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ARTICLE

Differences in Stocking Success among Geographically Distinct Stocks of Juvenile Muskellunge in Illinois Lakes

Matthew J. Diana,*[1] Curtis P. Wagner,[2] and David H. Wahl
Illinois Natural History Survey, Kaskaskia Biological Station, 1235 County Road 1000N, Sullivan, Illinois 61951, USA

Abstract
Muskellunge *Esox masquinongy* are broadly distributed across the northern United States and southern Canada. Intraspecific genetic variation suggests the existence of divergent stocks related to residence in major river drainages. Populations and stocks have likely adapted to specific environmental conditions associated with geographic location, especially latitude and the associated thermal regime. In this study, we examined differences in survival and growth among stocks of juvenile Muskellunge stocked into lakes throughout Illinois. Muskellunge from the Ohio River drainage stock, the upper Mississippi River drainage stock, and the current mixed Illinois broodstock were used for comparisons. Stocking mortality was related to temperature and was greatest for Illinois and Ohio River drainage fish that were stocked during the early fall. Mississippi River drainage fish experienced high mortality over the first summer after stocking, resulting in the lowest abundance during the second fall poststocking. In addition to low catch rates, Muskellunge from the Mississippi River drainage were significantly smaller than fish from the Illinois and Ohio River drainage stocks by the second fall. Populations from similar latitudes and climate (Illinois and Ohio) performed the best in terms of survival and growth and should be utilized in future stockings.

Muskellunge *Esox masquinongy* are large, piscivorous fish that are widely distributed throughout the north temperate United States and Canada. Muskellunge are highly sought after by anglers, and Muskellunge fisheries have high economic and societal value (Hanson 1986; Margenau 1999; Margenau and Petchenik 2004). Consequently, many Muskellunge fisheries are supplemented or entirely supported by the stocking of fingerlings (Wingate 1986; Margenau 1992; Szendrey and Wahl 1996; Wahl 1999); therefore, managing for recruitment to the creel depends heavily on an understanding of the life history characteristics of age-0 fish (Szendrey and Wahl 1996; Kampa and Jennings 1998; Wahl 1999). Even as Muskellunge are regularly stocked into new waters (within and outside their native range) to create additional recreational angling opportunities, wild populations have declined and in many areas have been extirpated from their native range (Koppelman and Philipp 1986; Wingate 1986; Wahl 1999; Farrell et al. 2006; Kapuscinski et al. 2007).These anthropogenic manipulations and their subsequent effects on the Muskellunge's range require a thorough knowledge of the appropriateness of source stocks and populations for management purposes (Crossman 1986; Clapp and Wahl 1996).

Fish stocking is a prominent practice in fisheries management, and introductions of Muskellunge are no exception (Wahl 1999; Wingate and Younk 2007). However, whether fish introductions are supplementing existing native fisheries or creating a nonnative fishery, the effects on fish communities and the genetic integrity of conspecifics must be considered (Koppelman and Philipp 1986; Philipp et al. 1993). With these considerations, there remain situations in which stocking is a logical and viable option for fisheries management. When Muskellunge are introduced into waters where a native population exists, that same population should ideally be used as a brood source. In other situations, Muskellunge are introduced into previously uninhabited waters to create new fisheries. Under these circumstances, knowledge of

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*Corresponding author: dianam@michigan.gov
[1] Present address: Michigan Department of Natural Resources, Fisheries Division, 621 North 10th Street, Plainwell, Michigan 49080, USA.
[2] Present address: Ohio Department of Natural Resources, Division of Wildlife, 912 Portage Lakes Drive, Akron, Ohio 44319, USA.
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population differentiation may be useful for planning stocking programs. Introducing the most appropriate populations or stocks into new waters increases the chances of creating a successful Muskellunge fishery.

After the Wisconsin glacial period, Muskellunge established their current range in the Mississippi River and Ohio River systems as well as through the tributaries of the Great Lakes (Crossman 1978, 1986). Three distinct stocks have been identified through genetic analyses of various populations separated by these major river drainages: the upper Mississippi River drainage stock, the Great Lakes/St. Lawrence River drainage stock, and the Ohio River drainage stock (Koppelman and Philipp 1986; Clapp and Wahl 1996; Wagner and Wahl 2007). As Muskellunge were isolated by major river drainages and experienced differing environmental conditions, it is likely that natural selection acted on these groups to structure adaptive physiological and behavioral differences (Altukhov 1981; MacLean and Evans 1981). Research on other fish species in the Great Lakes region has found differences in growth between stocks of Rainbow Smelt *Osmerus mordax* (Luey and Adelman 1984) as well as Lake Whitefish *Coregonus clupeaformis* (Ihssen et al. 1981). Survival and growth can also differ on a smaller scale within a stock and have been shown to vary for Muskellunge from different source populations (Younk and Strand 1992; Margenau and Hanson 1996; Wingate and Younk 2007) and for Largemouth Bass *Micropterus salmoides* from different drainages (Philipp and Claussen 1995). Food consumption, metabolism, and growth have been compared among populations and stocks of age-0 Muskellunge in the laboratory, and differences in growth and food consumption among populations were observed at temperatures over 15°C (Clapp and Wahl 1996). Growth differences among stocks could result in differential losses to predation (Wahl and Stein 1989) and overwinter survival (Carline et al. 1986), which also may indicate the potential for substantial differences in long-term growth among Muskellunge populations and stocks in field settings (Clapp and Wahl 1996).

Substantial effort has been directed toward understanding the factors that influence Muskellunge stocking success, including the size of fish and the timing of stocking to maximize survival and growth (Margenau 1992; Johnson and Margenau 1993; Wahl and Stein 1993; Szendrey and Wahl 1996; Wahl 1999) as well as the biotic and abiotic sources of stocking mortality (Carline et al. 1986; Mather and Wahl 1989; Wahl and Stein 1989; Hanson and Margenau 1992; Szendrey and Wahl 1995). Comparatively little work has been directed toward understanding physiological and life history differences among populations and stocks of Muskellunge along with their subsequent effects on stocking success and management programs. The objectives of this study were to determine whether (1) relative abundance, survival, and growth differed among three stocks of Muskellunge after stocking events in three Illinois impoundments; and (2) poststocking survival and growth varied in relation to stocking date, temperature at stocking, and winter and summer severity. The objectives were addressed by introducing three distinct stocks of Muskellunge into three Illinois lakes using a common-garden approach.

METHODS

Three sources of Muskellunge were examined in this study: upper Mississippi River drainage stock (hereafter, Mississippi River stock), Ohio River drainage stock (hereafter, Ohio River stock), and a mixed source that was bred from a mix of upper Mississippi River and Ohio River stock fish maintained in Illinois hatcheries since 1993 (hereafter, Illinois stock). Although Illinois fish are not a true genetic stock, we refer to them as “Illinois stock” here. Muskellunge from the Ohio River stock included Kentucky, New York, and Ohio populations, and the Mississippi River stock was represented by a Minnesota population (Table 1). Cooling degree-days (CDD) and heating degree-days (HDD) were calculated for each stock by using a base temperature of 18.3°C with 1961–1990 data from the National Oceanic and Atmospheric Administration (NOAA), Midwestern Regional Climate Center, and the New York State Climate Office (Table 1). Muskellunge from all sources were reared in hatching trays and grown in raceways to 101.6 mm (4 in) TL. They were then stocked into earthen ponds with Fathead Minnow *Pimephales promelas* as prey until they reached stocking size in the fall.

Survival and growth differences among the three Muskellunge stocks were evaluated via a common-garden approach. The three stocks were introduced over 3–4 years into each of three eutrophic lakes in Illinois: Mingo Lake (72 ha), Pierce Lake (61 ha), and Sam Dale Lake (79 ha; Figure 1). In each study year, all three stocks were introduced into a study lake concurrently so that they

TABLE 1. Sources of age-0 Muskellunge stocks used for evaluation of poststocking survival and growth. The Illinois stock comprised progeny of a mixed-stock brood source. Cooling degree-days (CDD) and heating degree-days (HDD) were calculated using a base temperature of 18.3°C with 1961–1990 data from the National Oceanic and Atmospheric Administration, Midwestern Regional Climate Center, and the New York State Climate Office.

Source population	Drainage (stock)	Latitude (°N)	CDD	HDD	Mean annual air temperature (°C)
Cave Run Lake, Kentucky	Ohio River	37°35′	641	2,618	12.9
Clear Fork Lake, Ohio	Ohio River	39°30′	391	3,500	9.8
Lake Chautauqua, New York	Ohio River	42°07′	194	3,488	9.7
Leech Lake, Minnesota	Upper Mississippi River	46°35′	193	5,275	4.4
North Spring Lake, Illinois	Mixed (Illinois)	40°40′	554	3,387	10.4

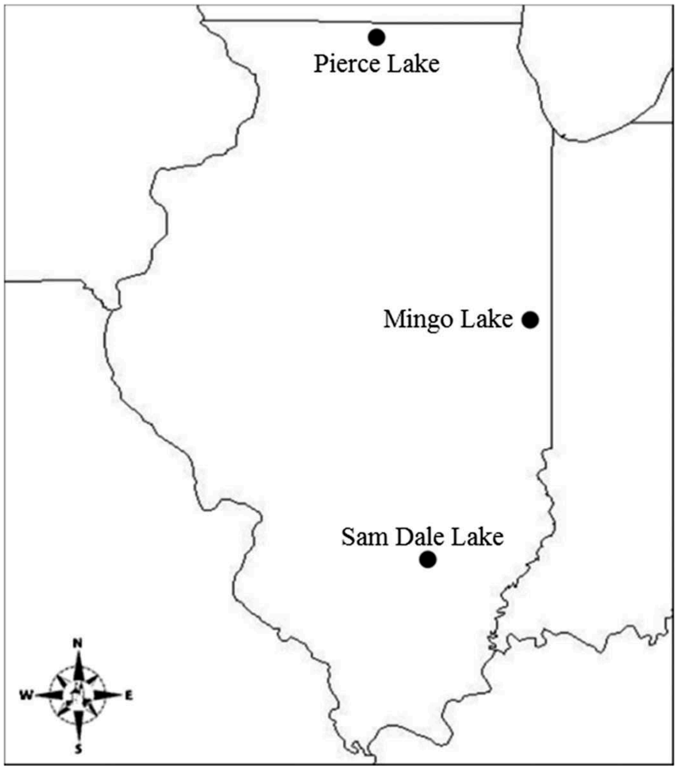

FIGURE 1. Map of Illinois, showing the locations of three lakes (Pierce, Mingo, and Sam Dale lakes) where three Muskellunge stocks (upper Mississippi River drainage, Ohio River drainage, and mixed Illinois) were stocked.

would experience the same environmental conditions throughout the study period. All three systems have prey communities consisting of Gizzard Shad *Dorosoma cepedianum* and Bluegills *Lepomis macrochirus* and have similar aquatic vegetation, water quality, and physical characteristics (Austen et al. 1993). Largemouth Bass *Micropterus salmoides* are the primary predators in these lakes. Muskellunge were historically stocked in Pierce and Mingo lakes, but numbers were very low at the initiation of this study (CPUE = 0.07 fish/h in Pierce Lake and 0 fish/h in Mingo Lake during spring and fall electrofishing in 1998–2002). All three stocks were introduced into Mingo and Pierce lakes during 2003, 2004, 2005, and 2007 and into Sam Dale Lake during 2005, 2007, and 2008. Muskellunge were transported from source hatcheries directly to the study lakes, where they were tempered to within 2°C of lake temperature before stocking to avoid thermal stress (Mather and Wahl 1989; Szendrey and Wahl 1996).

Fish were hauled to stocking locations using a double-sided hauling tank of 265 L per side (total = 530 L). Densities of fish in the hauling tank ranged from 5 to 79 g/L (0.2–0.9 fish/L), which are lower than the Illinois Department of Natural Resources' (IDNR) recommended hauling density of 90 g/L for fall fingerling Muskellunge (Steve Krueger, IDNR, personal communication). In addition, hauling density was below those that affected mortality of stocked Muskellunge in laboratory experiments (Mather and Wahl 1989). Prior to stocking, a sample of each stocked group was measured (mm TL) and weighed (g) to determine the stocking size (Table 2). Attempts were made to stock a similar density and size of fish from each respective stock. Across all lakes and stocks, the mean (±SE) stocking size was 263 ± 6 mm, and the mean stocking density was 4.0 ± 0.2 fish/ha. A larger target stocking size was used to increase initial survival as shown in previous studies (Carline et al. 1986; Szendrey and Wahl 1996; McKeown et al. 1999). All introduced fish were given a stock-specific, complete pelvic fin clip (single fin or both fins, which do not affect survival and growth; Wagner et al. 2009), followed by freeze-cauterization of the wound (Boxrucker 1982). Subsamples of each stocked group were held in three predator-free cages (3-m depth × 1-m diameter; 3.2-mm mesh; $N = 15$ fish/cage) for 48 h to assess initial mortality associated with stress from transport and stocking (Szendrey and Wahl 1996; Clapp et al. 1997; Diana and Wahl 1999). Hourly temperature readings were recorded using thermographs placed at 1-m depth in each lake for the duration of experiments.

Muskellunge were sampled at night by boat electrofishing (pulsed DC) that covered most of the perimeter or the entire perimeter of each lake. Electrofishing transects were standardized based on IDNR protocols, where the same Smith-Root Type-VI box was utilized with 250-V DC and the pulse width adjusted to target 4–5-A output. Weekly or biweekly samples were collected during the spring (March–April) and fall (October–November) after stocking to assess survival and growth to the first fall, first spring, second fall, and second spring poststocking for each year-class. Captured Muskellunge were measured (mm TL) and weighed (g).

Because Ohio River drainage fish were obtained from three different sources, we conducted a repeated-measures ANOVA with source, sampling period, and the source × sampling period interaction with lake as a random variable (see model description below) to determine whether mean CPUE and mean TL varied among Ohio River sources through time. If no significant differences were revealed among sources of Ohio River drainage fish, we treated them as a single stock for analysis purposes.

To address objective 1, differences in relative abundance among stocks were assessed using CPUE data (number of fish caught per hour). To account for variability in initial stocking numbers, CPUE was standardized by dividing by the number of fish introduced and was rescaled by multiplying by 1,000 (Brooks et al. 2002). The adjusted CPUE data were normalized using log transformations and were analyzed using a mixed-model, two-way, repeated-measures ANOVA (MIXED procedure in SAS version 9.2; SAS Institute 2009) with stocking cohort as the subject and lake as a random variable (Wagner et al. 2006). Because the treatment was applied to the cohort being stocked each year and because multiple measurements were made to that cohort through time (age-0 fall, age-0 spring, etc.), we treated each lake-specific cohort as the subject in the repeated model. A two-factor model was utilized to determine differences in catch rate

TABLE 2. Stocking information (stocking date, number, mean TL, and mean weight, ±95% confidence interval) for three Muskellunge stocks introduced into three Illinois lakes (Pierce, Mingo, and Sam Dale) during 2003–2008. Source populations for the Ohio River (OH), Mississippi River (MS), and Illinois (IL) stocks are described in Table 1.

Stock	Population	Stocking date	Number stocked	Stocking density (fish/ha)	TL (mm)	Weight (g)
			Mingo Lake			
IL	North Spring Lake, Illinois	Aug 29, 2003	500	7	258 ± 3.3	77 ± 2.9
OH	Clear Fork Lake, Ohio	Sep 4, 2003	288	4	227 ± 2.5	56 ± 2.2
MS	Leech Lake, Minnesota	Oct 31, 2003	285	4	237 ± 9.0	60 ± 7.7
IL	North Spring Lake	Aug 27, 2004	300	4.2	273 ± 4.6	88 ± 5.3
OH	Clear Fork Lake	Sep 14, 2004	245	3.4	261 ± 5.6	74 ± 5.3
MS	Leech Lake	Oct 30, 2004	193	2.7	280 ± 8.2	85 ± 9.1
IL	North Spring Lake	Aug 30, 2005	325	4.5	267 ± 4.8	79 ± 5.8
OH	Lake Chautauqua, New York	Sep 28, 2005	196	2.7	234 ± 3.7	45 ± 2.3
MS	Leech Lake	Oct 11, 2005	193	2.7	233 ± 5.5	48 ± 3.8
IL	North Spring Lake	Sep 13, 2007	300	4.2	286 ± 3.7	126 ± 5.5
OH	Cave Run Lake, Kentucky	Aug 2, 2007	397	5.5	231 ± 4.0	54 ± 2.8
MS	Leech Lake	Nov 30, 2007	270	3.8	326 ± 7.6	155 ± 11.5
			Pierce Lake			
IL	North Spring Lake	Aug 29, 2003	500	8.2	258 ± 3.3	77 ± 2.9
OH	Lake Chautauqua	Sep 19, 2003	234	3.8	225 ± 2.6	44 ± 1.7
MS	Leech Lake	Nov 7, 2003	100	1.6	197 ± 5.0	28 ± 2.5
IL	North Spring Lake	Aug 26, 2004	300	4.9	272 ± 4.7	88 ± 5.1
OH	Cave Run Lake	Sep 14, 2004	242	4	261 ± 5.0	76 ± 5.1
MS	Leech Lake	Oct 29, 2004	200	3.3	287 ± 7.9	96 ± 9.7
IL	North Spring Lake	Aug 31, 2005	300	4.9	270 ± 4.6	87 ± 5.1
OH	Clear Fork Lake	Sep 24, 2005	302	4.9	261 ± 4.1	75 ± 3.8
MS	Leech Lake	Oct 10, 2005	166	2.7	235 ± 5.1	50 ± 3.7
IL	North Spring Lake	Sep 13, 2007	300	4.9	285 ± 4.2	125 ± 6.0
OH	Clear Fork Lake	Sep 27, 2007	263	4.3	234 ± 5.4	55 ± 4.3
MS	Leech Lake	Nov 29, 2007	250	4.1	325 ± 7.2	153 ± 10.9
			Sam Dale Lake			
IL	North Spring Lake	Aug 31, 2005	300	3.8	273 ± 4.1	88 ± 5.2
OH	Clear Fork Lake	Sep 23, 2005	306	3.9	261 ± 4.1	75 ± 3.8
MS	Leech Lake	Nov 16, 2005	192	2.4	255 ± 5.9	57 ± 4.9
IL	North Spring Lake	Sep 13, 2007	300	3.8	284 ± 4.0	124 ± 5.7
OH	Clear Fork Lake	Sep 27, 2007	318	4.1	232 ± 5.2	54 ± 4.1
MS	Leech Lake	Nov 30, 2007	260	3.3	325 ± 7.6	156 ± 11.5
IL	North Spring Lake	Aug 24, 2008	300	3.8	290 ± 5.8	119 ± 7.9
OH	Cave Run Lake	Nov 18, 2008	193	2.5	338 ± 7.3	174 ± 14.2
MS	Leech Lake	Nov 19, 2008	257	3.3	217 ± 5.4	40 ± 3.2

with treatment (stock), time (sampling season after stocking), and the interaction of treatment through time as factors. To account for variability among lakes, we included lake as a random variable. These analyses were robust for examining differences among stocks, as comparisons could be made among stocks that are experiencing the same environmental variables through the duration of sampling (see Shoup et al. 2004; Diana and Wahl 2008, 2009; Michaletz 2009; Koenig et al. 2011). When appropriate, Tukey's honestly significant difference test was used post hoc to determine significant differences among stocks. Statistical significance was determined at α = 0.05. In addition to relative abundance, we also examined survival among stocks, calculated as the percent difference in adjusted CPUE from one sampling season to the next (Diana and Wahl 2008). This allowed us to examine the change in catch rate in addition to relative abundance, and differences were tested using the same design: repeated-measures ANOVA with stocking event as the subject and with lake as a random variable.

Size differences among stocks were evaluated after introduction by comparing the mean TL of survivors resampled on each electrofishing date in the first fall, first spring, second fall, and second spring poststocking. After the second spring, Muskellunge catch rates declined due to a lack of vulnerability to electrofishing gear, thus prohibiting further analysis of survival and growth. Differences in TL among stocks were assessed using repeated-measures ANOVA models (MIXED procedure in SAS) via the same approach employed for adjusted CPUE, with lake as a random variable and stocking cohort as the subject, which allowed for tests of growth differences for a particular stocking event through subsequent sampling of that cohort. Tukey's procedure for separation of means was used to examine for differences of significant effects. Transformations were not necessary to meet the assumption of normality for model residuals.

To address objective 2, we also evaluated how differences in survival and growth were influenced by a number of different stocking and lake-specific conditions. Size of fish at stocking was determined as the mean TL of a random 100-fish sample measured at each stocking event. Date of stocking was reported as the day of the year for each stocking event. Initial stocking mortality was calculated as the percentage of fish from mortality cages that did not survive to 48 h poststocking. Water temperature at the time of stocking was recorded at a depth of 1 m by using a YSI temperature and dissolved oxygen meter. Summer and winter air temperature data were acquired from the NOAA, Midwestern Regional Climate Center, and the New York State Climate Office. Mean daily air temperature was utilized from the weather station closest to each lake. Mean summer temperature (April 1–September 30) and mean winter temperature (October 1–March 31) were calculated for each lake during each year of sampling. In addition, summer severity was calculated as the 90th percentile of summer daily maximum temperature values for each lake during each year. Differences in stocking condition variables (fish size, water temperature, and fish mortality) were evaluated using ANOVA with treatment (stock), lake, and their interaction as fixed factors. Because fish were not acquired at the same time for all three lakes, there was a potential for differences in timing, mean TL, or density of fish stocked. These factors varied by year depending upon rearing success of the different stocks; therefore, year was included as a random factor in these models. All analyses were performed with SAS version 9.2 (SAS Institute 2009), and P-values less than 0.05 were considered significant.

RESULTS

Ohio River, Mississippi River, and Illinois stocks were introduced concurrently into Mingo and Pierce lakes during 4 years and into Sam Dale Lake during 3 years. We detected no significant differences in mean CPUE ($F = 2.45$, $P = 0.13$) or mean TL ($F = 31.24$, $P = 0.13$) among sources of Ohio River fish through time. Because there was no significant difference in the interaction of stock and time for CPUE and mean size, we did not expect variation within the Ohio River stock to affect our comparisons with Mississippi River and Illinois stocks, and we pooled all Ohio River drainage populations for the stock comparisons in this study. Stocking dates, sizes, and densities varied depending upon the availability of fish. The date of stocking (day of the year) was significantly different among stocks ($F = 40.7$, df = 2, $P < 0.0001$). Mean date of stocking was similar for the Illinois stock (September 1, SE = 2 d) and Ohio River stock (September 18, SE = 8 d; $t = 2.49$, $P = 0.09$); however, the Mississippi River stock fish were not available and therefore not stocked until significantly later in the year (November 8; SE = 6 d) in comparison with the Illinois ($t = 2.49$, $P < 0.0001$) and Ohio River ($t = 2.49$, $P < 0.0001$) stocking events. Despite differences in the timing of stocking, stocking size was similar among the three stocks ($F = 1.96$, df = 2, $P = 0.16$; mean ± SE = 274 ± 3.3 mm for the Illinois stock, 250 ± 9 mm for the Ohio River stock, and 265 ± 14 mm for the Mississippi River stock; Table 2). Stocking densities did vary significantly by stock ($F = 9.76$, df = 2, $P = 0.0007$) due to differences in availability of fish (Table 2). Illinois fish were stocked at the highest density (mean ± SE = 4.9 ± 0.4 fish/ha), while Mississippi River fish were stocked at the lowest density (3.1 ± 0.2 fish/ha), resulting in a significant difference between the two stocking rates ($t = 2.48$, $P = 0.0004$). The Ohio River fish were stocked at a rate of 3.9 ± 0.2 fish/ha, which was intermediate and not statistically different from stocking rates for the other two stocks ($t = 2.48$, $P > 0.06$).

Stocking mortality measured at 48 h after stocking differed among stocks ($F = 3.696$, df = 2, $P = 0.04$) but not among years ($F = 2.71$, df = 1, $P = 0.11$). Ohio River fish experienced the greatest stocking mortality (mean ± SE = 28.0 ± 10.7%), which was significantly greater than that of the Mississippi River fish (1.6 ± 0.9%; $t = 2.53$, $P = 0.04$). Illinois fish exhibited an intermediate level of stocking mortality (8.0 ± 5.3%) that was not significantly different from those of the other two stocks ($t = 2.53$, $P > 0.22$). Water temperature at stocking was significantly related to stocking mortality ($r = -0.53$, $P = 0.005$), and all high-mortality stocking events (>7% mortality) took place at temperatures over 21°C and earlier than September 24.

Catch rates of juvenile Muskellunge were generally low, so extended effort was required to estimate catch rates and growth. Mean seasonal electrofishing effort was 13.9 h across years in the three study lakes and resulted in an average of 35.4 Muskellunge per sampling season on each lake. Mean number of fish captured was highest in the first fall and first spring poststocking for all three stocks and declined through time (Table 3). We did not detect significant differences among stocks in CPUE through time (Figure 2A) or in CPUE adjusted for stocking rate (Figure 2B). Despite apparent declines in adjusted catch rates for Mississippi River fish, adjusted catch rates were initially similar among the stocks after stocking ($F = 0.35$, df = 2, $P = 0.71$), and there was no significant interaction between stock and time poststocking ($F = 1.03$, df = 6, $P = 0.41$). Stocking density was not related to the CPUE ($r = 0.12$, $P = 0.35$) or adjusted CPUE ($r = -0.19$, $P = 0.37$) in the first fall poststocking across all stocks.

We also examined survival among stocks, calculated as the percent difference in adjusted CPUE from one sampling season to the next (Figure 3). Mean overwinter survival in the first winter was 40.7% for the three stocks, and there was

TABLE 3. Mean number of fish captured from three Muskellunge stocks and mean electrofishing effort during fall and spring surveys conducted in three stocked lakes (Mingo, Pierce, and Sam Dale lakes, Illinois), 2003–2010. Catch of the Ohio River (OH), Mississippi River (MS), and Illinois (IL) stocks is presented for each year-class and season; source populations for the stocks are described in Table 1.

			Mean number of fish from each stock		
Lake	Season (age-class)	Hours of electrofishing	IL	OH	MS
Mingo	Year-1 fall (age 0)	16.8	16.5	21.3	17.0
	Year-1 spring (age 1)	16.8	15.0	10.5	17.3
	Year-2 fall (age 1)	15.9	5.0	2.8	0.5
	Year-2 spring (age 2)	18.4	1.0	1.7	0.3
Pierce	Year-1 fall (age 0)	15.9	21.0	17.0	17.8
	Year-1 spring (age 1)	19.1	5.8	3.8	8.5
	Year-2 fall (age 1)	13.8	5.0	5.0	1.0
	Year-2 spring (age 2)	16.2	0.0	0.0	0.0
Sam Dale	Year-1 fall (age 0)	10.6	17.0	1.0	0.0
	Year-1 spring (age 1)	8.2	1.0	2.0	0.0
	Year-2 fall (age 1)	8.7	7.0	3.5	1.0
	Year-2 spring (age 2)	6.1	2.0	3.0	0.0

no significant difference among stocks ($F = 0.33$, $P = 0.72$). Survival differed significantly among stocks in the summer ($F = 7.08$, $P = 0.003$), with Illinois fish surviving at a greater rate than Mississippi River fish ($t = 3.76$, $P = 0.002$). Ohio River stock fish had intermediate survival, which did not differ from the survival of either the Illinois stock ($t = 1.78$, $P = 0.20$) or the Mississippi River stock ($t = –1.98$, $P = 0.14$). Survival over the second winter did not differ among stocks ($F = 0.49$, $P = 0.62$), although due to reduced catchability, the catch rates of age-2 Muskellunge may not reflect their actual relative abundance.

We observed significant differences in mean TL among stocks after stocking (Figure 4). The stock × sampling period interaction was significant ($F = 5.48$, df = 6, $P < 0.0001$). No significant differences existed in mean TL of the three stocks during the first fall poststocking ($P > 0.047$). Stocking TL was significantly related to mean TL in the first fall ($r = 0.61$, $P = 0.003$). During the first spring poststocking, Illinois stock fish were similar in size to the Ohio River stock ($t = 2.87$, $P = 0.18$) but were significantly larger than the Mississippi River stock ($t = 4.2$, $P = 0.004$), whereas mean TL did not significantly differ between Ohio River fish and Mississippi River fish ($t = –1.48$, $P = 0.94$). The mean TL of fish in the first fall was not correlated to CPUE in the fall ($r = –0.04$, $P = 0.86$), but it was related to overwinter survival ($r = 0.50$, $P = 0.02$). The mean TLs of the three stocks were no longer significantly different in the second fall poststocking ($P > 0.05$). However, by the second spring poststocking, the Illinois and Ohio River fish were similar in TL ($t = 2.74$, $P = 0.23$), but the Mississippi River fish were significantly smaller than both the Illinois fish ($t = 5.19$, $P = 0.0001$) and the Ohio River fish ($t = –3.56$, $P = 0.03$).

Summer temperature severity was measured as the 90th percentile of summer daily maximum air temperature values for each summer period (mean ± SE = 31.3 ± 0.4°C). Despite latitudinal differences among the three lakes, summer temperature severity did not differ among lakes ($F = 2.88$, df = 2, $P = 0.07$). Mean daily temperature over the summer did vary by lake ($F = 36.3$, df = 2, $P < 0.0001$), with Pierce Lake having significantly lower temperature (18.3 ± 0.4°C) than Sam Dale Lake (20.2 ± 0.2°C; $t = 2.86$, $P = 0.006$). Mean summer temperature at Mingo Lake (19.4 ± 0.3°C) was intermediate and not significantly different from those in the other two lakes ($t = 2.86$, $P > 0.07$). Survival was lowest for the Mississippi River drainage fish over summer, but survival was not related to summer temperature severity ($r = –0.06$, $P = 0.86$) or to the mean daily temperature ($r = –0.19$, $P = 0.58$). Survival of Ohio River fish did not vary much over the summer and was also not related to summer temperature severity ($r = 0.07$, $P = 0.84$) or the mean daily temperature ($r = –0.01$, $P = 0.97$). Illinois fish experienced the highest and most variable survival over summer, but survival was not related to either summer temperature severity ($r = –0.52$, $P = 0.10$) or the mean daily temperature ($r = –0.57$, $P = 0.07$). A two-way ANOVA examining lake and stock effects on summer survival was significant ($F = 2.40$, df = 8, $P = 0.047$). Despite differences in mean summer temperature among lakes, there was no significant difference in summer survival among lakes ($F = 1.50$, df = 2, $P = 0.24$), and lake did not interact with summer survival ($F = 0.64$, df = 4, $P = 0.61$). Significant differences in summer survival were only related to stock ($F = 6.24$, df = 2, $P = 0.007$), and we did not detect a relationship with summer temperature severity over the first summer.

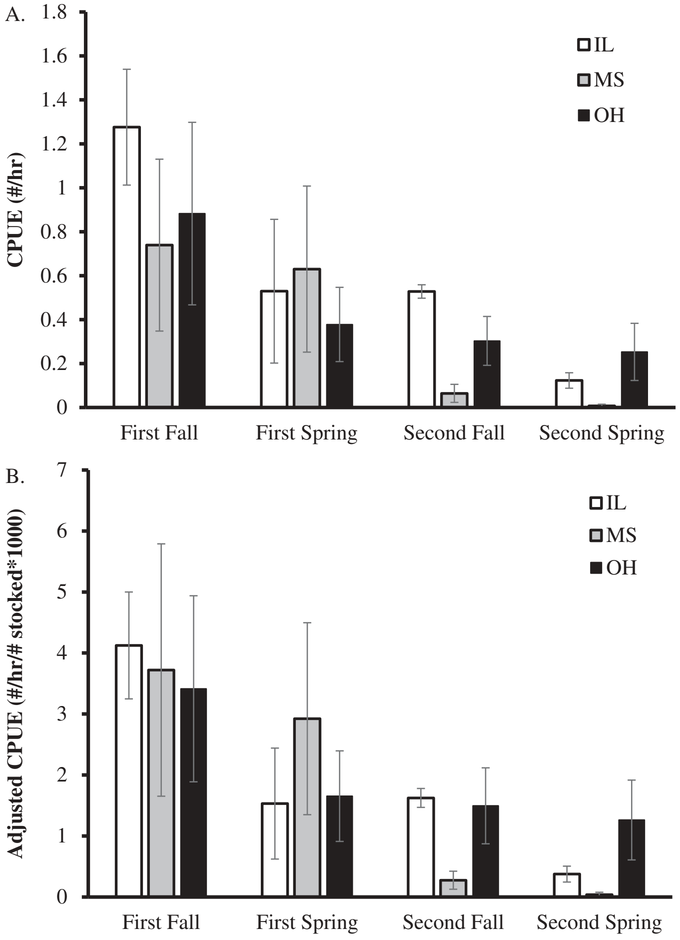

FIGURE 2. Mean (±SE) **(A)** CPUE and **(B)** adjusted CPUE for the three Muskellunge stocks (IL = mixed Illinois; MS = upper Mississippi River drainage; OH = Ohio River drainage) captured via electrofishing during the first fall, first spring, second fall, and second spring after stocking in three Illinois lakes.

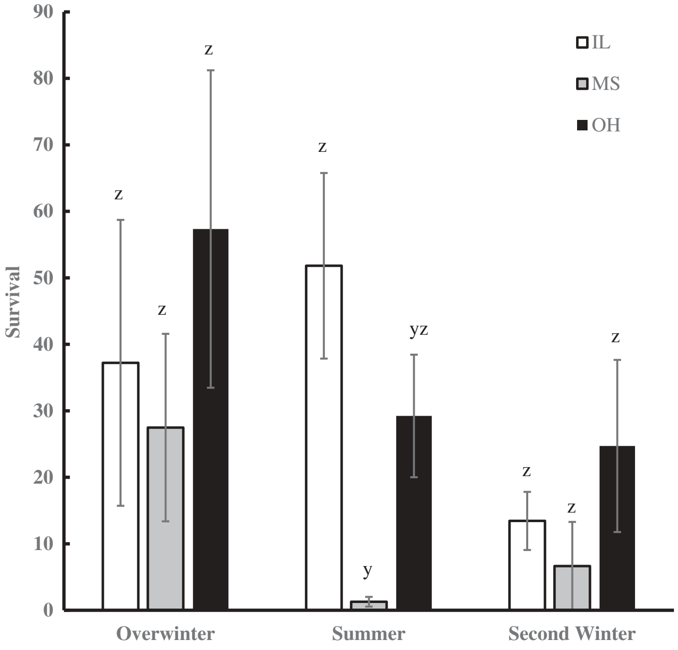

FIGURE 3. Mean (±SE) survival of Muskellunge from three stocks (IL = mixed Illinois; MS = upper Mississippi River drainage; OH = Ohio River drainage), calculated as the percent change in adjusted CPUE from electrofishing in the spring and fall of each year (overwinter = survival from the first fall to the first spring poststocking; summer = survival from the first spring to the second fall poststocking; second winter = survival from the second fall to the second spring poststocking). Means with a letter in common are not significantly different ($P > 0.05$).

DISCUSSION

Survival can be a primary indicator of evolutionary adaptation, and it demonstrates the ability of a population to persist in a given environment (Reisenbichler and McIntyre 1977; Fraser 1981; Philipp and Whitt 1991; Younk and Strand 1992; Wills 2006). Our findings suggest few differences in poststocking catch rates and survival among Muskellunge stocks through the first spring. However, 1-year poststocking survival differences were detected among stocks, with the upper Mississippi River stock experiencing very low survival over the summer, which resulted in decreased catch rates. The Illinois and Ohio River stocks generally exhibited similar survival across years and systems. Previous work has documented survival differences among Muskellunge populations of a single stock within a small geographic region of Minnesota and Wisconsin (Younk and Strand 1992; Margenau and Hanson 1996). Our findings demonstrating poor survival of the Mississippi River stock in comparison with the other two stocks substantiate that within-stock differences can also result in divergent survival and growth. Similarly, Philipp and Claussen (1995) showed significant survival differences among Illinois populations of Largemouth Bass when introduced into a reciprocal transplant regime within experimental ponds. These regional differences were complemented by significant differences in survival documented between Largemouth Bass stocks from broadly distributed sources (Illinois and Florida) in a central, common environment (Philipp and Whitt 1991). From our work and prior studies, it is clear that significant and meaningful survival differences can occur among populations and stocks of freshwater fish species.

The greatest mortality across all stocks was observed over the summer in the year after stocking. Illinois is near the southern extent of the Muskellunge's range, and summer temperatures could limit survival of these fish. Survival over the summer did vary by stock, with the Mississippi River stock particularly experiencing high levels of mortality. Summer temperature severity, however, was not related to the survival of any of the three stocks. The lack of a relationship with summer temperature severity could be due to the small variation in summer severity observed throughout the study. In addition, all three stocks generally experienced low survival over summer, and the lack of variation in mortality and temperature made it difficult to detect a relationship. Temperature may be driving the low survival of Mississippi

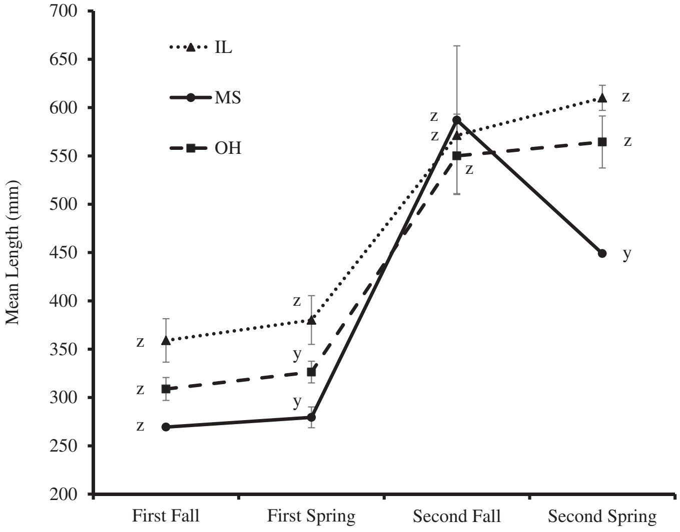

FIGURE 4. Mean (±SE) TL of Muskellunge from three stocks (IL = mixed Illinois; MS = upper Mississippi River drainage; OH = Ohio River drainage) captured via electrofishing during the first fall, first spring, second fall, and second spring after stocking in three Illinois lakes. Means with a letter in common are not significantly different ($P > 0.05$).

River stock fish, but we were limited in our ability to detect an effect, and other factors (e.g., local adaptation to prey or habitat) could be limiting their survival as well. We have identified the first summer as a critical period in which to evaluate differences in survival among these Muskellunge stocks, but presently the mechanism is unclear.

Stocking mortality differed among stocks and was related to temperature at the time of stocking. Mississippi River stock fish had significantly lower stocking mortality due to being stocked later in the fall, when temperatures were cooler. Temperature at the time of stocking has been shown to increase stocking-related mortality in Largemouth Bass (Carmichael et al. 1984; Porak et al. 2002; Diana and Wahl 2009) and Walleyes *Sander vitreus* (Clapp et al. 1997; Hoxmeier et al. 2006). Temperature was not related to poststocking mortality for Muskellunge in a previous study, but stocking events were only examined in July and August, with little differences in temperature (Mather and Wahl 1989). Our results suggest that stocking Muskellunge at cooler temperatures will result in greater initial stocking success.

In addition to survival, growth is critical to the success of stocking in order to produce a quality fishery. Growth differences can influence initial survival (Carline et al. 1986; Wahl and Stein 1989) as well as size at maturity and ultimate growth potential—all important factors in obtaining quality Muskellunge fisheries. Studies that have evaluated growth differences among populations and stocks of fish species have yielded varying results. For example, significant differences in growth were revealed among geographically distinct populations of Striped Bass *Morone saxatilis* (Brown et al. 1998) and Largemouth Bass (Isely et al. 1987; Philipp and Whitt 1991), whereas other studies have shown few or no growth differences among populations and stocks (Van Offelen et al. 1993; Galarowicz and Wahl 2003). The Muskellunge stocks in our study exhibited significant growth differences. In general, Mississippi River stock fish were consistently smaller than the Ohio River and Illinois stocks (except during the second fall poststocking); however, these growth differences were only significant during the second spring poststocking, when catch rates of Mississippi River fish were low. Juvenile Muskellunge can be difficult to capture, and electrofishing gear is less efficient for older age-classes of Muskellunge. Gear efficiency issues should not affect comparisons of relative survival, as there is no reason to expect that catchability would differ by stock, but efficiency issues did reduce the number of length measurements collected through time. Reduced capture rates due to gear efficiency coupled with mortality resulted in decreased sample sizes in each season and fewer fish in older age-classes with which to evaluate growth. Size differences in the second spring were based on low sample sizes of fish (<4 fish per sampling season), and caution should be used when interpreting these results. However, the small size of the few Mississippi River stock fish we observed provided evidence that they were not performing well in Illinois waters. Other than the first spring poststocking, Illinois and Ohio River Muskellunge were similar in size throughout the study. Clapp and Wahl (1996) also found few growth differences among Ohio River and Mississippi River Muskellunge stocks in laboratory experiments conducted at temperatures similar to those commonly experienced in Illinois lakes (15–27.5°C).

Acquiring fish for stocking from out-of-state or alternative sources can be difficult, and during our study, it resulted in the observed stocking variation in terms of the time of year, size, and density of fish stocked. Illinois fish were consistently stocked at the target density and size at similar dates in each year, whereas stocking of the Ohio River and Mississippi River fish varied. These variations made it difficult to directly compare the survival and growth differences of the three Muskellunge stocks independent of these variables; however, such variations are the reality of stocking populations of Muskellunge from a broad geographic range and should be considered by managers when seeking alternative strains of fish for stocking. In addition, we experienced difficulty in acquiring fish from the same source due to limitations in hatchery production. We utilized three sources of fish for the Ohio River stock. Although these sources of fish did not exhibit differences in survival or growth in our study, there is potential for variation due to the source population. For example, Clapp and Wahl (1996) found that these same source populations exhibited physiology that did not group as closely as expected in feeding trials. However, the genetic similarity of these Ohio River source stocks has been well established (Koppelman and Philipp 1986), and we did not observe significant variation in poststocking survival or growth due to the source of fish in this study.

Stocking conditions were related to a number of factors that could affect long-term survival and growth. Despite some initial differences in stocking density, there were no differences in the catch rates of fish during the first fall poststocking or during the subsequent spring. Mississippi River fish were, on average, stocked at the lowest density; however, they had similar mean catch rates in the first fall and the highest catch rates in the first spring. It was not until the second fall that catch rates of Mississippi River stock fish declined to very low levels in comparison with the Ohio River fish and Illinois fish. Stocking size was correlated with mean TL during the first fall poststocking, but neither stocking size nor mean TL in the first fall was related to catch rates during the first fall, and catch rates did not differ by stock. Mean TL at the time of stocking was similar among the three stocks of Muskellunge; however, the timing of stocking events differed among stocks. Mississippi River fish were available significantly later in the year than the other two stocks, which resulted in their smaller mean size in the fall and subsequent spring. Although the Mississippi River stock fish were not significantly smaller during the first fall, the size difference could influence long-term growth and survival. There is some evidence that the survival of stocked Muskellunge can be size selective (Johnson and Margenau 1993; Wahl and Stein 1993), with fish that are stocked earlier having the potential for greater growth and survival (Szendrey and Wahl 1996). Despite the potential for initial growth differences, we observed few differences until the second spring poststocking. Catch rates for the Mississippi River stock declined significantly by the second spring, and the few Mississippi River fish that were recaptured were much smaller than the Ohio River and Illinois fish at that time (age 2).

Growth rate differences among broadly (latitudinally) distributed populations and stocks may follow either the pattern of local adaptation or countergradient variation (Conover and Schultz 1995; Garvey et al. 2003; Houston and Belk 2006). Across all systems in our study, the Mississippi River stock generally exhibited poorer survival and growth, suggesting that local adaptation may be driving the survival and growth of juvenile Muskellunge. Our study systems exhibited water temperatures that were more similar to those found throughout the Ohio River drainage than to the cooler water temperatures commonly encountered in the upper Mississippi River drainage. Illinois and Ohio River stocks likely performed similarly in Illinois lakes because they were from similar latitudes and temperature regimes. The high mortality experienced by the Mississippi River stock over the summer may be due to temperature limitations of fish adapted to a more northerly climate.

In his introduction to the First International Muskellunge Symposium, Crossman (1986) emphasized the need for research to be directed toward understanding physiological, behavioral, and performance differences (or “uniqueness”) among populations and stocks of Muskellunge. Differences have been found among populations of one stock in Minnesota and Wisconsin waters (Younk and Strand 1992; Margenau and Hanson 1996). Additionally, a detailed examination of growth, metabolism, and food consumption differences among populations and stocks from throughout the Muskellunge’s range was conducted in the laboratory and found few differences in consumption and growth at higher temperatures (Clapp and Wahl 1996). Our work builds on these studies by examining differences within field environments. Understanding initial survival and growth differences among stocks can aid managers in choosing appropriate brood sources when introducing fish into waters where natural populations are not present. We provide evidence that fish that are locally adapted to similar climates may outperform those from different latitudes regardless of the survival and growth potential in their native range. Future research should evaluate the long-term differences in these stocks and in particular should determine the survival, longevity, and maximum size potential of fish that have already recruited to the fishery. Furthermore, understanding the causes of differences among Muskellunge populations and stocks will enable more informed management decisions, ultimately providing for more quality populations and fisheries.

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