood of getting so many negative slopes and few positive slopes for both spawning and ice-out suggest the trends are real.

Aside from being used as an indicator of climate change, the relationship between walleye spawning and ice-out may provide information about how climate change is affecting walleye populations. One potential consequence of earlier spawning may be a mismatch in the timing of larval walleye abundance and peak prey availability. Gotceitas et al. (1996) showed that larval Atlantic cod (*Gadus morhua*) tended to exhibit poorer growth and survival when there was a temporal mismatch in peak larvae abundance and peak prey availability compared to match conditions. This type of interaction has also been documented outside of the laboratory. Winder and Schindler (2004) found that there was a temporal mismatch in diatom and zooplankton blooms due to differences in sensitivity to warming in Lake Washington. *Daphnia* densities declined because the peak diatom bloom occurred too early to allow for maximum foraging by *Daphnia* populations. Because zooplankton availability significantly influences the survival and growth of larval walleye (Mayer and Wahl 1997; Hoxmeier et al. 2004), a temporal mismatch between peak larvae abundance and peak zooplankton (or other prey) availability may also significantly affect walleye populations. Additionally, change in the timing of walleye spawning may also affect recruitment if there is a temporal mismatch between the timing of peak larval emergence and optimal discharge events. There is strong evidence that discharge affects larval walleye survival (Becker 1983; Mion et al. 1998; Jones et al. 2006) and that discharge events may be significantly affected by climate change (Middelkoop et al. 2001; Peterson et al. 2002; Graham 2004).

We have presented evidence that the timing of walleye spawning may be a good biological indicator of climate change that could also provide insight into how climate change is affecting walleye populations. The timing of walleye spawning is a convenient indicator because walleye are an important sport and commercial fish that are continually monitored and managed in

Minnesota. Further research investigating lake and river characteristics is needed to identify factors that could be influencing the relationship between the timing of walleye spawning and ice-out. This information would be useful for developing models that may be able to reliably predict the timing of walleye spawning. It would also be useful for creating a universal climate change model instead of several models that vary based on individual locations.

Acknowledgments

Walleye spawning records were supplied by the Minnesota Department of Natural Resources. Ice-out records were provided by the Minnesota Ice Cover Database, the Minnesota Historical Society, the Minnesota Pollution Control Agency, the Minnesota State Climatologist’s Office, and the Cook Herald News. Funding for this project was provided by the Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources (LCCMR). Special thanks to the University of Minnesota (UMN) Conservation Biology Graduate Program, UMN Department of Fisheries, Wildlife and Conservation Biology, and the Minnesota Agricultural Experiment Station for additional funding. We also thank Lucinda Johnson, the principal investigator of the grant, and Rick Nelson and Maggie Gorsuch of the MN DNR for their help acquiring and organizing data for this project.

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Table 1. Summary of spawning locations and associated ice-out locations in Minnesota. Distance from spawning location to associated ice-out location was measured, and the number of years (N pairs) were counted where both spawning and ice-out data were available. Sampling range of years for both spawning and ice-out records is shown. The overlap range represents the range of years when spawning and ice-out data were both available, and superscripts identify the type of connectivity, if any, between spawning and ice-out locations.

Spawning location	Range (years)	Ice-out location	Range (years)	Site-to-site distance (km)	N pairs	Overlap range
Big Lake Creek	1971-2006	Big Turtle Lake[4]	1965-2008	21.86	29	1971-2005
Boy River	1970-2006	Long Lake (Cass)[4]	1974-2008	14.25	32	1974-2005
Bucks Mill	1985-1993	Long Lake[3] (Becker)	1980-2003	10.49	9	1985-1993
Dead River	1966-2007	McDonald Lake[4]	1968-2005	18.56	35	1969-2005
Lake Koronis	1996-2007	Lake Koronis[1]	1950-2005	NA	8	1996-2007
Lake Sallie	1971-2007	Lake Sallie[a]	1970-2007	NA	29	1971-2007
Lake Sallie		Detroit Lake[c]	1970-	1.2	37	1971-

			2007			2007
Little Cut Foot Sioux	1942-2007	Leech Lake[d]	1936-2007	48.10	61	1942-2007
Otter Tail River	1954-2002	McDonald Lake[d]	1968-2005	19.91	24	1971-2002
Pike River	1938-1946, 1971-2007	Lake Vermilion[b]	1906-2007	10.23	44	1938-2007
Pine River	1925-1942, 1970-2006	Edna[d]	1980-2005	17.33	26	1980-2005
		Ponto[d]		20.72		
		Gull[d]		26.99		
Rice Lake	1987-2007	Rice Lake[a] (& synthetic)	1962-2005	NA	10	1987-2005
St. Louis River	1992-2006	Fond du Lac[b]	1996-2007	< 1	11	1996-2006

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[a] Same location as egg-take

[b] Egg-take location runs into ice-out lake

[c] Connected to egg-take site through a system of lakes and streams

[d] No connection to egg-take location

Table 2. Summary of linear regressions of first egg-take versus year. The y-intercept, slope, *P*-value, and number of years with egg-take data (N) are shown for each spawning location. Years for restricted regressions are given in parentheses.

Spawning location	Y-intercept	Slope	*P*	N
Big Lake Creek	135.35	-0.013	0.891	33
Boy River	240.07	-0.067	0.453	37
Bucks Mill	-692.71	0.400	0.433	9
Little Cut Foot Sioux	195.49	-0.042	0.363	66
Little Cut Foot Sioux (1970-2007)	474.12	-0.182	0.108	38
Dead River	238.50	-0.067	0.388	39
Lake Koronis	3540.21	-1.714	0.005	8
Lake Sallie	419.29	-0.158	0.053	37
Otter Tail River	442.60	-0.168	0.037	32
Otter Tail River (1971-2002)	474.20	-0.184	0.213	23
Pike River	152.69	-0.022	0.640	46
Pike River (1971-2007)	493.09	-0.193	0.070	36
Pine River	122.36	-0.009	0.781	55
Pine River (1970-2006)	527.90	-0.213	0.061	37
Rice Lake	-218.55	0.160	0.484	12
St. Louis River	788.60	-0.339	0.383	15

Table 3. Summary of linear regressions of ice-out date versus year for full and restricted datasets. The y-intercept, slope, *P*-value, and number of years with ice-data (N) are shown for each location. Parentheses indicate datasets restricted to a range of years or restricted to years sampled at the corresponding spawning location. Brackets indicate county names for lakes with identical names.

Ice-out location	Y-intercept	Slope	*P*	N
Big Turtle Lake	383.00	-0.137	0.192	42
Big Turtle Lake (Big Lake Creek)	401.52	-0.146	0.387	30
Big Turtle Lake (1970-2007)	388.19	-0.139	0.276	37
Detroit Lake	558.91	-0.227	0.064	38
Detroit Lake (Lake Sallie)	509.32	-0.202	0.121	37
Edna, Ponto, and Gull	-124.09	0.116	0.500	26
Fond du Lac	1255.88	-0.573	0.283	12
Fond du Lac (St. Louis River)	1690.70	-0.791	0.211	11
Lake Koronis	437.74	-0.169	0.027	56
Lake Koronis (Lake Koronis)	2964.18	-1.429	0.041	8
Lake Koronis (1970-2005)	680.02	-0.291	0.084	36
Lake Sallie	512.55	-0.204	0.101	30
Lake Sallie (Lake Sallie)	551.48	-0.223	0.095	29
Lake Vermilion	130.30	-0.006	0.846	88
Leech Lake	256.29	-0.071	0.137	72
Leech Lake (1970-2007)	533.39	-0.210	0.069	38

Long Lake [Cass]	239.97	-0.066	0.640	34
Long Lake [Becker]	120.84	-0.007	0.974	24
McDonald Lake	486.45	-0.191	0.125	38
McDonald Lake (Dead River)	580.99	-0.238	0.082	35
McDonald Lake (Otter Tail River)	912.34	-0.405	0.007	27
Rice Lake (and synthetic)	372.96	-0.137	0.225	43
Rice Lake (1970-2005)	563.48	-0.233	0.042	36
Lake Vermilion	130.30	-0.0064	0.846	89
Lake Vermilion (1970-2007)	467.03	-0.176	0.106	38
Vermilion Lake (Pike River)	468.72	-0.177	0.243	32

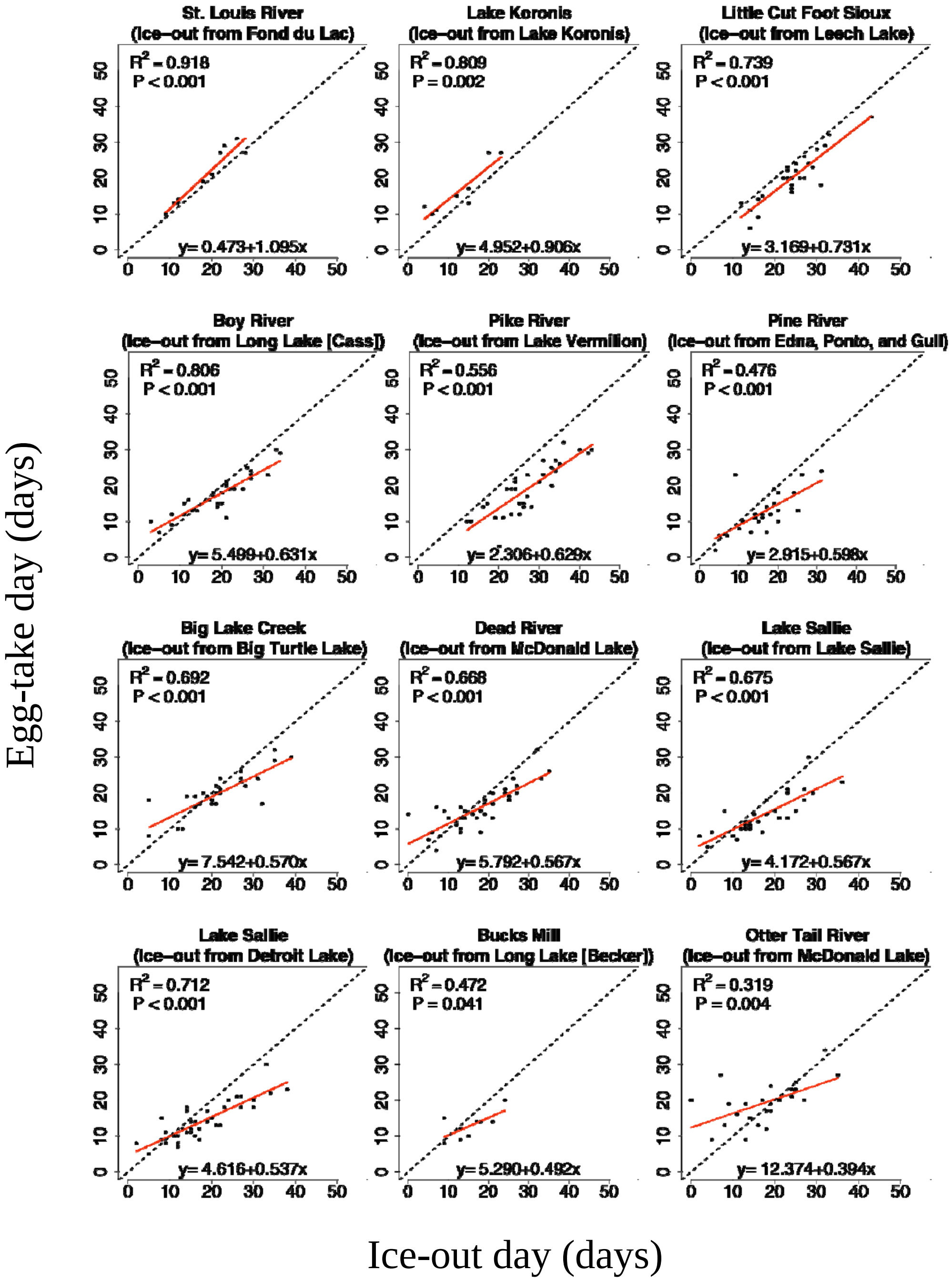
Figure 1. Regressions of first day of egg-take versus ice-out day in order of decreasing slope. All slopes were significant at the 0.05 level. The solid line is the linear regression. The dashed line is y=x. Each point represents one year, and the origin is April 1st.

Figure 2: List of linear model objects from regressions of egg-take day versus ice-out day with 95% confidence intervals in order of decreasing slope. All slopes were significantly less than 1 except for Lake Koronis and the St. Louis River.

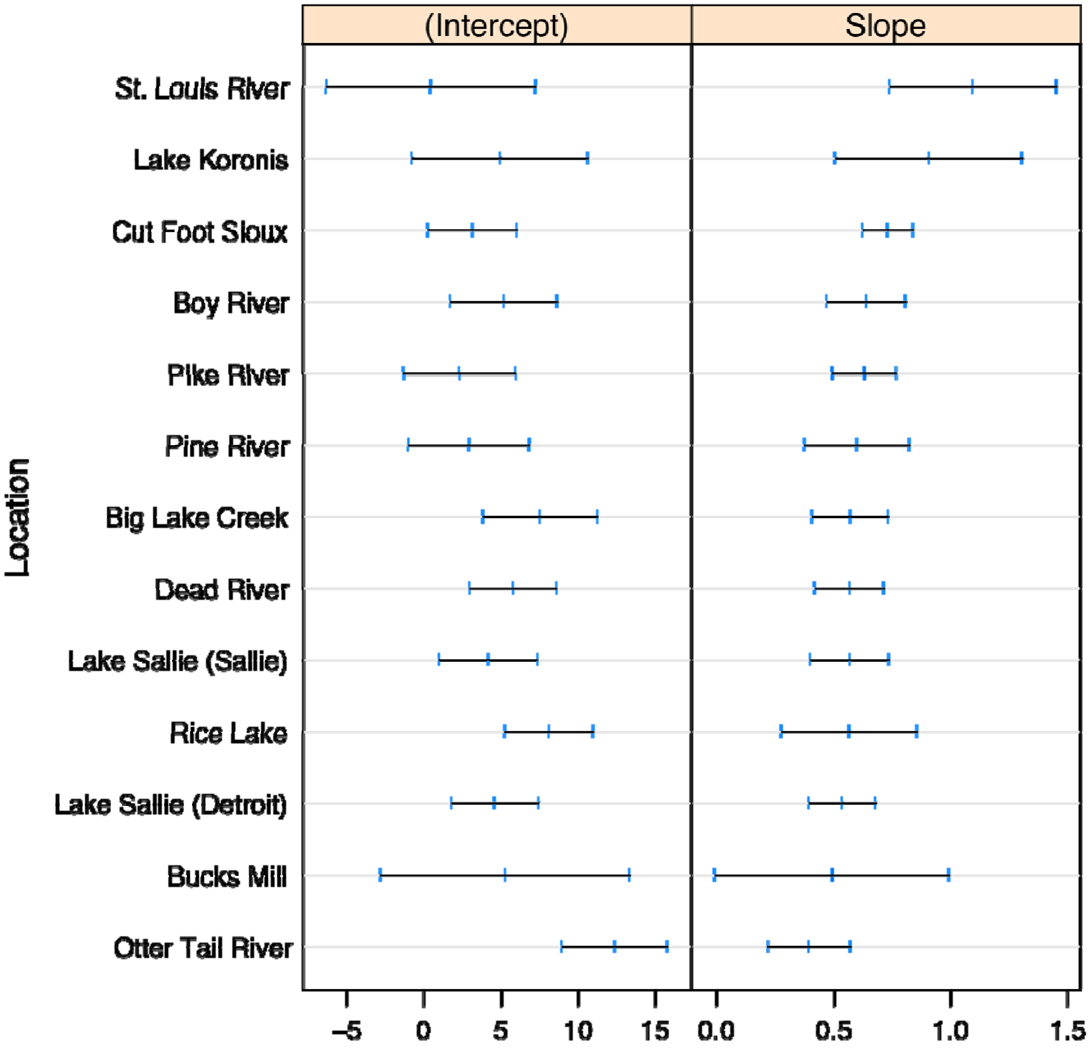
Figure 3. Example relationships of walleye first egg-take versus year. First egg take is recorded as the number of days from 1 January. The solid line is the linear regression, and the dashed line is the LOWESS fit. The linear regression was a better fit than the LOWESS smooth at all locations shown except Lake Koronis. All slopes shown except Little Cut Foot Sioux were significant at the 0.1 level. Little Cut Foot Sioux is shown as an example of a long-term time series that didn’t have a significant slope.

Figure 4. Example regressions of ice-out date over time. Ice-out is recorded as the number of days from 1 January. The solid line is the linear regression, and the dashed line is the LOWESS fit. All slopes shown except Leech Lake (full dataset) were significant at the 0.1 level. The Leech Lake time series is shown as an example of a long-term dataset that didn’t have a significant slope. The LOWESS smooth did not improve the fit of the data compared to linear regression for all time series shown.

Schneider Figure 1

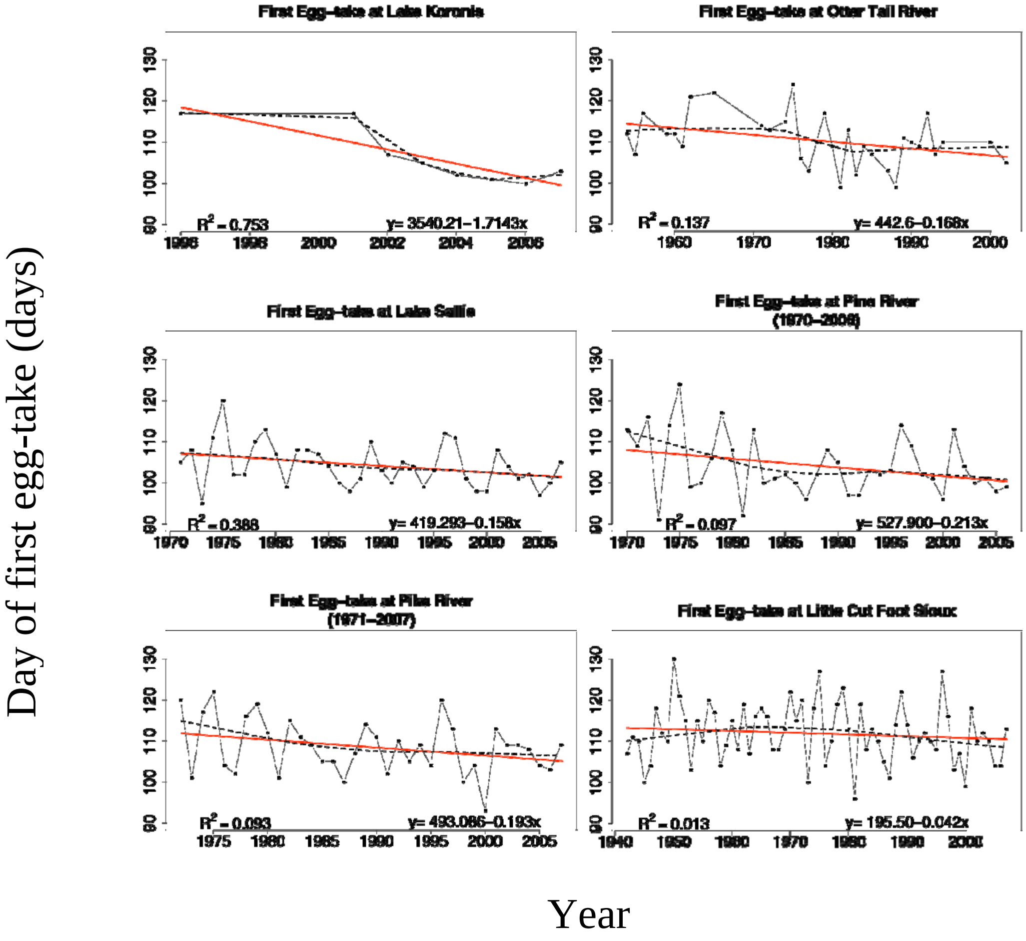


535 Schneider Figure 2



536

Schneider Figure 3



Schneider Figure 4