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FINAL REPORT
July 1, 2002 through June 30, 2012

EVALUATION OF GROWTH AND SURVIVAL OF DIFFERENT GENETIC STOCKS OF MUSKELLUNGE: IMPLICATIONS FOR STOCKING PROGRAMS IN ILLINOIS AND THE MIDWEST

M.H. Wolter, C.S. DeBoom, C.P. Wagner, M.J. Diana,
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TABLE OF CONTENTS

EXECUTIVE SUMMARY: Muskellunge *Esox masquinongy* are an important and increasingly popular sportfish throughout Illinois and much of the Midwestern United States. Stocking has become a primary management tool for establishing and maintaining muskellunge populations both within and outside of their native range. Great demand for these fish and the high costs associated with producing them create the need for efficient management practices. Additionally, muskellunge are primarily managed for trophy potential making growth rate and maximum size important characteristics to managers. Previous research efforts have determined the size of fish and timing of stocking to maximize growth and survival. However, additional information on muskellunge stocking strategies is needed. Specifically, more data on performance of different genetic stocks of muskellunge, both within and outside their native range, is needed to determine the best population to stock in a particular body of water to maximize growth and survival. In addition little research has focused on the response of fish communities and lake ecosystems to muskellunge stocking. As the muskellunge range is artificially expanded by more widespread stocking it becomes increasingly important to understand the potential impacts of muskellunge introduction on existing fisheries and aquatic communities.

Morphological characteristics have suggested multiple distinct groups of muskellunge. More recently, genetic analysis identified several different genetic stocks of muskellunge (Ohio River drainage, Upper Mississippi River drainage, and the Great Lakes drainage stocks), each with multiple unique populations. Genetically distinct stocks and populations are becoming a major focus in fisheries management in an attempt to optimize performance regionally. Understanding stock differentiation becomes increasingly important with a trophy species like muskellunge where anglers and managers are interested in utilizing populations of fish that grow the fastest, live longest, and obtain a largest maximum size. Because muskellunge populations are either not naturally found or have been extirpated in many Illinois lakes and reservoirs, it is not clear which stock and population to use in stocking efforts. The muskellunge population currently used as brood stock for the stocking program in Illinois is of an unknown origin and may be made up of several different populations. Additional information was needed on differences in growth and survival among stocks in waters at varying latitudes in Illinois to make management recommendations on which stock is most appropriate. The first two jobs of this study examined differences in growth and survival among different stocks of muskellunge in order to make recommendations regarding stocking in Illinois.

Previous research on interactions of muskellunge with the rest of the aquatic community has been sparse and generally inconclusive. In addition, the existing literature on muskellunge diet focuses on natural lakes in northern states, which limits the utility of this information to managers in the lower Midwest. Few studies exist in the literature that report fishery and community effects of muskellunge introductions. One study attributed muskellunge with the decline of largemouth bass populations in two Wisconsin lakes and another study documented a decline in black crappie and white sucker populations in Michigan in response to muskellunge stocking. More recently, a study by the Minnesota Department of Natural Resources reported no strong effects of introducing muskellunge across that state. The utility of these studies to inform managers about the potential effects of muskellunge introduction in lakes of the lower Midwest is limited by a lack of replication or adequate comparison to control systems. The third job of this study provides an evaluation of muskellunge diet and responses of resident fish to muskellunge introduction across a number of Illinois lakes.

This final report summarizes growth and survival comparisons among the three stocks from Mingo, Pierce, and Sam Dale Lakes. All activities outlined in the annual work plans were accomplished and were completed within the specified budget. Two jobs related to muskellunge stock evaluation and one job related to food habits and effects of muskellunge introduction have been completed. In the final report, we compare growth and survival of muskellunge from the Upper Mississippi River drainage stock, the Ohio River drainage stock, and the Illinois North Spring Lake progeny in three Illinois lakes. Populations were sampled by electrofishing and modified fyke net surveys during spring. Data was compiled from all years to describe long-term trends in growth and survival of muskellunge stocks in Illinois. Across years and lakes, the Ohio River drainage stock and the Illinois population generally appear to have similar growth rates through age-1. Few Upper Mississippi River drainage stock were available for growth comparisons and there is a need to continue to collecting these fish in the future. Analysis of body morphology indicates that fish from the Upper Mississippi River drainage are consistently leaner than those of the other stocks. Results from lake introductions suggest that after the first summer following stocking, the Ohio River drainage stock and Illinois population typically have similar rates of survival, both of which are higher than the Upper Mississippi River drainage stock. This pattern led to consistently lower survival of Upper Mississippi River drainage stock year classes to adulthood as well. The Ohio River drainage stock and Illinois population show similar survival both to adulthood and annually through adult age classes. The specific mechanism responsible for differences in survival rate among stocks is still unknown. Year classes will need to be monitored over additional years to further assess potential differences in long-term growth, maximum length, and survival among stocks, particularly in Lake Sam Dale where adult muskellunge from the Upper Mississippi River drainage stock have been recaptured with greater consistency.

Growth and survival patterns among stocks through age-1 were also compared in a series of controlled pond studies. Muskellunge from the Ohio River drainage stock, the Upper Mississippi River drainage stock, and the current Illinois brood stock population were used in these comparisons. Overwinter survival was similar among stocks; however, growth varied overwinter, with Ohio River drainage stock muskellunge exhibiting higher growth rates than conspecifics. One-year post-stocking survival was generally similar between the Ohio River drainage stock and the Illinois stock, with both having higher survival than the Upper Mississippi River drainage stock. In experimental ponds, the Ohio River drainage stock grew faster than the Illinois and Upper Mississippi River drainage muskellunge. These survival results were very similar to lake evaluations showing greater survival of Ohio River Drainage and Illinois stock muskellunge than the Upper Mississippi River Drainage stock.

Muskellunge diet samples were collected from fish across 7 Illinois lakes from fall 2007 to spring 2012. These lakes included Lake Shelbyville, Lake Mingo, Ridge Lake, Pierce Lake, Lake of the Woods, Otter Lake, and Sam Dale Lake. Thus far food habits data has shown that where present, gizzard shad dominate muskellunge diet in both numbers and biomass across all size classes and seasons. Gizzard shad are not present in Ridge Lake where muskellunge diets consist primarily of bluegill, although a small percentage of the samples contained largemouth bass. Results from diet analysis are conclusive in that where available gizzard shad are the primary forage of muskellunge in Illinois lakes followed by bluegill. This pattern is generally consistent between seasons, although there is some evidence that bluegill become a slightly more important prey item in the spring. While this data provides a preliminary analysis of muskellunge diets in these lakes, more data is required to adequately characterize annual and seasonal fluctuations occurring over time. Specifically it is unclear how food habits of muskellunge may change in response to annual fluctuations in prey availability or whether size related trends are present. Furthermore, more data is needed on muskellunge diet in systems where gizzard shad are not present.

This final report summarizes a set of analyses on effects of muskellunge stocking involving a sample of lakes taken from the state Fishery Analysis System (FAS) database. Examination of muskellunge stocking records identified a series of lakes that received concurrent initial stockings of muskellunge. This analysis provides a rigorous examination of muskellunge effects on existing fisheries due to the inclusion of multiple replicate lakes. Our results suggest that across 8 lakes in a time series ranging from 4-10 years after muskellunge introduction abundance of largemouth bass increased while no negative effects on size structure were observed. With the exception of decreasing white crappie abundance, muskellunge introductions had either nonnegative or positive effects on size structure and abundance of sport and prey fishes including bluegill, redear sunfish and crappie. Muskellunge introductions appear to have very little impact on common carp or gizzard shad populations.

This final report provides a summary of adult and juvenile muskellunge growth and survival trends observed in Lakes Mingo and Pierce since 2002. Muskellunge stocking in Lake Sam Dale did not begin until 2005. Additional years of sampling will be required to describe patterns of muskellunge survival in Lake Sam Dale. The results of this study will be combined with those from future years to identify the long-term growth and survival differences among genetic stocks of muskellunge. In particular, these long-term data will be used to examine attributes such as longevity, maximum size-at-age, and size-at-maturity. Results of this study can be used to develop guidelines for future muskellunge stockings that maximize growth, survival, and angler satisfaction in lakes throughout Illinois. Understanding intraspecific variation in muskellunge growth rate and survival as well as the effects of these highly predacious fishes on the existing aquatic community contribute to a more informed and holistic approach to muskellunge management in Illinois and the lower Midwest.

Job 101.1. Evaluating growth of different stocks of muskellunge.

OBJECTIVE: To determine differences in growth among various stocks and populations of muskellunge in Illinois waters.

INTRODUCTION: The taxonomy of the muskellunge has undergone significant revisions over the last century (Crossman 1978; Crossman 1986). During the late 1800's and early 1900's, perceived correlations between muskellunge color patterns (spotted, clear, barred) and location led to the distinction of three separate species for a short time (Crossman 1978). As interpretation of the color and marking distinctions progressed, the idea of subspecies was introduced (Hubbs and Lagler 1958; McClane 1974; Smith 1979) but this distinction lost favor by the late 1970's and all of these color variants are now considered the same species (Crossman 1978). Existing information indicates muskellunge survived the Wisconsinian glacial period in the Mississippi refugium and upon glacial recession, moved north up the Mississippi valley and established its current range via the Mississippi and Ohio River systems, as well as precursors to tributaries of the Great Lakes (Crossman 1978; Crossman 1986). Genetic analysis of various populations from these major river drainages revealed three distinct clusters (separated by river drainage) suggesting the existence of divergent stocks (Koppelman and Philipp 1986). This divergence suggests that as these groups became geographically isolated within each river drainage processes such as natural selection, resulted in stocks of muskellunge that are genetically dissimilar, and are likely to display physiological, behavioral, and possibly morphological differences (Altukhov 1981; MacLean and Evans 1981; Ihssen et al. 1981; Clapp and Wahl 1996; Begg et al. 1999). Current delineation of muskellunge stocks recognizes three distinct groups, the Great Lakes/ St. Lawrence River drainage stock, the Ohio River drainage stock and the Upper Mississippi River drainage stock (Koppelman and Philipp 1986; Clapp and Wahl 1996).

Evolutionarily derived differences in physiology and behavior between stocks of muskellunge have been suggested by previous research and similar differences have been documented in a number of other fish species. Such differences have been shown to affect performance characteristics, measured in terms of growth rate and maximum body sizes. Past research comparing source populations of muskellunge in Minnesota found differences in growth rate and maximum size between two genetically divergent populations native to Shoepack Lake and Leech Lake Minnesota (Younk and Strand 1992, Wingate and Younk 2007). As a result of these findings the Minnesota Department of Natural Resources switched its hatchery brood source from Shoepack to Leech Lake muskellunge greatly increasing performance (Wingate and Younk 2007). A similar study focused on two populations of muskellunge from within Wisconsin found a difference in growth performance attributable to both environmental and genetic components (Margenau and Hanson 1996). Research conducted by the Illinois Natural History Survey compared food consumption, metabolism, and growth among populations of YOY muskellunge from each of the major stocks and found differences in growth and food consumption at temperatures from 15-27.5°C (Clapp and Wahl 1996). 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). In addition, research within Illinois has documented growth differences between stocks of largemouth bass *Micropterus salmoides* from major river drainages within the state (Philipp and Claussen 1995). These studies provide evidence that physiological and behavioral adaptations should be a significant factor in determining the source population for a stocking program such as the Illinois muskellunge program. Investigation of such variation will not only allow for selection of a broodstock which maximizes the growth potential for muskellunge fisheries within Illinois but the possibility that different stocks may be more appropriate for specific waters (for example if the latitudinal variation in local thermal regime displayed across the state is an important factor).

While differences in growth between genetically isolated fish stocks has been demonstrated, the ecological mechanisms for the evolution of growth rates are still in question and the lack of consensus makes it difficult to predict which stocks should perform best under a specified temperature regime. Two competing theories with empirical support exist to predict how poikilothermic organisms should respond to latitudinal variation in temperature regimes. These theories are based on the idea that selective agents such as winter severity, length of growing season, and temperature can induce variation in somatic growth rates across a gradient of latitudes (Levinton 1983).

The first model called “local adaptation” focuses on temperature as the selective agent that organisms should evolve to grow best at the temperature regimes most commonly encountered in their environment (Lonsdale and Levinton 1985). If this model is correct then organisms from northern populations should adapt by both beginning growth and reaching maximal growth rates at lower temperatures than southern populations, which would result in comparable growth rates in their home environments. The trade off is that outside of their native temperature regime the locally adapted stocks would show poorer growth. This model has been supported by studies of marine invertebrates (Levinton 1983, crustaceans (Lonsdale and Levinton 1985) and fish (Galarowicz and Wahl 2003; Belk et al. 2005).

The second model focuses on the duration of the growing season as the selective agent. In northern latitudes where winters are more severe, a large body size is necessary to store sufficient energy to maintain metabolism through the long winter (Henderson et al. 1988, Post and Evans 1989). This model called “countergradient variation” states that size dependent overwinter survival in northern latitudes should select for higher maximum growth rates in northern populations which need to reach a large body size in a shorter period of time (Conover and Present 1990; Yamahira and Conover 2002). If this model is correct stocks should display an increase in growth rates with increasing latitude and should maintain those growth rates when introduced outside of their native range. This model has received empirical support for amphibians (Riha and Berven 1991), reptiles (Ferguson and Talent 1993), insects (Gotthard et al. 1994) and fishes (Conover and Present 1990, Nicieza et al. 1994, Schultz et al. 1996, Conover et al. 1997, DiMichele and Westerman 1997, Jonassen et al. 2000).

Based on the model of thermal adaptation, we would expect muskellunge from higher latitudes (e.g. Minnesota’s Leech Lake population) to exhibit higher growth rates at low temperatures and muskellunge from low latitudes (e.g. Kentucky’s Cave Run Lake population) to possess higher growth rates at high temperatures. In contrast, if countergradient variation is the mechanism driving growth rates of muskellunge stocks we would expect to see muskellunge from northern latitudes display higher growth rates than those from lower latitudes in all environments.

In addition to growth rate, maximum body size is a characteristic of interest when managing trophy fish like muskellunge. Bergmann’s rule dictates that intraspecific variation in body size should show increased maximum body size in higher latitude populations and is supported by numerous taxa (Blackburn et al. 1999). The mechanism for this cline in body size may be nonadaptive, such as a physical restriction on cell size or cell differentiation rates, or it may be adaptive, related to timing of maturation or energy allocation (Angilletta et al. 2004). As the year classes of muskellunge included in this study reach older ages we will be able to monitor differences in maximum body size between stocks.

In this report, we detail our investigations of stock differentiation in growth for muskellunge in both the field and in pond studies. Long-term growth of muskellunge was evaluated in three lakes covering the latitudinal range of Illinois. Identifying growth differences at this scale may be important in determining the appropriate brood sources for specific management applications. Populations from different latitudes may vary in long-term growth, longevity, size-at-maturity, and maximum size. In this job we continue to assess long-term growth and maximum sizes of previously introduced populations across the latitudinal gradient of Illinois.

PROCEDURES: Prior to the evaluation of growth among muskellunge stocks in reservoirs, we conducted two trials of a pond experiment to evaluate growth among stocks in a more controlled environment. Advantages of this approach include greater precision via increased sample sizes, individual fish growth measurements, and replication by means of using several ponds. Each year, three 0.4-ha experimental ponds at the Sam Parr Biological Station, Kinmundy, Illinois, were used for these trials. Muskellunge from the Upper Mississippi River drainage stock, the Ohio River drainage stock, and the Illinois population were stocked into the experimental ponds in the falls of 2003, and 2004; herein referred to as trial 1 and trial 2 (Table 1). Immediately prior to stocking, fish were anesthetized and intraperitoneally implanted with a passive integrated transponder (PIT) tag (Wagner et al. 2007). Following the tagging, each fish was measured in length (nearest mm) and weight (nearest g) and allowed to recover prior to being stocked into one of the ponds. An effort was made to obtain and stock as similar size fish as possible; however, the sizes were ultimately determined by availability of muskellunge based on local spawning times and growing conditions (Table 1). For both trials, an equal number of muskellunge (N = 33, but see exception, Table 1) from all stocks were introduced into each pond. Hourly temperature readings were recorded using thermographs placed at 1-m depth and on the bottom. Experimental ponds were drained each spring and fall following initiation for two years. Muskellunge were collected and identified by the PIT tag. All fish were measured in length (nearest mm) and weight (nearest g) and placed back into one of three 1-acre (0.4-ha) experimental ponds for future evaluations. These data were used to compare mean relative daily growth rates among the stocks of muskellunge in experimental ponds. Relative daily growth rates (RDGR, g/g/d) were calculated as:

$$RDGR = \left[\frac{W2 - W1}{W1}\right] \times \Delta t,$$

where W1 and W2 were initial and final weights (g) respectively, and Δt was the time elapsed (d). Initial sizes and RDGR differences among stocks were assessed using ANOVA models, blocking by pond, and Tukey's means separation was used when differences were detected. For both trials, survival and growth was examined for two distinct time periods: overwinter (fall-to-spring) and through one year after stocking (following fall).

Lakes in this study included Lake Mingo (Vermillion County), Pierce Lake (Winnebago County), and Sam Dale Lake (Wayne County). These reservoirs represent the climatic variation associated with latitude that exists throughout Illinois. Stockings from various source populations (Table 2) representing each stock were introduced into Lake Mingo since Fall of 2002, Pierce Lake since Fall of 2003 and Sam Dale Lake since 2005 (Table 2). At each stocking, attempts were made to stock as similar of sizes and condition of fish as possible in each lake. Subsamples of each source population were held in three 3-m deep predator-free cages (N=15/cage) for 48-hrs to monitor mortality associated with transport and stocking stress (Clapp et al. 1997). Muskellunge from each population were stocked at rates between 3.3-4.9 fish per hectare and a subsample of each population was measured in length (nearest mm) and weighed (nearest g) prior to each stocking (Table 3). Each fish was given an identifying complete pelvic fin clip and freeze cauterization of the wound for later identification of the stock (Boxrucker 1982). In the fall 2004 we began freeze branding all stocked fish in an effort to improve age determination (in combination with scale ageing). The brand location differs by year.

To determine growth rates of juvenile fish (ages 0-2) we conducted nighttime pulsed DC boat-electrofishing from October through November and March through April annually from 2002-2012. Beginning in spring 2006 we began sampling adult muskellunge (ages 2+) with modified fyke net surveys in Lakes Mingo and Pierce, and in 2010 we began modified fyke netting surveys on Sam Dale Lake. Nets in Lake Mingo (N=11), in Pierce Lake (N=10), and in Sam Dale (N=10), were 3.8 cm bar mesh (1.5 in) and frames were 1.2 X 1.8 m with six 0.75 m hoops. During a two to four week period each spring on each lake nets were checked between 0800 and 1200 hr each day over surface temperatures from 7.0 – 11.0 ˚C. Upon capture the pelvic fin clip was used to identify the stock and population and caudal fin clips were used to conduct Schnabel population estimates within each sampling season (Ricker 1975). Scales were taken from all sampled muskellunge older than YOY (age-0) to determine age class. Muskellunge older than YOY were implanted with a Passive Integrated Transponder (PIT) tags prior to release to aid in future identification (Wagner 2007). Data were used to determine mean daily growth rates (g/d) and mean relative daily growth rates standardized by weight (g/g/d) among the stocks through age-1. Growth rates were analyzed using analysis of variance (ANOVA) models. General patterns in size-at-age (length and weight) and growth trajectory between stocks were compared using ANOVA models including terms for stock and year class at each age and von Bertalanffy growth functions (Beverton and Holt 1957). Where sample sizes allowed all analyses of adult growth were stratified by lake and gender. All analyses were performed with the SAS® System and P-values less than 0.05 were considered significant.

FINDINGS:

Pond Experiment

No short-term mortality was observed and ponds were drained each subsequent spring and fall. Across both pond trials, significant differences in relative growth rates (RDGR) were detected among stocks ($P < 0.0001$). Muskellunge from the Ohio River drainage stock grew fastest during the overwinter periods in both trials ($P < 0.0001$, Figure 1A). During trial 1, the Upper Mississippi River drainage stock had higher overwinter growth rates than the Illinois population ($P = 0.02$); however growth rates overwinter were similar between these two stocks during trial 2 ($P = 0.19$, Figure 1A). Comparisons of RDGR across trials indicatee that the Ohio River drainage stock consistently exhibited faster one-year post-stocking growth rates compared with conspecifics (all $P < 0.0001$, Figure 1B). During trial 1, the Upper Mississippi River drainage stock muskellunge had higher one-year post-stocking growth rates than the Illinois population ($P < 0.0001$); however, the same comparison for trial 2 revealed no differences ($P = 0.21$, Figure 1B).

Modified Fyke Net Surveys

A total of 472 muskellunge were captured during 216 net-nights of modified fyke net sampling in Pierce Lake between 2007 and 2012, yielding an average of 2.19 fish per net-night. Of the 472 muskellunge sampled, 110 were Ohio drainage stock, 355 were Illinois stock and 8 were Upper Mississippi River drainage stock. The largest muskellunge captured over this period was 1023 mm. Males represented 70% of the sampled muskellunge and females the other 30%.

A total of 419 muskellunge were captured during 532 net-nights of modified fyke net sampling in Lake Mingo between 2006 and 2011 (netting could not be completed on Lake Mingo in 2012 due to an unexpected overwinter drawdown followed by an extended period of low precipitation) yielding an average of 0.79 fish per net-night. Of the 419 muskellunge sampled over this period 146 were Ohio stock, 268 were Illinois stock, and four were Upper Mississippi stock. The largest muskellunge sampled during this period was 1069 mm. Males represented 51% of the sampled muskellunge and females the other 49%.

A total of 215 muskellunge were captured during 312 net-nights of modified fyke net sampling in Lake Sam Dale between 2010 and 2012 yielding an average of 0.69 fish per net-night. Of the 215 muskellunge sampled over this period 106 were Ohio stock, 99 were Illinois stock, and six were Upper Mississippi stock. The largest muskellunge sampled during this period was 975 mm. Males represented 51% of the sampled muskellunge and females the other 49%.

Data from modified fyke net surveys was integrated with electrofishing data for calculations of growth and survival.

Juvenile Growth Rate

We compared relative daily growth rates (RDGR, standardized by weight) for age-1 muskellunge in Lake Mingo, Pierce Lake and Sam Dale Lake stratified by stocking year class. In addition we conducted multiple trials of a pond experiment to compare stocks in a more controlled environment. In the reservoir experiment overwinter RDGR was not significantly different between the Ohio River drainage stock and the Illinois stock for any of the year classes from 2003-2007 (Table 4). The Upper Mississippi river drainage stock exhibited a significantly lower overwinter RDGR than the Illinois stock for fish introduced in 2005 and a significantly lower RDGR than both the Ohio River drainage stock and the Illinois stock in 2007. Overwinter growth for all other year classes were similar to the other two stocks. In Pierce Lake overwinter RDGR was not significantly different between the Ohio River Drainage stock and the Illinois stock for any of the year classes from 2003 through 2007 while the Upper Mississippi River drainage stock showed significantly lower rates than both of these stocks for the 2003 and 2004 year classes. The 2005 year class showed higher RDGR for Ohio River drainage muskellunge compared to Upper Mississippi River drainage muskellunge with Illinois stock being intermediate. Growth rates through age-1 in both Lake Mingo and Pierce Lake were similar between the Illinois stock and the Ohio River drainage stock for muskellunge introduced from 2003-2007. In general overwinter growth rates in the reservoirs were similar between Illinois stock and Ohio River drainage stock muskellunge through age-1 and lower for muskellunge from the Upper Mississippi River drainage. From 2003-2007 only two Upper Mississippi River drainage muskellunge were sampled at age-1 across year classes and reservoirs. This poor survival (see Job 101.2) limited our ability to make inferences on the juvenile growth rates for this stock through age-1 in these reservoirs.

In Lake Sam Dale, due to limited recaptures of muskellunge from the 2005-year class and a lack of available populations for stocking in 2006 (due to VHS), growth rate comparisons were not possible for these year classes. The 2007 year class showed a significant difference in relative daily growth rates during overwinter with the Illinois population having a higher rate of growth than the Upper Mississippi River drainage stock (Table 4). No Ohio River drainage stock or Upper Mississippi River drainage stock muskellunge from the 2007-year class were recovered during fall 2008 sampling preventing statistical comparisons of growth through age-1. The 2008-year class was sampled during spring 2009 electrofishing to assess overwinter growth rates. Two Ohio River drainage stock, one Illinois population and no Upper Mississippi River drainage stock muskellunge were sampled during eight hours of nighttime pulsed-DC electrofishing which preventing statistical comparisons of growth rates. In the fall of 2009 we captured sufficient numbers of all three stocks to make a comparison of growth rate through age-1. The 2008 year class showed significantly higher growth for Upper Mississippi stock fish at age-1 than Ohio stock and Illinois stock fish (Table 4). While these results provide an assessment of differences in growth rates through the first year of life, there may be other differences between stocks (e.g. age of maturation, maximum body size) that cause other differences for adult growth rates. Therefore we continued to examine long-term differences in growth through adulthood.

Adult Size-at-Age

In Lake Mingo mean length-at-age was significantly different among stocks (ANOVA, $P < 0.01$, Table 5). The Illinois stock and the Ohio River drainage stock were longer than the Upper Mississippi River stock at age-2. For male muskellunge there also was a significant difference in mean length at age-5 with the Ohio River drainage stock being significantly longer than the Illinois stock (ANOVA, $P < 0.05$). No differences were found among the stocks for female muskellunge through age-7. Few older fish and few Upper Mississippi River drainage fish limited our ability to make comparisons between stocks (Table 5). In general all three stocks of muskellunge appear to be growing at similar rates in Lake Mingo although our inferences concerning the Upper Mississippi River drainage stock are limited to age-2, age-3 males, and age-5 females due to poor survival of this stock (Table 5).

Mean weights of muskellunge in Lake Mingo were also significantly different among stocks at age-2 (ANOVA, $P < 0.01$) with the Illinois and Ohio River Drainage stocks being significantly heavier than the Upper Mississippi River Drainage stock (Table 5). The three stocks of muskellunge appear to be growing at similar rates measured by their average weights through time. Previous analysis showed differences in age-5 males and age-4 females, but the additional sample of fish from spring 2011 spring sampling now indicate no differences in these age classes. In general, few differences in mean weight-at-age were found among the stocks, although inferences concerning the Upper Mississippi River drainage stock were again limited by poor survival.

Examination of Von Bertalanffy growth functions fit to length-at-age data for each stock and gender of muskellunge in Lake Mingo revealed patterns similar to those based on mean length and weight. Male muskellunge from the Ohio River Drainage stock have lower lengths at ages 1-3 but then surpass Illinois males at ages 4-7, resulting in a higher asymptotic lengths for Ohio males than Illinois males (Table 6, Figure 2). Female muskellunge showed similar growth trajectories between stocks with nearly identical asymptotic lengths and growth coefficients (Table 6, Figure 3). A growth function was also constructed for Upper Mississippi River drainage muskellunge by pooling both genders. The Upper Mississippi River drainage function was based on limited samples but shows a growth trajectory very similar to the other two stocks with similar asymptotic lengths and growth coefficients (Table 6, Figure 3). Collectively these analyses show similar growth trajectories for these three different muskellunge stocks in Lake Mingo.

In Pierce Lake, male muskellunge from the Upper Mississippi River drainage stock were significantly longer than that of either of the other two stocks through age-4 (ANOVA $P = 0.02$, Table 7). However, at ages 5 and 6 there were no statistically significant differences between stocks. For female age-3 Illinois fish were significantly longer than Ohio River drainage fish. No Upper Mississippi River drainage females have been sampled in Pierce Lake, limiting comparisons between all stocks. In general, Ohio River drainage and Illinois fish appear to grow at similar rates in Pierce Lake. While the Upper Mississippi River Drainage stock males were longer than the other stocks at age-4 and age-6 this difference is based on a limited sample size of these fish (N=8) and should be interpreted with caution. These patterns were not evident in Lake Mingo and are suggestive of a latitudinal effect within the state. Further data will be required on size-at-age of adult fish from each lake (particularly from Sam Dale Lake in southern Illinois) to clarify whether this is a consistent pattern.

For weight, no differences were found among stocks in Pierce Lake at age-2. Female muskellunge showed a significant difference in weight at age-3 with the Illinois stock being heavier than the Ohio River drainage stock (ANOVA, $P < 0.05$) but there were no significant differences for older females at ages 4-6 (Table 7). Mean weight-at-age seemed to be similar among stocks in Pierce Lake although inferences on the Upper Mississippi River drainage stock are limited to males due to poor survival.

Examination of Von Bertalanffy growth functions fit to length-at-age data for male muskellunge in Pierce Lake show Illinois fish being longer than Ohio fish at younger ages although asymptotic lengths are nearly identical (Table 6, Figure 4). The growth trajectory of female muskellunge in Pierce Lake was generally also similar among stocks (Figure 5). No differences in asymptotic length or growth coefficients were found between stocks (Table 6, Figure 4). Due to poor survival of the Upper Mississippi River drainage stock both sexes were pooled to obtain Von Bertalanffy parameters. The growth trajectory for Upper Mississippi muskellunge in Pierce Lake was similar to Ohio River drainage and Illinois muskellunge (Table 6, Figure 5)

In Sam Dale Lake, Upper Mississippi River drainage muskellunge were significantly longer than Ohio River drainage muskellunge at age-2 with Illinois muskellunge intermediate (ANOVA, $P < 0.01$, Table 8). Length-at-age was similar between Ohio and Upper Mississippi River drainage fishes at age-3 for both genders. At age-4 Ohio River drainage males were longer than Illinois males. Upper Mississippi River drainage fish were significantly longer than Illinois females at age-4 with Ohio River drainage females being intermediate (Table 8).

In Sam Dale Upper Mississippi muskellunge were significantly heavier than Ohio River muskellunge at age-2 with Illinois muskellunge intermediate (ANOVA, $P < 0.01$, Table 8). Weight-at-age was similar for age-3 fish across all stocks. At age-4 Ohio River Drainage males were heavier than Illinois males. Age-4 female weight-at-age was similar between all stocks. Additional year classes of adult fish are needed to construct growth curves and compare mean length and weight at older ages for these stocks in Sam Dale Lake. Comparisons of length and weight differences were not possible for age-5 fish due to limited sample sizes to date. Additionally, Von Bertalanffy growth curves could not be completed for any stock because of limited data from older fish. Future years of sampling will allow this comparison in Sam Dale Lake.

RECOMMENDATIONS: In Lake Mingo, these populations/stocks generally exhibit similar growth trajectories and size-at-age. While the Illinois population seems to have a slight growth advantage over Ohio fish at ages 1-2 they are surpassed by Ohio fish at older ages. Ohio males did show higher asymptotic lengths than Illinois males when comparing growth trajectories. Growth of Ohio River drainage muskellunge in Pierce Lake appeared to be slower and ultimately shorter than Illinois muskellunge. With current data we find a pattern of very similar growth trajectories and few differences in mean length or weight at older ages between all three stocks. There is some evidence that the Upper Mississippi River drainage stock is longer than the other stocks at older ages in Pierce Lake. Coupled with slightly slower growth of Ohio fish, these findings support the hypothesis of thermal adaptation over the countergradient variation hypothesis to explain growth patterns in muskellunge. The natal climate of the Ohio River drainage stock is generally more similar to Lake Mingo than Pierce Lake. Under the assumptions of the thermal adaptation concept, it would be predicted that the Ohio River drainage stock would exhibit better performance in Lake Mingo than in Pierce Lake, which agrees with our results. However, initial results from Sam Dale Lake, the southernmost lake included in the study, also show Upper Mississippi fish growing faster across several age classes. If this pattern continues through older age classes it would provide evidence to support the countergradient variation theory which states that fish from northern latitudes should grow faster across all thermal environments. However, based on current results, the conclusion is no difference in growth among stocks at any latitude within Illinois.

Continued monitoring of these stocks across all lakes, and in particular Sam Dale Lake, will help to identify the patterns of growth across stocks including differences in maximum size as these populations reach older year classes. Any long-term differences among muskellunge populations we observe in these experiments will have important implications for new introductions or maintenance stockings of muskellunge populations. When introducing muskellunge into areas where they have not naturally occurred, such as Illinois impoundments, knowledge of population differentiation will be a valuable tool in designing appropriate stocking programs.

Job 101.2. Evaluating survival of different stocks of muskellunge.

OBJECTIVE: To investigate survival of various stocks and populations of muskellunge in Illinois waters.

INTRODUCTION: Population survival rates are a consequence of life history modes to which stocks have evolved and are important determinants of the productivity and evolutionary potential of a species (Begg et al. 1999, Shaklee and Currens 2003). Differences in survival rates among distinct fish stocks in common environments have been demonstrated for recreationally important fish species such as largemouth bass (Leitner and Bulak 2008, Philipp and Claussen 1995), lake trout *Salvelinus namayacush* (MacLean 1981) and several others. In a recent paper Leitner and Bulak (2008) showed significant differences in survival rates between source populations of largemouth bass from the Piedmont and Coastal Plain regions of South Carolina with the Coastal Plain stock exhibiting higher survival to ages 3-4. Studies of stock specific survival of largemouth bass showed differences in survival between bass populations from two river drainages within Illinois (Phillip and Claussen 1995). These studies provide evidence that stock origin can influence survival rates of introduced sportfish and should be considered when selecting the appropriate stock for management purposes.

Muskellunge are long-lived (Casselman and Crossman 1986), are commonly managed for trophy fisheries (Hanson et al. 1986), and naturally occur at low densities (Margenau and AveLallemant 2000) causing small fluctuations in mortality rates to have a relatively large influence on fishery quality (see Brenden et al. 2007 for an example of such sensitivity to mortality rates). Research focused on differences in mortality between muskellunge stocks has been limited to comparisons of populations from within the Upper Mississippi River drainage stock in Minnesota and Wisconsin. In a comparison of survival rates among four native muskellunge populations in Minnesota, Younk and Strand (1992) found that the Shoepack Lake population exhibited lower survival than populations from three other Minnesota waters. Survival was also compared among five local populations in Wisconsin as well as the Leech Lake, Minnesota population (Margenau and Hanson 1996). Survival was significantly higher for the Mud/Calahan Lake population compared to the other four Wisconsin populations and results demonstrated that the Leech Lake population could be introduced into Wisconsin waters and survive but this population showed no significant difference in survival rate compared to local muskellunge. Because these studies have focused on comparisons of populations within one muskellunge stock, there exists a need to evaluate potential survival differences among genetically divergent stocks. Stockings of muskellunge into waters where the species has been extirpated or does not naturally occur sustain many muskellunge fisheries, including those in Illinois. In these scenarios, it would be beneficial to know which stocks and populations have the highest survival in the thermal regime of the region to be stocked. In this job, we are investigating differences in survival among stocks and populations of muskellunge in lakes in Illinois.

PROCEDURES: General stocking and sampling procedures for this job were identical to those presented in Job 101.1 and are therefore not described here. Juvenile survival rates were assessed in the replicated pond experiments described previously. Experimental ponds were drained every spring and fall at approximately 6 mo intervals. Muskellunge were collected and population identified by PIT tags (Wagner et al. 2007). All surviving fish were returned into one of three 0.4-ha experimental ponds for future evaluations. These data were used to determine survival among the stocks of muskellunge in experimental ponds using a two-factor logistic analysis of variance model (Proc Genmod, SAS) with stock and pond as factors.

Because muskellunge stocks were identified in the field by pelvic fin clips, we conducted a laboratory experiment to evaluate the potential for fin clipping to affect fitness characteristics (e.g. foraging, growth). Previous research has suggested that the loss of any single paired fin is equally detrimental to short-term survival (3-mos) and the loss of pelvic fins is less detrimental than loss of a pectoral fin (McNiel and Crossman 1979). Results from the laboratory experiment indicated that there are no significant negative effects of pelvic fin clips on foraging behavior or growth of juvenile muskellunge (Wagner et al. 2009). This information provides evidence that our clipping methods did not differentially affect fitness characteristics (and therefore survival) of the unique stocks.

In previous reports we compared survival rates among stocks by individual year class using adjusted catch-per-unit effort (CPUE) data (adjusted for stocking mortality) from electrofishing (juveniles to age-1) and spring modified fyke net surveys (adults ages 2+). The assessment of juvenile survival rates has been completed for all lakes and these findings are summarized in this report. Survival rates (CPUE) of stocked fish overwinter and through age-1 were completed on all lakes. ANOVA was used to compare survival among stocks stratified by year class and lake.

We continued a global analysis of adult survival rates in lakes Pierce and Sam Dale. These analyses have been made possible by the establishment of multiple age classes in Lakes Pierce and Sam Dale combined with multiple years of catch data from spring modified fyke net surveys. Fyke netting surveys could not be completed in Lake Mingo in 2012 so data presented in this report only goes through 2011. In Lake Sam Dale two year classes (2007 and 2008) have been established and recruited to adulthood following several largely unsuccessful year classes (2005 and 2006). Comparisons of survival to adulthood and annual survival between stocks are presented in this report. To estimate survival and evaluate potential differences between stocks we utilized CPUE data from spring fyke net samples collected during 2007-2011 (Lake Mingo), 2008-2012 (Pierce Lake) and 2010-2012 (Sam Dale). Catch rates were used to compare both survival to adulthood between stocks and annual survival of adult fish after age 3 between stocks and across years. To compare survival of each stock to adulthood an adjusted CPUE for each age class was calculated and compared among stocks within each lake using a blocked one way ANOVA (blocked by year class). Annual survival estimates for adult fish were calculated by the ratio of CPUE estimates in successive years for each age class (Ricker 1975). The analyses do not require the assumption of constant recruitment common to many techniques designed for estimation of survival rates (e.g. catch-curves). Analysis was restricted to adult muskellunge year classes (ages 3-7) because these were the year classes fully recruited to the gear (Ricker 1975). Mean annual survival rates of adult fish were then compared between stocks using paired t-tests on pooled survival estimates from ages 3-7 in each lake. Significance for all analyses was determined at $P \leq 0.05$.

FINDINGS:

Pond Experiments

As discussed in greater detail in Job 101.1, two pond trials (2003-2004) were conducted at the Sam Parr Biological Station. Each trial consisted of three ponds (0.4-ha) that were stocked with equal numbers of each of three stocks during the fall and drained in subsequent springs and falls. A logistic analysis of variance (Proc Genmod, SAS) was used to assess survival differences one year after stocking among genetically distinct stocks of muskellunge fingerlings. Overwinter survival did not differ among stocks during either trial ($P > 0.11$, Figure 6A), averaging 80% for trial 1 and 47% for trial 2. One year after stocking, the Ohio River drainage stock in trial 1 had the highest survival ($P \leq 0.0001$, Figure 6B) and the Upper Mississippi River drainage muskellunge survived the poorest ($P \leq 0.0001$, Figure 6B); the Illinois population was intermediate and different from the other two stocks. In contrast, no differences in one-year post-stocking survival (average 31%, Figure 6B) were observed during trial 2 (P = 0.09). Across both overwinter trials, there was little pond effect (P ≥ 0.12).

Juvenile Survival Summary

Relative survival rates were compared based on adjusted CPUE (adjusted for stocking related mortality) through age-1 of introduced muskellunge in Lake Mingo, Pierce Lake and Sam Dale Lake stratified by stocking year class. Results from year classes 2003 through 2008 in the reservoir experiment are presented in Table 9. Overwinter survival of juvenile muskellunge in Lake Mingo was significantly different among stocks for the 2004, 2006, and 2007-year classes. Overwinter survival of juvenile muskellunge in the 2004-year class was higher for the Upper Mississippi River drainage stock compared to the Illinois population and the Ohio River Drainage stock was intermediate. The 2006-year class in Lake Mingo showed significantly higher survival for Illinois population muskellunge compared to the Ohio River drainage stock and no Upper Mississippi River drainage muskellunge were recovered. The Upper Mississippi River drainage stock again showed higher overwinter survival as compared to the other two stocks for the 2007-year class while the Illinois population and the Ohio River drainage stock had similar survival rates. Overwinter survival of juveniles was similar among all stocks for the 2003 and 2005-year classes in Lake Mingo.

For age-1 fish, survival in Lake Mingo was significantly different among stocks for the 2003-year class. The Ohio River drainage stock exhibited higher survival to age-1 than the Illinois population and no Upper Mississippi River drainage muskellunge were sampled. Survival to age-1 was similar between the Upper Mississippi River drainage stock and the Illinois population for the 2004-year class while no muskellunge from the Ohio River drainage stock were sampled. Comparisons of survival to age-1 among stocks in Lake Mingo were not possible for year classes 2005-2007 due to low survival of Upper Mississippi River drainage and Ohio River drainage stocks.

Juvenile survival in Pierce Lake was not statistically different either overwinter or through age-1 among stocks of muskellunge introduced from 2003-2007. Low survival of Upper Mississippi River drainage muskellunge to age-1 limited statistical comparisons to catch rates between the Illinois population and Ohio River drainage stock for all year classes except the 2005-year class. There were marginally significant differences in survival to age-1 between the Ohio River drainage stock and the Illinois population for muskellunge introduced in 2003 and 2004 with the Illinois population showing marginally higher survival in 2003 and the Ohio stock having the advantage in 2004.

Year classes of muskellunge were introduced into Sam Dale Lake each year from 2005-2008 (Table 3). The 2005-year class experienced significant stocking related mortality and no fish from this year class were recovered in the spring or fall of 2006. In 2006 only Illinois population muskellunge were introduced due to a limited availability of muskellunge source populations caused by concerns over the viral hemorrhagic septicemia virus (VHSV). Full introductions of each muskellunge stock were completed in 2007 and 2008. Muskellunge from the 2007-year class showed similar overwinter survival for fish from the Upper Mississippi River drainage stock and Illinois population while no Ohio River drainage muskellunge from this year class were captured (Table 9). The 2008-year class sampled spring 2009 showed similar survival between the Illinois population and Ohio River drainage stock and no Upper Mississippi River drainage stock muskellunge were recovered. The 2008 year class was sampled again in the fall of 2009 to assess survival to age-1. Illinois muskellunge showed the highest adjusted CPUE, Ohio fish were intermediate, and Upper Mississippi muskellunge showed the lowest catch rates although the differences between stocks were not significant (Table 9).

Adult CPUE and Survival in Lakes Mingo, Pierce and Sam Dale

We compared survival to adulthood (age-3) in Lakes Mingo and Pierce among stocks across year classes. In Lake Mingo, Ohio River Drainage fish had significantly higher survival to adulthood than Upper Mississippi River drainage fish (Table 10, ANOVA, P = 0.03). Survival of the Illinois population muskellunge was intermediate. There was no significant difference in survival to adulthood in fish stocked into Pierce Lake (ANOVA, P = 0.23). There were no significant differences in survival to adulthood in fish stocked into Lake Sam Dale (ANOVA, P=0.16) from limited samples conducted thus far.

Data from spring fyke net surveys conducted on Lakes Mingo, Pierce, and Sam Dale allowed estimation of annual survival rates for adult muskellunge ages 3-6+ in all lakes (Tables 11-12). Due to low numbers of age-6 and greater muskellunge captured across lakes and years these fish were pooled and used to estimate an average survival rate of adult muskellunge after age-5. In Lakes Mingo and Pierce estimates could be calculated for Illinois and Ohio River drainage stock but not the Upper Mississippi River drainage stock due to low survival of this stock. In Lake Sam Dale annual survival of all three stocks is compared. In several instances CPUE increased within a year class from one sampling year to the next (See Table 11 for examples). This may be a result of these fish not being fully recruited to the gear at age-3 or differences in the number of net nights among surveys. In these instances survival estimates of 1.0 were used for that year class. Survival rates of each stock were compared using a paired t-test (paired by age and time period) or ANOVA, depending on the number of stocks being compared. Average annual survival estimates for adult Illinois population muskellunge in Lake Mingo was 54% for the period from 2007-2011 (Table 11). Average annual survival of the the Ohio River drainage stock in Lake Mingo was 57% across the same time span. No significant difference in average annual survival of adult muskellunge between the Illinois population and Ohio River drainage stock were found (Paired t = –0.35; P = 0.37) and the mean annual survival estimates for both populations were very similar.

Estimates of adult annual survival rates for muskellunge introduced into Pierce Lake were determined for the period from 2008-2012. The average annual survival estimate for the Illinois population from 2008-2012 was 50%. The Ohio River drainage stock also had 50% mean annual survival across the same timespan (Table 12). Adult Upper Mississippi River drainage fish were captured in low numbers, limiting our ability to describe annual mortality. Paired t-test analysis did not find a significant difference between the Illinois population and the Ohio River drainage stock (Paired t = 0.9; P = 1.0).

Annual survival estimates for all three stocks in Lake Sam Dale between 2010 and 2012 were calculated (Table 13). The average annual survival over that timespan was 16% for the Illinois population, 21% for the Ohio stock, and 7% for the Upper Mississippi River stock. These rates of survival were not significantly different from one another (ANOVA, P=0.68), however these estimates are based on only two year classes. Additional sampling will allow statistically stronger comparisons of survival in Lake Sam Dale.

RECOMENDATIONS: The results of the reservoir experiment suggest similar survival between the Illinois population and Ohio River drainage muskellunge and much lower survival for the Upper Mississippi River drainage stock in all lakes. During spring netting surveys of adult muskellunge, the Illinois population and the Ohio River drainage stock were consistently represented at similar levels in catches. In contrast, few Upper Mississippi River drainage muskellunge have been sampled beyond age-1 in all three lakes. The recapture rate of Upper Mississippi River drainage stock muskellunge in most cases was too low to allow quantitative comparisons with the other stocks. Limited recaptures of Upper Mississippi River drainage fish in Lake Sam Dale allowed some comparisons that also indicated lower survival of this stock, but there was low statistical power associated with these tests.

Survival of all stocks in all lakes was typically lower between 2011 and 2012 than in other years. All three study lakes occur on reservoirs meaning that dam escapement is a possible source of fish loss that could explain some reduction in CPUE in these waterbodies. The spring of 2011 had above average precipitation leading to sustained periods of water discharge from all three study lakes. We monitored escapement during this time on Lake Sam Dale. A fixed PIT tag antennae detected tags in 24 escaping fish comprising 21% of the population tagged in this study. While other factors including warm summer temperatures, predation, or delayed mortality from catch and release angling likely contribute to annual mortality of muskellunge populations in Illinois, dam escapement should also be considered to be a factor influencing populations.

Further fall and spring monitoring of introduced muskellunge should be conducted in Lake Sam Dale. Survival of these stocks in Sam Dale Lake which is the southernmost lake in the study is of particular interest. Once compiled, results from all lakes may reveal latitudinal differences in survival within the state among the introduced stocks. Capturing additional year classes during these spring nettings will be vital for a more powerful assessment of differences between stocks. Long-term data will allow us to detect any biologically significant differences in longevity or survival between the distinct stocks of muskellunge in Illinois lakes.

Job 101.3. Evaluating diet composition of muskellunge and potential direct and indirect interactions between muskellunge and other piscivorous fishes.

OBJECTIVE: To evaluate diet composition of muskellunge and potential direct and indirect interactions between muskellunge and other piscivorous fishes.

INTRODUCTION: Due to the desire to produce new sport fisheries, the introduction of muskellunge (*Esox masquinongy*) outside its native range has become increasingly common in the U.S. For example, since their initial introduction in 1979, the number of Illinois lakes with muskellunge introductions has risen each year and now includes over 34 water bodies. Outside of Illinois intentional and unintended introductions have occurred in over 12 U.S states in recent decades (Fuller 2011). Despite the increasing trend of muskellunge introduction there is little information on the effects of muskellunge introductions on lake ecosystems and existing fisheries. Although muskellunge introduction has led to the development of successful fisheries, it has sparked considerable controversy among angling groups over fears that they will compete with and/or prey upon resident species and impact alternative existing fisheries. Specific concerns regarding muskellunge introductions include the predatory effects that these introduced populations may have on other ecologically and recreationally important fishes and the potential for negative interactions with resident fish predators (Brenden et al 2004). Although muskellunge are providing new and exciting fisheries in Illinois waters, it is essential to consider their potential effects on other recreationally and ecologically important sportfish populations both to better guide management actions and to address public concerns. In this job we test for effects of introduced muskellunge (Esox masquinongy) on resident fish populations representing several recreationally and ecologically important species across eight Illinois lakes.

Recent published studies on effects of muskellunge introduction have mainly examined predatory effects in river systems (Brenden et al 2004, Curry et al 2007). A few studies exist which report competitive or predatory effects in one or two lake systems. For example Becker (1983) attributed muskellunge with the decline of largemouth bass populations in two Wisconsin lakes. Another study documented a decline in black crappie and white sucker populations in a Michigan lake as a result of muskellunge introduction (Siler and Bayerle 1986). More recently the Minnesota DNR published the results of a largescale evaluation of muskellunge introduction in Minnesota lakes. This study examined 41 lakes in 12 lake classes for trends in relative abundance of seven fish species before and after muskellunge introduction and found no consistent pattern of significant declines in relative abundances after muskellunge introduction (Knapp et al. 2012). While these studies have been important steps toward a better understanding of the effects of muskellunge introduction the above studies were either lacking in key experimental elements or were conducted on systems very different from those in the lower Midwest. A particular problem in previous work has been a lack of controls in studies of impacts in natural systems, which complicates the separation of trends due to natural variation and muskellunge introduction (Underwood 1994). In addition to issues related to adequate controls, the previous studies of muskellunge introduction have been conducted in northern natural lake systems (Siler and Bayerle 1986; Knapp et al. 2012) which have many ecological and fish community differences from the man-made lower Midwestern systems examined in this study (Thornton 1990). Therefore our objective in this job was to both evaluate muskellunge diet in Illinois lakes as well as the responses of several ecologically and recreationally important fish species in response to muskellunge introduction.

PROCEDURES:

Muskellunge Food Habits

Diet samples were collected from muskellunge between May 2007 and May 2012 across seven Illinois lakes including Lakes Mingo, Otter, Pierce, Ridge, Sam Dale, Shelbyville, and Lake of the Woods. The majority of muskellunge were sampled using methods identical to those presented in Job 101.1. All sampling consisted of nighttime pulsed DC electrofishing or modified fyke netting surveys (spring and fall 2008-2011) in lakes Mingo, Pierce, and Sam Dale and angled fish sampled as part of the long term creel on Ridge Lake (May – November 2007-2011). Diet contents were removed from all sizes of muskellunge sampled via pulsed gastric lavage (Foster 1977). Diet samples were labeled with the date, location, length and weight of muskellunge, stored in plastic bags and immediately frozen upon return from the field. Diet samples were later thawed, measured for total, fork, or backbone length, weighed and identified to species using scales and muscle tissue (Oates et al. 1993). We sacrificed and later dissected a subsample of muskellunge to verify that lavage completely sampled all gut contents.

Measurements of prey length were used to back-calculate wet weight of each item using regression equations from Wahl and Stein (1988), Anderson and Neuman (1996), and Bozek et al. (1999). Data were then used to calculate frequency of occurrence and proportion by weight of prey species found in muskellunge diets.

Fishery Effects of Muskellunge Stocking

To begin addressing angler concerns and scientific uncertainty surrounding muskellunge introduction in lower Midwestern lakes we analyzed time series of various fisheries metrics for 16 Illinois lakes collected as part of standardized fishery sampling conducted by the Illinois Department of Natural resources and the Illinois Natural History Survey (INHS). The set of 16 lakes chosen for analysis included lakes with muskellunge introductions (N = 8) and reference waters (N = 8) selected for analysis by examination of muskellunge stocking records provided by the Illinois DNR and the Jake Wolf Memorial Fish Hatchery. Data for each lake was acquired and compiled from two sources including the Illinois Fisheries Analysis System (FAS; Bayley et al. 1990) and data collected by INHS as part of ongoing or previous Federal Aid in Sport Fish Restoration Projects (F-135-R and F-128-R). Each standardized sampling protocol (both IDNR and INHS) consisted of daytime three-phase AC boat mounted electrofishing (3,000 W, 230V AC, and 50 Hz; see Bayley and Austin 2002 for a detailed description) conducted on three one-half hour fixed shoreline transects sampled in the fall (October – November). During each sampling run all fish were netted, identified to species, counted and a subsample of each species (up to 50 individuals) was measured for total length and weight.

Lakes were selected for analysis on the basis of data availability and verifiable development of adult muskellunge populations. Lakes were selected for analysis if available data included a minimum of 4 years of pre and post muskellunge introduction electrofishing data. Evidence that significant adult populations of muskellunge had developed was based on targeted modified fyke-net catches (3.8 cm bar mesh, 1.2 X 1.8 m frames with six 0.75 m hoops) and electrofishing (Table 14). Lakes were selected if at any time within the post introduction period (4-7 years) the average catch rate of muskellunge exceeded 0.5 stock length or greater fish per net per night (50% of the IDNR management goal for muskellunge lakes, IDNR personal communication). In one instance (Mill Creek Lake) fyke net data were not available to verify adult muskellunge populations; however this lake had electrofishing catch rates of stock length and greater muskellunge comparable to lakes with known established adult populations in the years following initial introduction and was therefore included in our analysis (Table 14). Each selected muskellunge lake was paired with a nearby control lake that was not stocked with muskellunge (Figure 7). After identifying qualifying muskellunge lakes, a list of potential control lakes was generated based on lakes with concurrent annual electrofishing time series. This list was then trimmed to a set of lakes or lake with the closest geographic distance and fish community (presence or absence of gizzard shad). In cases where muskellunge lakes overlapped in their prospective controls due to close proximity (Wheel, Johnson and Shovel Lakes) or where candidate controls were within 10km of each other, lakes were paired based on size (e.g. Lakes Shovel – Lou Yeager and Johnson-Springfield respectively).

While muskellunge populations in lakes selected for analysis were verified using targeted sampling consisting of modified fyke nets only AC electrofishing data was available from control systems; therefore our analysis of effects of muskellunge introduction was restricted to electrofishing data. Boat electrofishing is a seasonally, and compositionally selective gear that is most suited to indexing abundance and size structure of nearshore species (Bonar et al. 2010). In order to control for seasonal trends and to ensure that our gear adequately indexed relative abundance, we restricted our analysis to fall samples of species known to have high vulnerability to electrofishing gear (Bayley and Austen 2002). These species included largemouth bass, bluegill, redear sunfish (*Lepomus microlophus*), gizzard shad (*Dorosoma cepedianum*), common carp (*Cyprinus carpio*), black crappie (*Pomoxis nigromaculatus*) and white crappie (*Pomoxis annularis*). All species did not occur in all lakes, which limited the number of lake pairs included in our analysis in some cases. Response variables for each lake included several common fisheries management metrics including relative abundance (CPUE; number per hour), size structure (proportional stock distribution (PSD) and relative stock distribution - preferred (RSD-P)), and condition (relative weight (Wr)).

Individual lakes selected for analysis varied in the timing of muskellunge introduction from 1996-2005. In order to minimize the effects of temporal differences in data collection on our analysis, each stocked and reference lake combination was treated as an independent experiment and analyzed using paired before-after control-impact analysis (BACIP, Underwood 1994). Paired analysis using waters from the same geographic region is a commonly utilized approach in whole lake studies as a control for regional climate related variation (Carpenter 1989). Paired time series were analyzed using a linear mixed model with fixed effects of before or after muskellunge introduction (BA) and control or introduced lakes (CI) and their interaction (BA*CI). Two random terms were included to account for variation within sites across time. One term for year nested within before-after periods (Y(BA)) and one term for the interaction of control or introduced lakes and year within the before or after period CI*Y(BA) (see Downes et al 2002 for a formal description of this model). The BA*CI term tests for any changes in average values of the parameter of interest coincident with the effect in question (muskellunge introduction) and is tested with the CI*Y(BA) term (Downes et al. 2002). This test addresses the hypothesis that there was a change coincident with muskellunge introduction in receiving lakes that was not present in the control system.

In order to draw more general conclusions concerning the effects of muskellunge introduction we utilized a recently described “meta-BACI” approach to conduct a meta-analysis of each metric across lake pairs following the general approach described by Gurevitch and Hedges (1993) and modified for BACI designs by Conner et al (2007). For each metric of interest, meta-analysis was conducted by comparing the change in the least squares means for control and reference systems from before and after muskellunge introduction (estimated from the above linear mixed model). The difference in mean values before and after muskellunge introduction was used to calculate an effect size (*d*) using the formula:

$$d_i = (M_{ia} - M_{ib}) - (M_{ca} - M_{cb})$$

and

$$SE(d_i) = \sqrt{}var(M_{ia}) + var(M_{ib}) + var(M_{ca}) + var(M_{cb})$$

Where d_i = relative effect in lake i, M = least squares mean of parameter of interest with subscripts: ia, M of lakes receiving muskellunge after introduction; ib, M of lakes receiving muskellunge before introduction; ca, M of control lakes after introduction; cb M of control lakes before introduction. In this BACI approach changes are considered relative because the value of the effect size does not necessarily represent a true change in the mean of the lake receiving muskellunge. Rather it is possible that the mean value changed relatively less than its paired control and this situation would still be considered a measurable effect (Connor et al. 2007). Each of the paired effect sizes was weighted by the reciprocal of its respective variance to account for differences in sample sizes and variability and evaluated with a paired t-test (Gurevitch and Hedges 1993). This technique allowed us to examine the generality of effects of muskellunge introduction in a more general analysis.

FINDINGS:

Muskellunge Food Habits

Stomach contents of 1728 muskellunge from seven Illinois lakes were sampled between May 2007 and May 2012 yielding 552 diet items (1176 fish had empty stomachs). Diet samples were pooled across years to describe the diet of muskellunge in each of the study lakes. In Lakes Mingo, Pierce, and Sam Dale sample sizes allowed for description of diets by season (Spring/Fall). Gizzard shad were the dominant diet item by frequency and wet weight in Lakes Mingo (Figure 8), Pierce (Figure 9), Sam Dale (Figure 10), Shelbyville (Figure 11), and Otter (Figure 12), Bluegill were the dominant diet item in Ridge Lake (Figure 13). Bluegills were the secondary prey species in Mingo, Pierce, Sam Dale, and Shelbyville while largemouth bass were a secondary prey in Ridge Lake. Low sample sizes limited our ability to describe the diets of muskellunge in Lake of the Woods however, out of 10 diet items recovered from this lake, 9 consisted of single gizzard shad while 1 bluegill was recovered. Other species found in low frequency included: black crappie (Pierce), brook silverside (Pierce, Sam Dale), largemouth bass (Shelbyville, Pierce, Mingo) yellow bullhead (Mingo), white bass (Shelbyville, Otter), white crappie (Sam Dale), walleye (Shelbyville) and yellow perch (Pierce). Seasonal separation of diet contents in lakes Mingo, Pierce, and Sam Dale indicated that non-shad species were slightly more common diet items in the spring compared to the fall (Figures 8-10) however, diets were still overwhelmingly dominated by gizzard shad in this season. A similar pattern of greater diet breadth in spring was found in Ohio reservoirs (Wahl and Stein 1991) which may be attributable to lower abundances of gizzard shad during this time of year. Gizzard shad were the most frequent prey item in all lakes where they are present (Lakes Mingo, Sam Dale, Shelbyville, Otter, and Pierce). In Ridge Lake where gizzard shad are not present bluegill were found to be the dominant prey item. Largemouth bass comprised a very small percentage of the overall muskellunge diet but become a more important secondary diet item in the absence of gizzard shad (Figure 13).

Fishery Effects of Muskellunge Stocking

On the individual lake scale largemouth bass populations exhibited significant changes in relative abundance in three lakes and significant changes in size structure in four lakes. In all three cases (Johnson Lake, Wheel Lake, and Shovel Lake) where largemouth bass relative abundance showed statistically significant changes after muskellunge introduction the effect size represented a relative increase. Similarly in all four cases (Johnson Lake, Ridge Lake, Shovel Lake, and Wheel Lake) where significant changes in size structure were detected effect sizes were positive representing relative increases in size structure after muskellunge introduction. These changes were in the form of increases in RSDP in three cases and increases in PSD in two cases. Meta-analysis of largemouth bass population parameters indicated an overall significant effect size for relative abundance across eight lake pairs (Table 15; Figure 14). Effect sizes for largemouth bass relative abundance were positive for 7 of 8 lake pairs resulting in a positive mean effect size of 22.31(95%CI ± 16.16) largemouth bass per hour of electrofishing. No significant overall effects were detected across lake pairs for size structure or condition (Table 15).

Paired analysis of bluegill population parameters in individual lakes indicated significant changes in relative abundance in one lake (Mill Creek Lake), significant changes in size structure in three lakes (Argyle Lake, Johnson Lake, and Mill Creek Lake), and significant changes in condition in one lake (Lake Mingo). Changes in relative abundance were in the form of a relative increase of 14 bluegills per hour in Mill Creek Lake. Size structure increased in two lakes including Argyle Lake and Mill Creek Lake after muskellunge introduction and declined in Johnson Lake. Despite the noted changes in some parameters in individual lakes there was no overall effect detected across lake pairs in the meta-analysis for any of the measured bluegill population characteristics (all $P > 0.16$; Table 15).

Results of paired analysis for redear sunfish relative abundance, and condition (Wr) were available from three lake pairs. In addition data on size structure was available from one lake pair. A statistically significant change in relative abundance was noted in Johnson Lake (increase of 3.2 fish per hour of electrofishing). A significant increase in size structure was noted in Mill Creek Lake. Meta-analysis across three lake pairs where data was available indicated no consistent changes in redear sunfish relative abundance or condition after muskellunge introduction (all $P > 0.12$; Table 15).

Across five lake pairs for which data were available gizzard shad populations showed no significant changes for any parameter including relative abundance, size structure and condition at the scale of individual lake pairs. This lack of change was also apparent in the meta-analysis where no overall changes were found after muskellunge introduction for these population characteristics (all $P > 0.54$; Table 15).

Data was available for common carp relative abundance, size structure (PSD) and condition from two lake pairs including Argyle Lake and Johnson Sauk Trail Lake. There were no significant changes in any of these population characteristics for either lake pair after the introduction of muskellunge although there was a marginally significant decline in common carp condition in Argyle Lake where mean relative weight declined by 7.3 points. No significant effects were detected for any population metric when averaging effect sizes across these two lakes (Table 15).

Paired analysis on four lake pairs indicated significant changes in black crappie relative abundance in one lake, size structure in two lakes and condition in one lake. Size structure of black crappie increased after muskellunge introduction in Wheel Lake (PSD and RSDP) and Johnson Lake (RSDP). Black crappie relative abundance and condition also increased after muskellunge introduction in Wheel Lake. Meta-analysis of black crappie population characteristics across four lake pairs indicated a significant effect of muskellunge introduction on black crappie RSDP (Table 15, Figure 15). All four lakes examined showed positive relative effect sizes for this size structure metric ranging from 2.5 to 19.1 points.

Data on white crappie populations was available from two lake pairs (Argyle Lake and Wheel Lake) and included relative abundance, size structure (both PSD and RSDP) and condition (Wr). The only significant effect on the scale of these individual lake pairs after muskellunge introduction was a relative increase in size structure in Argyle Lake. White crappie RSDP increased by a relative effect size of almost 21 points in this lake after muskellunge introduction. Effect sizes for relative abundance in both lakes for which data were available were both negative and of a similar magnitude resulting in an overall significant effect of muskellunge introduction and a net decrease across lakes of 6.35 white crappie per hour of electrofishing (Table 15, Figure 16).

RECOMENDATIONS: Muskellunge diet information showed a consistent pattern of little predation on largemouth bass or other game species in lakes where gizzard shad are present. Diet information from Lakes Mingo, Pierce, Sam Dale, Otter, and Shelbyville indicates that gizzard shad make up the bulk of muskellunge diet wherever they are available. These findings are similar to other studies that have shown gizzard shad to be the dominant prey item in Ohio impoundments and that muskellunge prefer gizzard shad and other soft rayed fishes when present (Wahl and Stein 1988). This suggests that muskellunge are not responsible for significant amounts of direct predation on most popular game species where gizzard shad are present. However our data set is limited to spring and fall seasons when muskellunge are vulnerable to sampling gear and further research will be necessary to describe summer and mid-winter diets. Diet composition from Ridge Lake shows that when gizzard shad or other soft rayed prey are not present, bluegill become the primary diet item making up more than 80 % of the diet. In these types of lakes largemouth bass become a more common prey item (although still less than 15 % of the total diet). Managers should consider that the availability of soft rayed alternative prey such as gizzard shad may largely determine the degree to which introduced muskellunge consume recreationally important species such as bluegills and largemouth bass.

Our results show no negative effects of muskellunge introduction on largemouth bass relative abundance. In contrast we found that largemouth bass catch-per-hour increased significantly relative to controls in three of the eight lake pairs examined and effect sizes were positive for seven of the eight cases. Although the available data precludes any definitive interpretation as to the cause of the increases in largemouth bass catch rates, recent research and past studies implicate three likely candidate causes for this observation. In a recent pond study the presence of muskellunge lead to increased growth of largemouth bass when controlling for predator densities and biomass (Carey and Wahl 2010). Laboratory observations indicated that this effect was likely due to a facilitative interaction between largemouth bass and muskellunge when foraging on shared prey (Carey and Wahl 2011). Such facilitative interactions have been documented among other piscivorous predators and are known to increase population growth rates of the benefiting predator (Eklov and VanKooten 2001; Schulze et al. 2006). These observations may offer an explanation for the numerical response of largemouth bass to muskellunge introduction. Alternatively, studies involving the introduction of new predator types often result in shifts in habitat utilization of resident predators (Werner and Hall 1977). For example, the introduction of pikeperch (*Sander lucioperca)* to a European lake resulted in increased use of the littoral zone by resident piscivorous perch (*Perca fluviatilis*). A similar effect might be expected in largemouth bass as they reach smaller adult sizes than muskellunge and body size is a known determinant of intra-guild competitive interactions (Fedriani et al. 2000). If competition with adult muskellunge caused largemouth bass to increase their utilization of littoral areas we would expect electrofishing catch rates to increase as this gear primarily indexes the littoral zone. A third hypothesis for the observed increase in largemouth bass relative abundance may be that lakes targeted for muskellunge introduction may be selected non-randomly by biologists undertaking active management to increase largemouth bass populations. Because these lakes may have been selected non-randomly it is possible that alternative management activities may have contributed to the improvement of largemouth bass populations in lakes where muskellunge were introduced. Nevertheless our results suggest that muskellunge introduction is not a significant barrier to improving largemouth bass populations. A growing body of research supports a need to further explore interactions between largemouth bass and muskellunge at the lake scale to determine mechanisms by which these two species interact.

With the exception of largemouth bass the only other species exhibiting consistent responses to muskellunge introduction in our study lakes were black and white crappie. These results are consistent with one of the few previous studies examining responses of lake fish communities to muskellunge introduction, which implicated predatory effects on crappie populations (Siler and Bayerle 1986). Furthermore, responses of crappie population characteristics including increased size structure and decreased relative abundance are consistent with predictions of a direct predatory effect. Several previous studies have implicated a role of predators including largemouth bass, northern pike (*Esox luscious)* and saugeye (*Sander vitreus x Sander canadense)* in regulating crappie abundance and size structure (Gabelhouse 1984; Willis et al. 1984; Boxrucker 2002; Galinet et al. 2002). The response of crappie populations to muskellunge introduction are in contrast to those of the other sunfishes in our lakes posing a question as to why crappie populations may be more sensitive to this predator. We can only speculate as to the potential explanations for this disparity in responses between species however previous research has suggested differences in habitat selection and diel movements between crappie and other sympatric sunfishes (Keast et al. 1992), which may alter the likelihood of interactions with muskellunge. These differences in movement and habitat selection may result in greater predation on these species during mid-summer and mid-winter seasons not well represented by our diet data. Regardless of the potential causes of differing responses among species our results may be of particular interest in crappie management of lower latitude lakes where the development of high density, slow growing populations comprised of smaller individuals is a common problem (Mitzner 1984). Our results suggest muskellunge may influence abundance and size structure of crappie populations however we caution that these results are based on findings from a limited number of lake pairs and a limited number of years post introduction. Further study will be required to determine the generality of these findings, long-term responses and potential mechanisms governing interactions among crappie populations and introduced muskellunge.

With the exception of crappie populations we found little evidence for predatory impacts of introduced muskellunge on important prey species in these systems including bluegills, redear sunfish and gizzard shad. We found evidence for a potentially strong positive interaction between introduced muskellunge and largemouth bass populations when generalizing across eight Illinois lakes, which we feel warrant further study of the interactions between these species. In addition we found evidence that muskellunge may influence the size structure and/or abundance of crappie populations although these findings are from a smaller number (four) of lakes systems. The known preference for muskellunge to consume gizzard shad combined with the lack of population responses by this species suggests that muskellunge may be utilizing an abundant and potentially underutilized forage base in these systems. While we feel this study represents a valuable first step in exploring fish community responses of lower Midwestern lakes to muskellunge introduction we urge that more research will be necessary to validate the generality of these findings. As the introduction of muskellunge into systems outside its native range continues there is a particular need for longer-term assessments of the effects of this introduced predator as well as a need to evaluate responses of other potentially important fishes not evaluated here.

Job 101.4. Analysis and reporting.

OBJECTIVE: To prepare annual and final reports summarizing information and develop guidelines for proper selection of muskellunge populations for stocking in Illinois impoundments.

PROCEDURES and FINDINGS: Data collected in Jobs 101.1 – 101.3 were analyzed to develop guidelines regarding appropriate muskellunge populations for stocking throughout Illinois. Recommendations were made that will allow hatchery and management biologists to make decisions that will maximize benefits for the muskellunge program in Illinois (See Jobs 1-3).

BUDGET TABLE:

Project Segment 10

Job	Proposed Cost	Actual Cost
Job 101.1	$38,992	$38,992
Job 101.2	$38,992	$38,992
Job 101.3	$28,929	$28,929
Job 101.4	$18,867	$18,867

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Table 1. Mean total lengths (mm) and wet weights (g) of three stocks (OH: Ohio River drainage stock, MISS: Upper Mississippi River drainage stock, IL: Illinois population) of age-0 muskellunge introduced in equal numbers into each of three 0.4 ha experimental ponds (three ponds for each trial) at the Sam Parr Biological Station, Kinmundy, Illinois. Experiments were initiated in October or November of each year and ponds were drained the following spring (April) and fall (October) for each experiment. Standard deviations are in parentheses.

Trial and stock	Population	Total length	Wet weight	Number stocked/pond
Trial 1				
OH	Cave Run Lake, Kentucky	290.5 (20.4) y	94.7 (19.8) y	33
MISS	Leech Lake, Minnesota	279.9 (31.5) z	94.4 (35.2) y	33
IL	North Spring Lake, Illinois	353.2 (16.9) x	190.1 (32.7) x	33
Trial 2				
OH	Chautauqua Lake, New York	233.5 (9.5) z	50.7 (7.4) z	33
MISS	Minocqua Chain, Wisconsin	303.6 (12.7) y	136.7 (19.8) x	33
IL	North Spring Lake, Illinois	308.3 (17.2) x	128.4 (28.4) y	32[a]

[a] Thirty-two muskellunge were stocked into two ponds and 30 into the third pond.

Table 2. Sources of young-of-year muskellunge stocks used for evaluation of growth and survival. Kentucky, Ohio, Pennsylvania, and New York populations are from the Ohio River drainage (Ohio stock); Minnesota and Wisconsin populations are from the Upper Mississippi River drainage (Mississippi stock); St. Lawrence River muskellunge are from the Great Lakes drainage (Great Lakes stock). Cooling (CDD) and heating (HDD) degree days are calculated using a base temperature of 65° F, with 1961 - 1990 data from the National Oceanic and Atmospheric Administration, Midwest Climate Center, Pennsylvania State Climatologist, and the New York State Climate Office.

Population (abbreviation)	Source Water	Drainage (stock)	Latitude (north)	Cooling Degree Days (CDD)	Heating Degree Days (HDD)	Mean Annual Temp. (F)
Kentucky (KY)	Cave Run Lake	Ohio River	37° 35′	1154	4713	55.2
Ohio (OH)	Clear Fork Lake	Ohio River	39° 30′	703	6300	49.6
Pennsylvania (PA)	Pymatuning Reservoir	Ohio River	41° 30′	322	6934	47.4
New York (NY)	Lake Chautauqua	Ohio River	42° 07′	350	6279	49.4
St. Lawrence (SL)	St. Lawrence River	Great Lakes	42° 25′	551	6785	45.4
Wisconsin (WI)	Minocqua Chain	Mississippi River	45° 30′	215	9550	39.3
Minnesota (MN)	Leech Lake	Mississippi River	46° 35′	347	9495	39.9
Illinois (IL)	North Spring Lake	*	40° 40′	998	6097	50.8

Table 3. Stocking summary of muskellunge populations from the Upper Mississippi River drainage (MISS), Ohio River drainage (OH), and North Spring Lake, IL progeny (IL) introduced in Pierce Lake, Lake Mingo and Sam Dale Lake during falls 2005-2008. Adjusted number of fish and number per hectare account for initial mortality as determined by mortality cage estimates. Total length (nearest mm) and weight (nearest g) were measured prior to stocking. Values in parentheses represent 95% confidence intervals.

Lake	Stock	Population	Stocking Date	Number of Fish		Number per Hectare		Mean Length (mm)	Mean Weight (g)
				Stocked	Adjusted	Stocked	Adjusted		
			2005						
Pierce	MISS	Leech Lake, MN	October 10, 2005	166	154	2.7	2.5	235 (±5.1)	50 (±3.7)
	OH	Clear Fork Lake, OH	September 24, 2005	302	161	4.9	2.6	261 (±4.1)	75 (±3.8)
	IL	North Spring Lake, IL	August 31, 2005	300	300[†]	4.9	4.9	270 (±4.6)	87 (±5.1)
Mingo	MISS	Leech Lake, MN	October 11, 2005	193	186	2.7	2.6	233 (±5.5)	48 (±3.8)
	OH	Chautauqua Lake, NY	September 28, 2005	196	196	2.7	2.7	234 (±3.7)	45 (±2.3)
	IL	North Spring Lake, IL	August 30, 2005	325	325	4.5	4.5	267 (±4.8)	79 (±5.8)
Sam Dale	MISS	Leech Lake, MN	November 16, 2005	192	185	2.4	2.4	255 (±5.9)	57 (±4.9)
	OH	Cave Run Lake, KY	August 19, 2005	306	10[‡]	3.9	0.1	232 (±5.0)	56 (±3.5)
	OH	Clear Fork Lake, OH	September 23, 2005	306	115[‡]	3.9	1.5	261 (±4.1)	75 (±3.8)
	IL	North Spring Lake, IL	August 31, 2005	300	186	3.8	2.4	273 (±4.1)	88 (±5.2)

Table 3. Continued.

Lake	Stock	Population	Stocking Date	Number of Fish		Number per Hectare		Mean Length (mm)	Mean Weight (g)
				Stocked	Adjusted	Stocked	Adjusted		
			2006						
Pierce	IL	North Spring Lake, IL	August 23, 2006	303	303[†]	5.0	5.0	286 (±6.3)	116 (±8.8)
Mingo	OH	Cave Run Lake, KY	August 16, 2006	332	192	4.6	2.7	244 (±5.3)	66 (±5.9)
	IL	North Spring Lake, IL	August 23, 2006	302	282	4.2	3.9	281 (±7.6)	112 (±10.1)
Sam Dale	IL	North Spring Lake, IL	August 23, 2006	303	20	3.9	0.3	278 (±7.2)	106 (±10.0)

Table 3. Continued.

Lake	Stock	Population	Stocking Date	Number of Fish Stocked	Number of Fish Adjusted	Number per Hectare Stocked	Number per Hectare Adjusted	Mean Length (mm)	Mean Weight (g)
			2007						
Pierce	MISS	Leech Lake, MN	November 29, 2007	250	250	4.1	4.1	325 (±7.2)	153 (±10.9)
	OH	Clear Fork Lake, OH	September 27, 2007	263	263	4.3	4.3	234 (±5.4)	55 (±4.3)
	IL	Spirit Lake, IA*	September 13, 2007	300	300	4.9	4.9	285 (±4.2)	125 (±6.0)
Mingo	MISS	Leech Lake, MN	November 30, 2007	270	270	3.8	3.8	326 (±7.6)	155 (±11.5)
	OH	Cave Run Lake, KY	August 2, 2007	397	267	5.5	3.7	231 (±4.0)	54 (±2.8)
	IL	Spirit Lake, IA*	September 13, 2007	300	293	4.2	4.1	286 (±3.7)	126 (±5.5)
Sam Dale	MISS	Leech Lake, MN	November 30, 2007	260	260	3.3	3.3	325 (±7.6)	156 (±11.5)
	OH	Clear Fork Lake, OH	September 27, 2007	318	312	4.1	4.0	232 (±5.2)	54 (±4.1)
	IL	Spirit Lake, IA*	September 13, 2007	300	300[†]	3.8	3.8	284 (±4.0)	124 (±5.7)

Table 3. Continued.

Lake	Stock	Population	Stocking Date	Number of Fish		Number per Hectare		Mean Length (mm)	Mean Weight (g)
				Stocked	Adjusted	Stocked	Adjusted		
			2008						
Sam Dale	MISS	Leech Lake, MN	November 19, 2008	257	257	3.3	3.3	217 (±5.4)	40 (±3.2)
	OH	Cave Run Lake, KY	November 18, 2008	193	193	2.5	2.5	338 (±7.3)	174 (±14.2)
	IL	North Spring Lake, IL	August 24, 2008	300	300	3.8	3.8	290 (±5.8)	119 (±7.9)

[†] Mortality cages not utilized due to logistical constraints

*Eggs obtained from Iowa Department of Natural Resources and reared at the Jake Wolf Fish Hatchery, Illinois Department of Natural Resources

Table 4. Analysis-of-variance type III tests of the fixed main effect of stock on relative daily growth rates of three stocks (OH: Ohio River drainage stock, MISS: Upper Mississippi River drainage stock, IL: Illinois population) of age-0 muskellunge introduced into Mingo and Pierce Lakes, Illinois, during fall 2003-2007 and Sam Dale Lake 2005-2008. The overwinter period represents the 6 months following stocking and age-1 fall represents one year after stocking.

Lake	Stocking year class	Time period	Num *DF*	Den *DF*	F	P
Mingo	2003	Overwinter	2	61	1.07	0.35
Mingo	2004	Overwinter	2	60	57.77	<0.0001
Mingo	2005	Overwinter	2	11	5.94	0.018
Mingo	2006	Overwinter	.	.	.	.
Mingo	2007	Overwinter	2	26	0.21	0.81
Mingo	2003	Age-1 Fall	1	16	1.05	0.32
Mingo	2004	Age-1 Fall	.	.	.	.
Mingo	2005	Age-1 Fall	.	.	.	.
Mingo	2006	Age-1 Fall	.	.	.	.
Mingo	2007	Age-1 Fall	.	.	.	.
Pierce	2003	Overwinter	2	19	13.21	0.0003
Pierce	2004	Overwinter	2	23	13.93	0.0001
Pierce	2005	Overwinter	2	31	5.01	0.013
Pierce	2006	Overwinter	.	.	.	.
Pierce	2007	Overwinter	2	7	1.30	0.33
Pierce	2003	Age-1 Fall	1	7	0.07	0.80
Pierce	2004	Age-1 Fall	1	5	0.39	0.56
Pierce	2005	Age-1 Fall	2	7	0.05	0.95
Pierce	2006	Age-1 Fall	.	.	.	.
Pierce	2007	Age-1 Fall	.	.	.	.
Sam Dale	2005	Overwinter	.	.	.	.
Sam Dale	2006	Overwinter	.	.	.	.
Sam Dale	2007	Overwinter	1	4	22.64	0.04
Sam Dale	2008	Overwinter	.	.	.	.
Sam Dale	2005	Age-1 Fall	.	.	.	.
Sam Dale	2006	Age-1 Fall	.	.	.	.
Sam Dale	2007	Age-1 Fall	.	.	.	.
Sam Dale	2008	Age-1 Fall	2	14	13.4	0.0006

Table 5. Comparisons of mean length-at-age and weight-at-age of adult muskellunge from three stocks introduced into Lake Mingo stratified by gender. Means are estimated from pooled data from spring samples taken during 2003-2011. Lower case letters denote statistical differences following Tukey's means separation. Values in parentheses represent 95% confidence intervals.

Sex	Age	Mississippi River Drainage	Ohio River Drainage	Illinois	P Value
Length					
Combined	2	449 (±0)^{a}	605 (±13)^{b}	628 (±11)^{b}	<0.01
Male	3	782 (±57)	756 (±10)	772 (±8)	0.05
	4	-	845 (±14)	840 (±12)	0.57
	5	-	910 (±17)^{a}	883 (±17)^{b}	0.02
	6	-	900 (±0)	921(±38)	0.60
	7	-	945 (±38)	-	-
Female	3	-	790 (±29)	784 (±10)	0.77
	4	-	885 (±27)	882 (±17)	0.83
	5	909 (±0)	963 (±18)	962 (±14)	0.25
	6	962 (±0)	967 (±139)	1005 (±111)	0.75
	7	-	-	1068 (±0)	-
Weight					
Combined	2	480 (±0)^{a}	1519 (±112)^{b}	1740 (±96)^{b}	<0.01
Male	3	3680 (±762)	3283 (±162)	3428 (±128)	0.28
	4	-	4712 (±222)	4562 (±99)	0.32
	5	-	5941 (±362)	5424 (±387)	0.06
	6	-	6350 (±0)	5778 (±567)	0.37
	7	-	6150 (±225)	-	-
Female	3	-	3669 (±457)	3871 (±332)	0.47
	4	-	6033 (±475)	5634 (±274)	0.15
	5	5880 (±0)	7448 (±574)	7294 (±434)	0.32
	6	6190 (±0)	6940 (±2723)	8171 (±2424)	0.40
	7	-	-	9650 (±0)	-

Table 6. Parameter estimates and 95% confidence intervals of Von Bertalanffy growth functions fitted to pooled length-at-age data from three stocks of muskellunge introduced into Lake Mingo and Pierce Lake 2002-2012 stratified by gender. Upper Mississippi River drainage parameters estimates were calculated by combining genders.

Strain/ Sex	N	L∞ (mm)	95% C.I. Limit Upper	95% C.I. Limit Lower	K	95% C.I. Limit Upper	95% C.I. Limit Lower
Lake Mingo							
Illinois							
Male	310	927	908	945	0.64	0.59	0.69
Female	224	1094	1051	1138	0.42	0.37	0.47
Ohio							
Male	186	999	963	1035	0.50	0.44	0.55
Female	128	1080	1029	1132	0.45	0.39	0.52
Mississippi	74	1074	902	1206	0.41	0.27	0.55
Pierce Lake							
Illinois							
Male	294	951	925	978	0.48	0.43	0.53
Female	135	1070	1022	1118	0.40	0.34	0.45
Ohio							
Male	98	934	904	964	0.52	0.45	0.59
Female	58	1038	951	1126	0.43	0.30	0.56
Mississippi	45	1016	878	1155	0.47	0.27	0.67

Table 7. Comparisons of mean length-at-age and weight-at-age of adult muskellunge from three stocks introduced into Pierce Lake stratified by gender. Means are estimated from pooled data from spring samples taken during 2003-2012. Lower case letters denote statistical differences following Tukey's means separation. Values in parentheses represent 95% confidence intervals.

Sex	Age	Mississippi River Drainage	Ohio River Drainage	Illinois	P Value
			Length		
Combined	2	-	511 (±75)	578 (±31)	0.10
Male	3	695 (±47)	711 (±17)	772 (±8)	0.27
	4	859 (±41)[a]	805 (±16)[b]	801 (±8)[b]	0.02
	5	863 (±50)	852 (±16)	871 (±10)	0.12
	6	937 (±52)	885 (±20)	886 (±16)	0.15
	7	-	-	-	-
Female	3	-	680 (±48)[a]	758 (±27)[b]	0.01
	4	-	871 (±31)	844 (±13)	0.11
	5	-	910 (±27)	924 (±16)	0.36
	6	-	941 (±37)	968 (±45)	0.23
	7	-	998 (±0)	999 (±31)	0.98
			Weight		
Combined	2	-	839 (±595)	1266 (±330)	0.22
Male	3	2240 (±656)	2576 (±233)	2653 (±109)	0.41
	4	4422 (±711)	4021 (±274)	3779 (±132)	0.08
	5	4450 (±0)	4622 (±482)	4981 (±287)	0.41
	6	5690 (±0)	5439 (±536)	5133 (±438)	0.61
	7	-	-	-	-
Female	3	-	2175 (±882)[a]	3356 (±456)[b]	0.02
	4	-	5122 (±537)	4844 (±213)	0.33
	5	-	5882 (±666)	6380 (±389)	0.20
	6	-	6743 (±908)	7086 (±1138)	0.62
	7	-	7920 (±0)	8608 (±1719)	0.61

Table 8. Comparisons of mean length-at-age and weight-at-age of adult muskellunge from three stocks introduced into Sam Dale Lake stratified by gender. Means are estimated from pooled data from spring samples taken in 2010 and 2011. Lower case letters denote statistical differences following Tukey's means separation. Values in parentheses represent 95% confidence intervals.

Sex	Age	Mississippi River Drainage	Ohio River Drainage	Illinois	P Value
		Length			
Combined	2	702 (±0)[a]	622 (±19)[b]	662 (±13)[ab]	<0.01
Male	3	753 (±42)	759 (±12)	764 (±10)	0.70
	4	-	835 (±19)[a]	799 (±22)[b]	0.01
	5	-	871 (±0)	-	-
Female	3	817 (±36)	793 (±15)	821 (±10)	0.05
	4	964 (±58)[a]	908 (±24)[ab]	893 (±13)[b]	0.04
	5	-	975 (±0)	910 (±0)	-
		Weight			
Combined	2	2910 (±0)[a]	1752 (±214)[b]	2182 (±153)[ab]	<0.01
Male	3	2665 (±665)	3284 (±196)	3390 (±159)	0.10
	4	-	4520 (365)[a]	3396 (±524)[b]	<0.01
	5	-	5160 (±0)	-	-
Female	3	3750 (±1383)	3858 (±335)	4485(±227)	0.05
	4	7140 (±0)	6231 (±490)	5751 (±400)	0.19
	5	-	7750 (±0)	7550 (±0)	-

Table 9. Adjusted catch-per-unit effort from spring and fall electrofishing surveys and statistical comparisons for the OH: Ohio River drainage stock, MISS: Upper Mississippi River drainage stock, IL: Illinois population of age-0 muskellunge introduced into Mingo and Pierce Lakes, Illinois, during fall 2003-2007 and Sam Dale Lake 2005-2008. The overwinter period represents the 6 months following stocking and age-1 fall represents one year after stocking. Letters represent significant differences following Tukey's means separation.

				Adjusted CPUE			
Lake	Stocking year class	Time period	Effort (hr)	Miss	OH	IL	P
Mingo	2003	Overwinter	21.0	2.28	3.83	3.53	0.47
Mingo	2004	Overwinter	28.4	6.30^{a}	3.11^{ab}	2.43^{b}	0.031
Mingo	2005	Overwinter	11.1	2.45	1.35	1.43	0.99
Mingo	2006	Overwinter	15.8	0	0.79^{a}	4.67^{b}	0.01
Mingo	2007	Overwinter	6.5	24.99^{a}	3.81^{b}	8.02^{b}	0.01
Mingo	2003	Age-1 Fall	22.6	0	1.26^{a}	0.74^{b}	0.014
Mingo	2004	Age-1 Fall	17.7	0.46	0	0.34	0.49
Mingo	2005	Age-1 Fall	15.7	0	0	0.75	.
Mingo	2006	Age-1 Fall	10.8	NA	0	0.67	.
Mingo	2007	Age-1 Fall	7.7	0	0	0.78	.
Pierce	2003	Overwinter	16.5	2.92	3.33	0.74	0.22
Pierce	2004	Overwinter	26.0	1.77	1.08	1.10	0.79
Pierce	2005	Overwinter	15.6	8.53	1.55	1.86	0.078
Pierce	2006	Overwinter	11.3	0	0	1.94	.
Pierce	2007	Overwinter	8.7	4.5	1.96	0.67	0.18
Pierce	2003	Age-1 Fall	17.6	0	0.55^{a}	0.98^{b}	0.05
Pierce	2004	Age-1 Fall	18.1	0	1.20^{a}	0.37^{b}	0.05
Pierce	2005	Age-1 Fall	13.8	0.39	0.94	1.72	0.41
Pierce	2006	Age-1 Fall	10.1	NA	NA	3.04	.
Pierce	2007	Age-1 Fall	6.6	0	0	0.76	.
Sam Dale	2005	Overwinter	12.5	0	0	0	.
Sam Dale	2006	Overwinter	2.33	0	0	0	.
Sam Dale	2007	Overwinter	6.2	2.50	0	2.17	0.62
Sam Dale	2008	Overwinter	8.2	0	0.24	0.12	0.51
Sam Dale	2005	Age-1 Fall	0	0	0	0	.
Sam Dale	2006	Age-1 Fall	0	NA	NA	0	.
Sam Dale	2007	Age-1 Fall	10.56	0	0	0.56	.
Sam Dale	2008	Age-1 Fall	9.55	0.54	0.90	1.78	0.18

Table 10. Adjusted catch-per-unit effort from spring trap netting surveys and statistical comparisons of survival to adulthood (Age-3) by year class of the Upper Mississippi River drainage stock, Ohio River drainage stock, and Illinois population of muskellunge sampled from Mingo and Pierce Lakes, Illinois, during spring 2005-2010. 95% confidence limits are in parenthesis and letters represent significant differences following Tukey's means separation.

	Year Class	Mississippi River Drainage	Ohio River Drainage	Illinois Population	P Value
Mingo	2002	NA	1.34	0.76	
	2003	0.00	0.71	0.47	
	2004	0.09	2.35	1.06	
	2005	0.10	1.44	1.04	
	2006	NA	0.37	0.89	
	2007	0.00	0.09	1.07	
	Mean	0.05 (±0.05)^{b}	1.05 (±0.73)^{a}	0.88 (±0.21)^{ab}	0.03
Pierce	2003	0.00	0.00	0.00	
	2004	0.00	0.69	1.11	
	2005	0.00	4.09	2.26	
	2006	NA	NA	1.35	
	2007	0.17	0.49	2.41	
	Mean	0.04 (±0.10)	1.32 (±2.21)	2.41 (±0.96)	0.23
Sam Dale	2007	0.14	0.73	1.48	
	2008	0.04	0.58	0.61	
	Mean	0.09 (±0.10)	0.66 (±0.15)	1.05 (±0.85)	0.16

Table 11. Catch-per-unit effort (number per net night) from spring fyke net surveys conducted 2007-2010 and annual survival estimates for adult muskellunge introduced into Lake Mingo by age class. Estimates of annual survival are for the time period between successive spring fyke net surveys. Numbers in parentheses represent 95% confidence intervals.

Age	2007 CPUE	Survival	2008 CPUE	Survival	2009 CPUE	Survival	2010 CPUE	Survival	2011 CPUE
					Illinois Population				
3	0.31		0.32		0.24		0.31		
		0.97		0.61		0.59		1.00	
4	0.24		0.30		0.20		0.14		0.39
		0.47		0.35		0.41		1.00	
5	0.09		0.11		0.11		0.08		0.17
		0.22		0.00		0.19		0.63	
6+	-		0.02		0.00		0.02		0.05
		-		-		-			
Mean		0.55 (±0.40)		0.32 (±0.35)		0.40 (±0.22)		0.88 (±0.24)	
					Ohio River Drainage				
3	0.35		0.28		0.04		0.02		
		0.60		0.05		1.00		1.00	
4	0.16		0.21		0.01		0.06		0.02
		0.61		0.19		1.00		1.00	
5	0.21		0.09		0.04		0.01		0.22
		0.09		0.35		0.00		1.00	
6+	-		0.02		0.04		0.00		0.01
		-		-		-		-	
Mean		0.43 (±0.33)		0.19 (±0.17)		0.67 (±0.65)		1.00 (±0)	

Table 12. Catch-per-unit effort (number per net night) from spring fyke net surveys conducted 2007-2012 and annual survival estimates for adult muskellunge introduced into Pierce Lake by age class. Estimates of annual survival are for the time period between successive spring fyke net surveys. Numbers in parentheses represent 95% confidence intervals.

Age	2008 CPUE	Survival	2009 CPUE	Survival	2010 CPUE	Survival	2011 CPUE	Survival	2012 CPUE
					Illinois Population				
3	1.28		0.34		0.72		-		
		0.39		1.00		0.49		-	
4	0.36		0.50		0.65		0.35		-
		0.44		0.46		0.43		0.54	
5	0.59		0.16		0.23		0.28		0.19
		0.31		0.13		1.00		0.00	
6+	-		0.18		0.02		0.55		0.00
Mean		0.39 (±0.08)		0.53 (±0.22)		0.64 (±0.36)		0.27 (±0.53)	
					Ohio River Drainage				
3	0.36		-		0.13		-		
		0.75		-		1.00		-	
4	0.23		0.27		-		0.60		-
		0.30		1.00		-		0.13	
5	0.27		0.07		0.45		-		0.08
		0.42		1.00		1.00		-	
6+	-		0.11		0.09		0.60		-
Mean		0.49 (±0.17)		1.00 (±0)		1.00 (±0)		0.13 (±0)	

Table 13. Catch-per-unit effort (number per net night) from spring fyke net surveys conducted 2010-2012 and annual survival estimates for adult muskellunge introduced into Lake Sam Dale by age class. Estimates of annual survival are for the time period between successive spring fyke net surveys. Numbers in parentheses represent 95% confidence intervals.

Age	2010 CPUE	Survival	2011 CPUE	Survival	2012 CPUE
		Illinois Population			
3	1.48		0.61		-
		0.26		0.08	
4	-		0.39		0.05
		-		0.03	
5	-		-		0.01
Mean		0.26 (±0)		0.05 (±0.05)	
		Ohio River Drainage			
3	0.73		0.58		-
		0.33		0.08	
4	-		0.24		0.05
		-		0.08	
5	-		-		0.02
Mean		0.33 (±0)		0.08 (±0)	
		Upper Mississippi Drainage			
3	0.14		0.04		
		0.14		0.0	
4	-		0.02		0.0
		-		0.0	
5	-		-		0.0
Mean		0.14 (±0)		0.0 (±0)	

Table 14. Years of available data and muskellunge stocking density, relative abundance and size structure from electrofishing (EF) and fyke net (Net Night) surveys conducted on stocked and control systems before and after muskellunge introduction in 8 Illinois lakes (column headings). Values for stocking density, catch rates, and size structure represent means from the period after initial muskellunge introduction while values in parentheses represent ranges (min-max) from the same period.

Treatment Lake	Argyle Lake	Johnson Lake	Mill Creek Lake	Lake Mingo	Ridge Lake	Sauk Trail Lake	Shovel Lake
Control Lake	Lake Jacksonville	Lake Springfield	Lincoln Trail Lake	Homer Lake	Walnut Point Lake	Lake Le-aqua-na	Lake Lou Yeager
Years Before	1991,1995,1997 1998, 2000	1994-1997 1999-2001	1983-1992	1998-2002	1998,1999 2001-2005	1988,1989 1991-2000	1996-1999
Years After	2002, 2005-2007	2003-2007	1997,2001 2005,2007	2003-2008	2006-20010	2001-2007	2000,2002 2003,2006
Years Stocked	2000,2002-2003 2006-2007	2001-2003 2005-2007	1999-2003 2005-2007	2002-2008	2005-20010	2000-2002 2006-2007	1999,2000,2001-2003 2005-2007
MUE Stocking Density	6.15 (2.85-9.20)	4.16 (2.47-9.05)	1.11 (1.11-1.12)	7.20 (2.47-14.06)	11.08 (7.27-14.53)	3.11 (2.47-4.94)	2.50 (2.47-2.69)
Mean MUE Per Net Night	1.29	1.11 (0.81-1.38)	no data	1.33 (0.75-1.77)	0.64 (0.57-1.12)	1.03 (0.25-2.00)	1.77 (0.5-4.25)
Mean MUE EF CPUE	1	1.06(0.85-1.4)	1.11(0.35-2)	2.85(2.00-4.00)	1.95(1.28-2.86)	3.03	1.63(0.74-5.2)
Mean MUE PSD	83	39.55 (9.5-69.6)	no data	64.5 (56-77)	100	83.33 (50-100)	57.67 (35-74)

Table 15. Species population metrics, mean relative effect sizes, standard errors and results of meta-analysis across 8 Illinois lake pairs evaluated for effects of muskellunge introduction.

Parameter	Mean Relative Effect Size (SE)	DF	Paired t	P
LMB CPUE	22.30(6.83)	7	3.26	**0.01**
LMB PSD	-0.46(6.05)	7	-0.08	0.94
LMB RSDP	6.26(6.88)	7	0.91	0.39
LMB WR	0.33(1.35)	7	0.25	0.81
BLG CPUE	1.85(7.39)	7	0.25	0.81
BLG PSD	1.85(7.34)	7	0.25	0.81
BLG WR	-2.43(1.52)	6	-1.59	0.16
GZS CPUE	-0.85(4.41)	4	-0.19	0.86
GZS PSD	1.88(3.19)	4	0.59	0.59
GZS WR	2.04(3.05)	4	0.67	0.54
CAP CPUE	-1.44(1.13)	1	-1.27	0.42
CAP PSD	1.71(5.37)	1	0.32	0.8
CAP WR	-6.59(1.69)	1	3.89	0.16
RSF CPUE	-2.92(1.14)	2	2.55	0.13
RSF PSD	.	0	.	.
RSF WR	2.40(1.76)	2	1.36	0.31
BLC CPUE	2.35(2.84)	3	0.83	0.47
BLC PSD	22.92(17.28)	3	1.33	0.28
BLC RSDP	10.88(2.95)	3	3.68	**0.03**
BLC WR	3.05(4.13)	3	0.74	0.43
WHC CPUE	-6.35(0.04)	1	173.94	**<0.01**
WHC PSD	23.07(10.10)	1	2.29	0.26
WHC RSDP	4.71(4.77)	1	4.71	0.13
WHC WR	6.19(3.07)	1	2.01	0.29

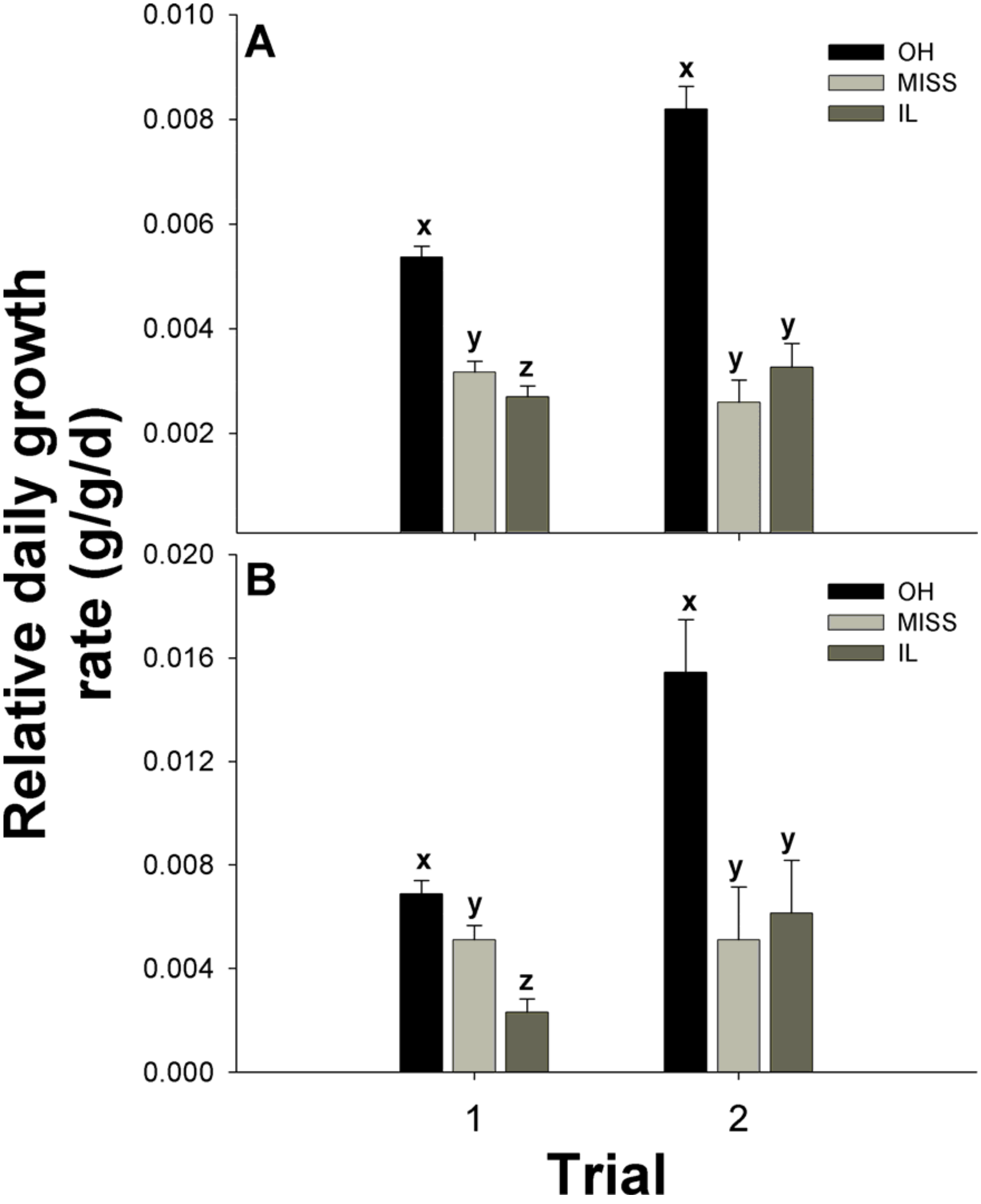

Figure 1. Spring (A) and fall (B) relative daily growth rates (g/g/d) of three stocks (OH: Ohio River drainage stock, MISS: Upper Mississippi River drainage stock, IL: Illinois population) of age-0 muskellunge introduced into three 0.4 ha experimental ponds (for each trial) during the fall at the Sam Parr Biological Station, Kinmundy, Illinois. Spring growth rates represent the overwinter period and fall represents one year after stocking. Vertical lines represent ± 1 standard error and, within a trial, bars with different letters are significantly different ($P < 0.05$) by comparison of least squares means and Tukey's means separation.

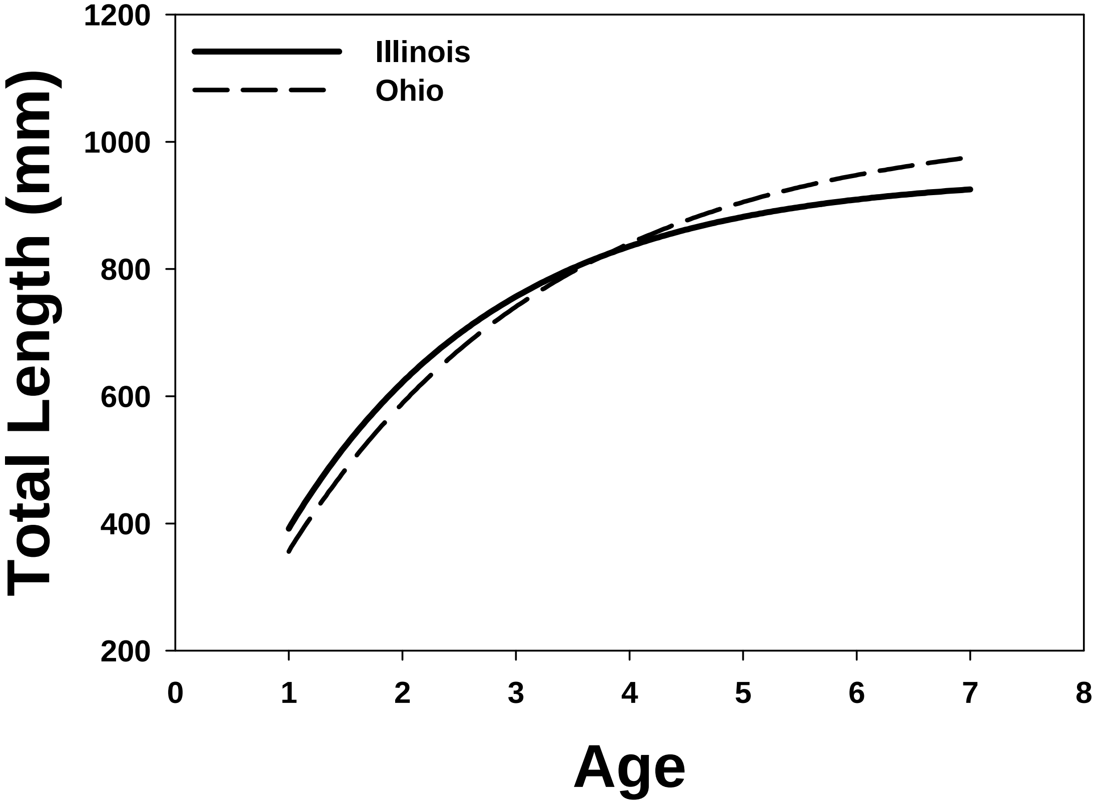

Figure 2. Fitted von Bertalanffy growth functions for male muskellunge from the Illinois population (solid line) and the Ohio River drainage stock (dashed line) sampled in Lake Mingo from fall 2003 through spring 2012.

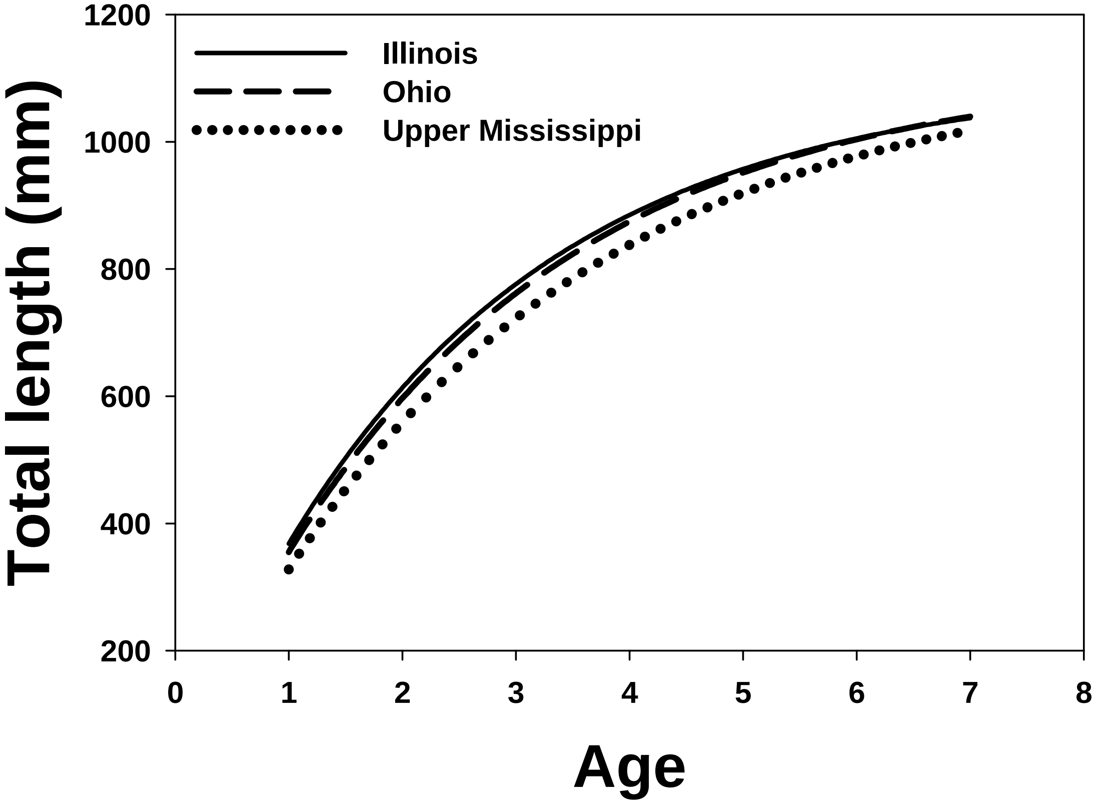

Figure 3. Fitted von Bertalanffy growth functions for female muskellunge from the Illinois population (solid line) the Ohio River drainage stock (long dashed line) and the Upper Mississippi River drainage stock sampled in Lake Mingo from fall 2003 through spring 2012. The growth function for the Upper Mississippi River drainage stock (short dashed line) was fit by pooling both genders due to low survival of this stock.

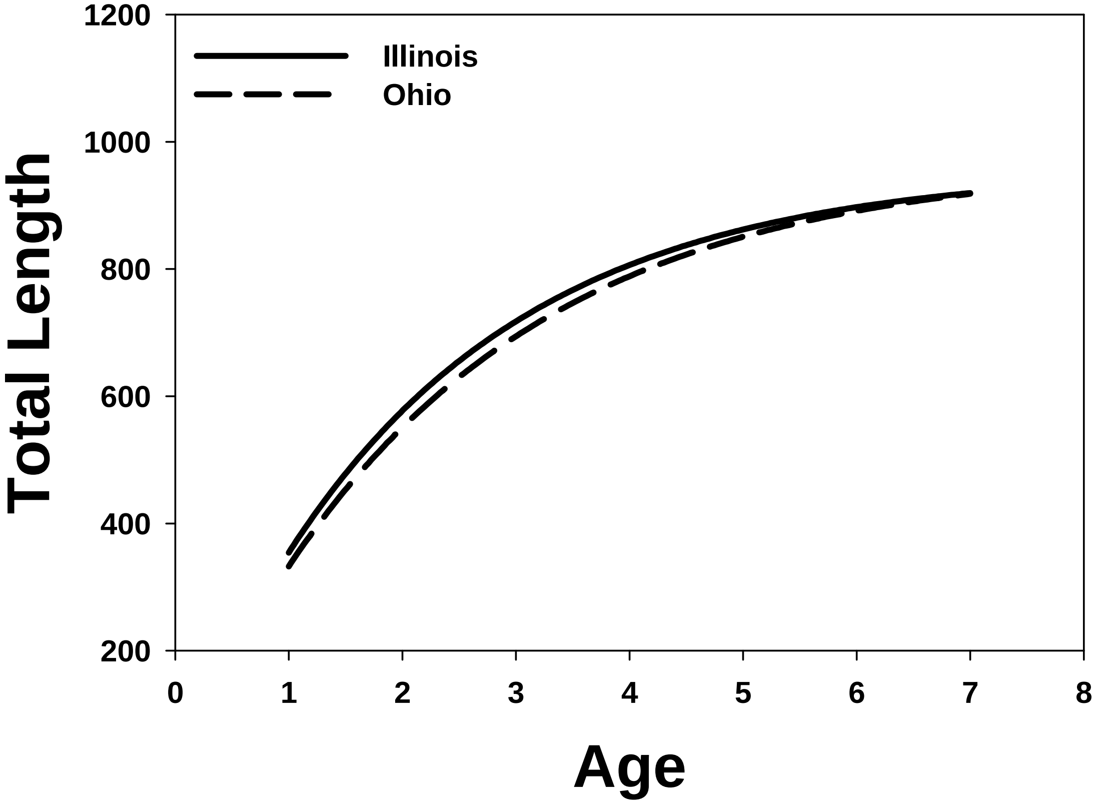

Figure 4. Fitted von Bertalanffy growth functions for male muskellunge from the Illinois population (solid line) and the Ohio River drainage stock (dashed line) sampled in Pierce Lake from fall 2004 through spring 2012.

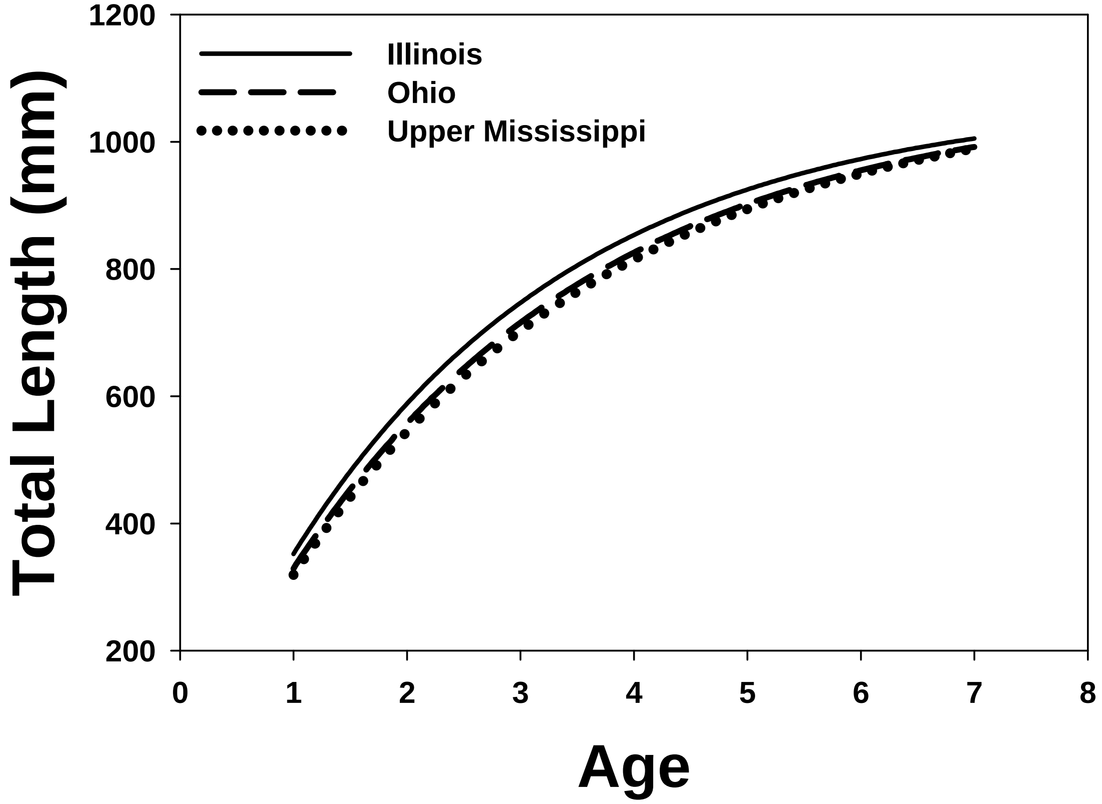

Figure 5. Fitted von Bertalanffy growth functions for female muskellunge from the Illinois population (solid line), the Ohio River drainage stock (long dashed line), and the Upper Mississippi river Drainage stock sampled in Pierce Lake from fall 2004 through spring 2012. The growth function for the Upper Mississippi River drainage stock (short dashed line) was fit by pooling both genders due to low survival of this stock.

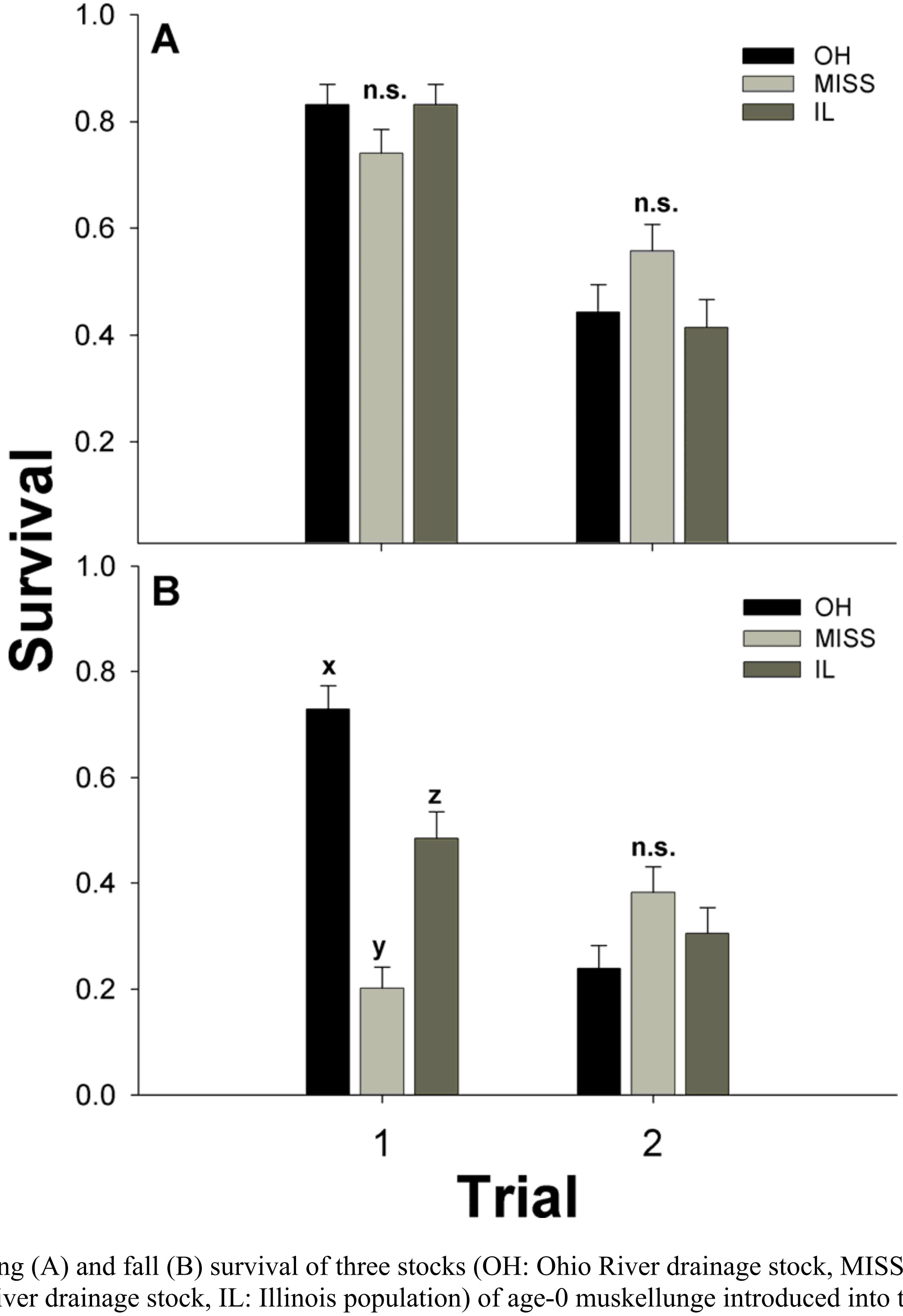

Figure 6. Spring (A) and fall (B) survival of three stocks (OH: Ohio River drainage stock, MISS: Upper Mississippi River drainage stock, IL: Illinois population) of age-0 muskellunge introduced into three 0.4 ha experimental ponds (for both trials) during the fall at the Sam Parr Biological Station, Kinmundy, Illinois. Spring survival represents the overwinter period and fall represents one year after stocking. Vertical lines represent ± 1 standard error and, within a trial, bars with different letters are significantly different ($P < 0.05$) by Bonferroni-adjusted pairwise comparisons.

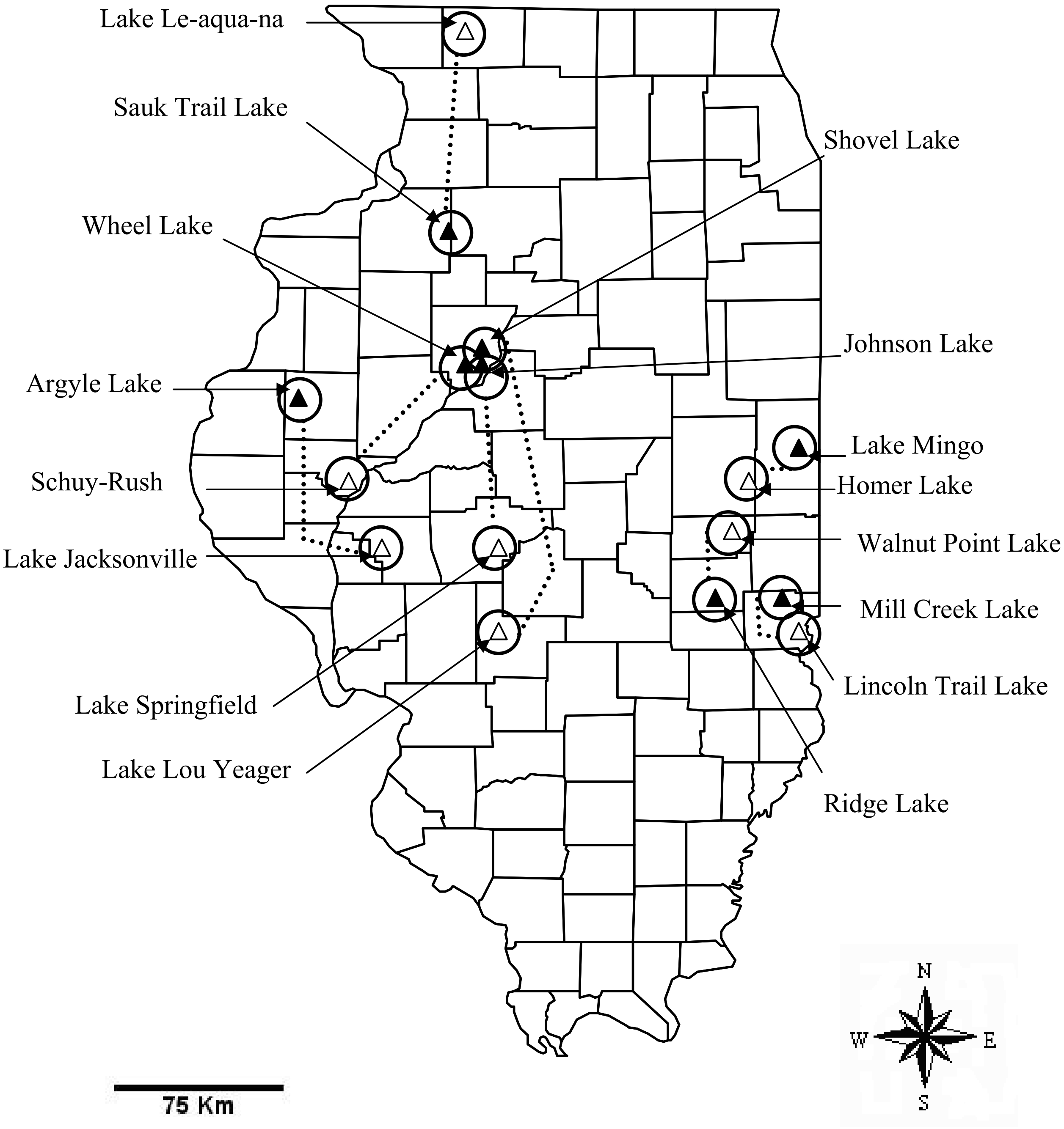

Figure 7. Locations of 16 spatially paired Illinois lakes used to evaluate effects of muskellunge (Esox masquinongy) introduction on population characteristics of resident fishes. Filled symbols were lakes stocked with muskellunge whereas open symbols were controls. Circles connected by dashed lines indicate specific lake pairings.

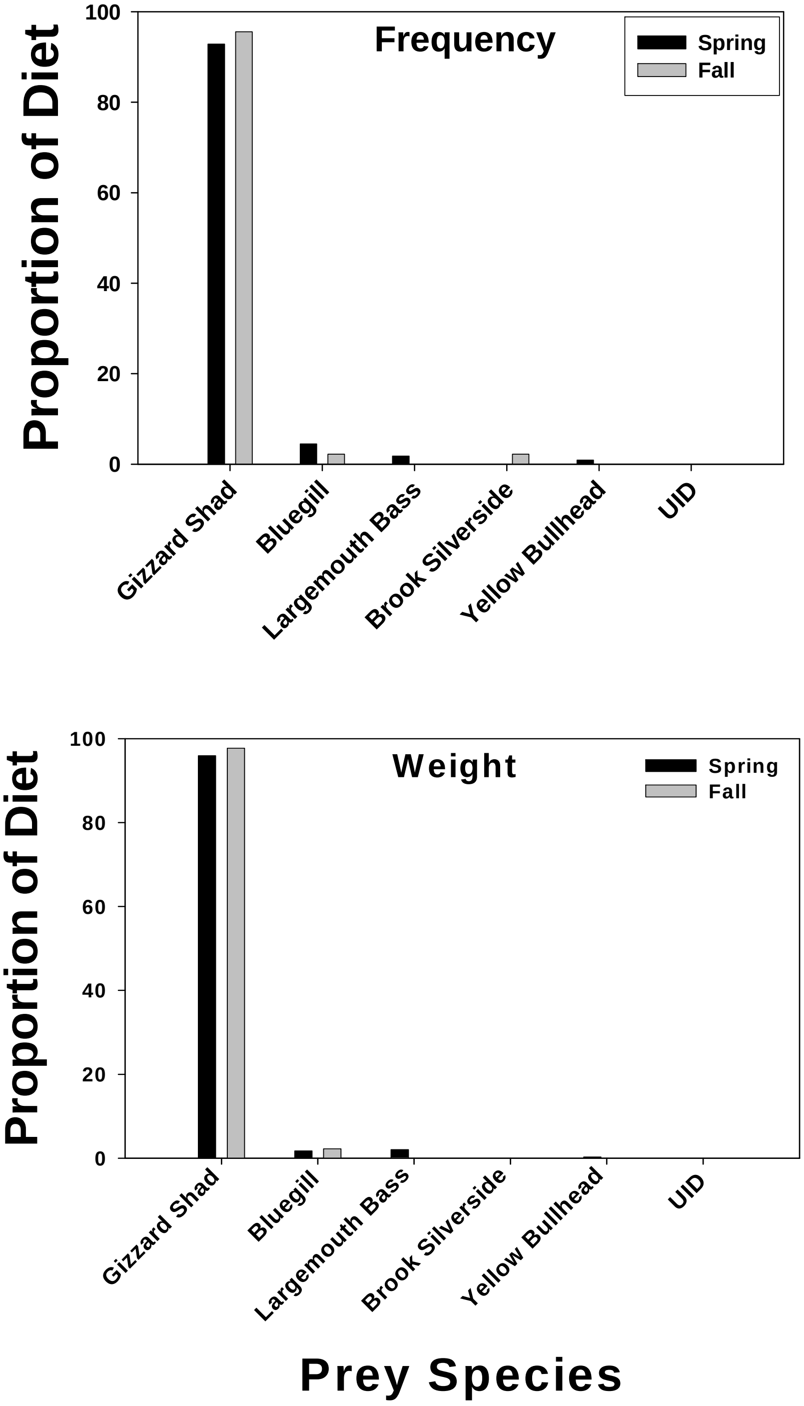

Figure 8. Diet composition of muskellunge sampled in Mingo Lake via trap netting and shoreline electrofishing, May 2007 – May 2012, by season. Spring is March, April, and May, while Fall is September, October, November. Data are pooled across years, upper panel shows diet by frequency of occurrence, lower shows proportion by wet weight. Proportions of diet by wet weight and frequency are transformed to percentages by multiplying by 100.

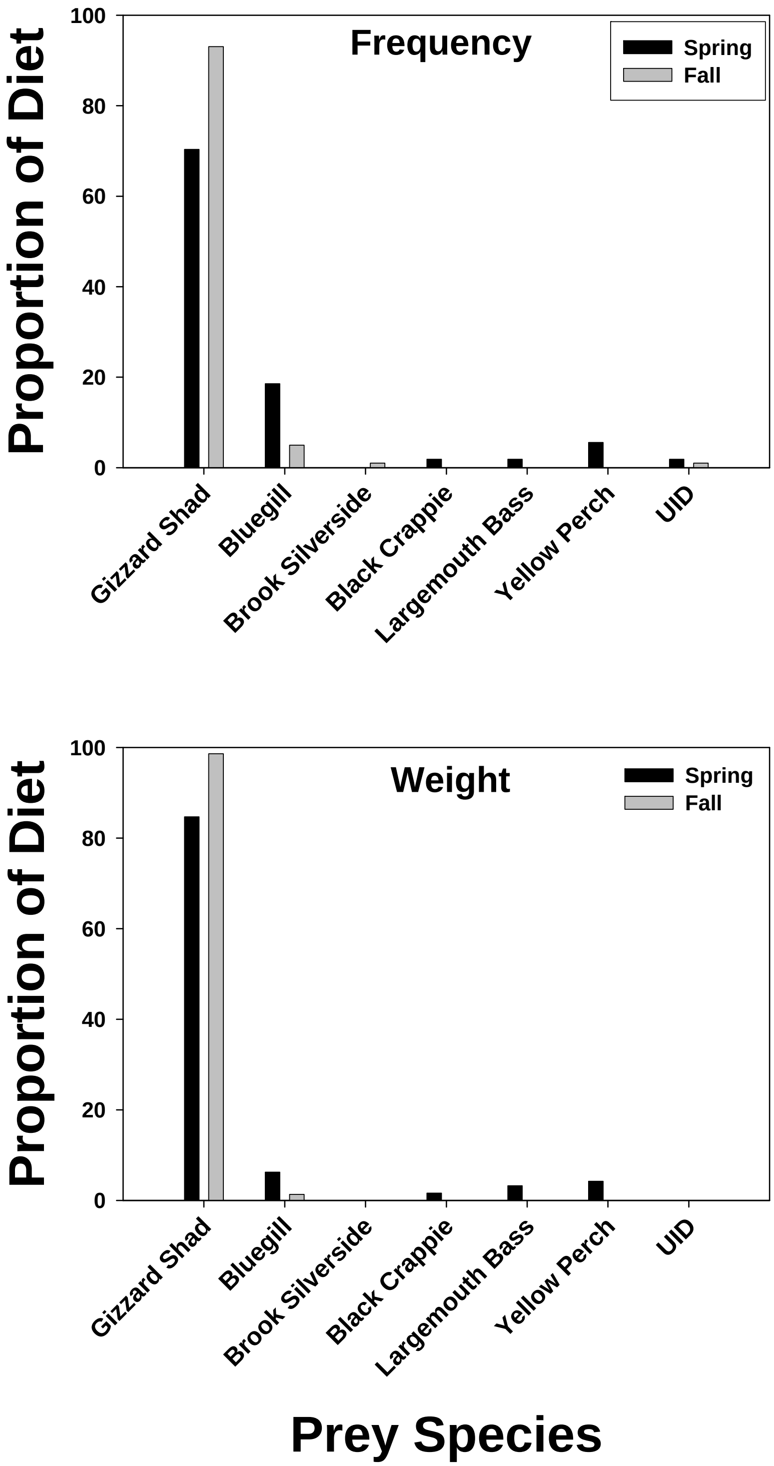

Figure 9. Diet composition of muskellunge sampled in Pierce Lake via trap netting and shoreline electrofishing, May 2007 – May 2012, by season. Spring is March, April, and May, while Fall is September, October, November. Data are pooled across years, upper panel shows diet by frequency of occurrence, lower shows proportion by wet weight. Proportions of diet by wet weight and frequency are transformed to percentages by multiplying by 100.

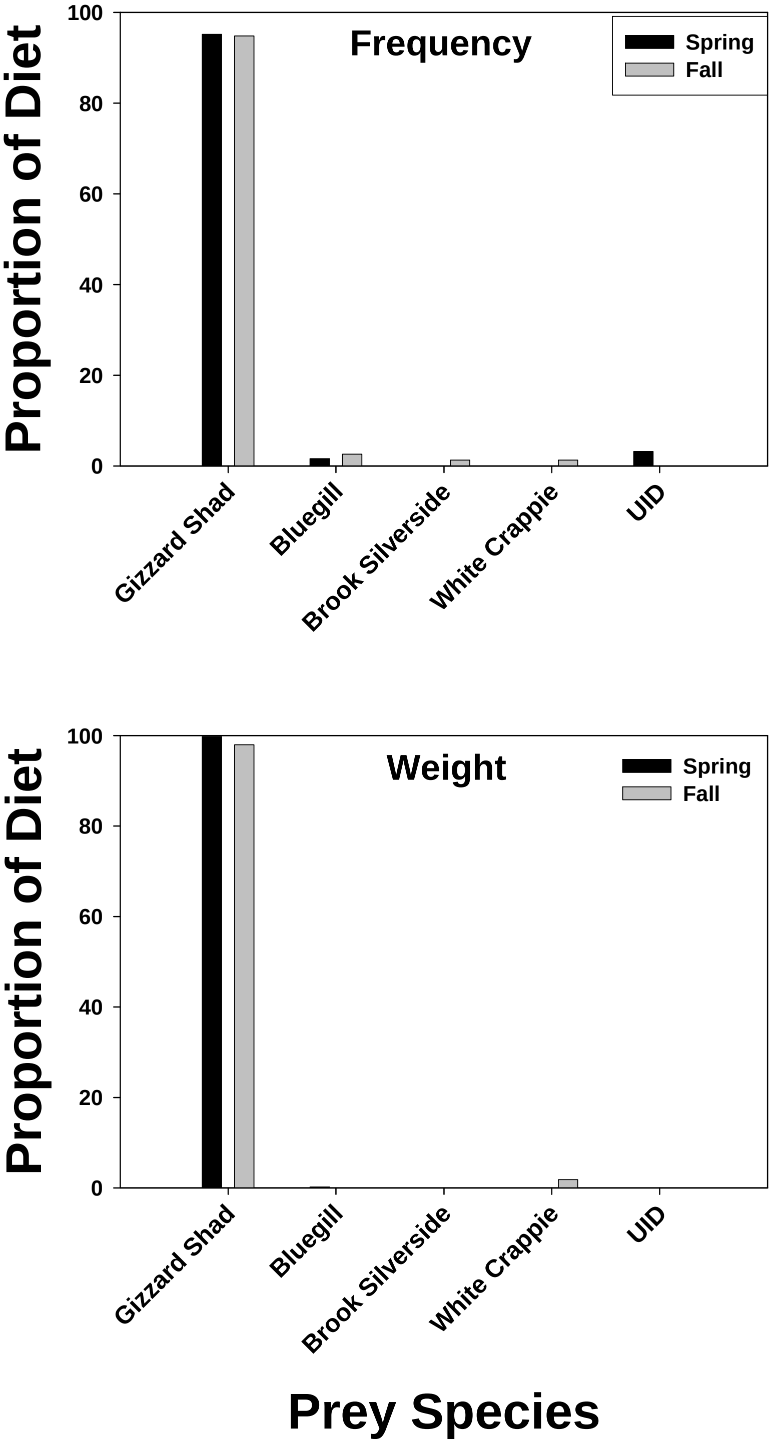

Figure 10. Diet composition of muskellunge sampled in Sam Dale Lake via trap netting and shoreline electrofishing, May 2007 – May 2012, by season. Spring is March, April, and May, while Fall is September, October, November. Data are pooled across years, upper panel shows diet by frequency of occurrence, lower shows proportion by wet weight. Proportions of diet by wet weight and frequency are transformed to percentages by multiplying by 100.

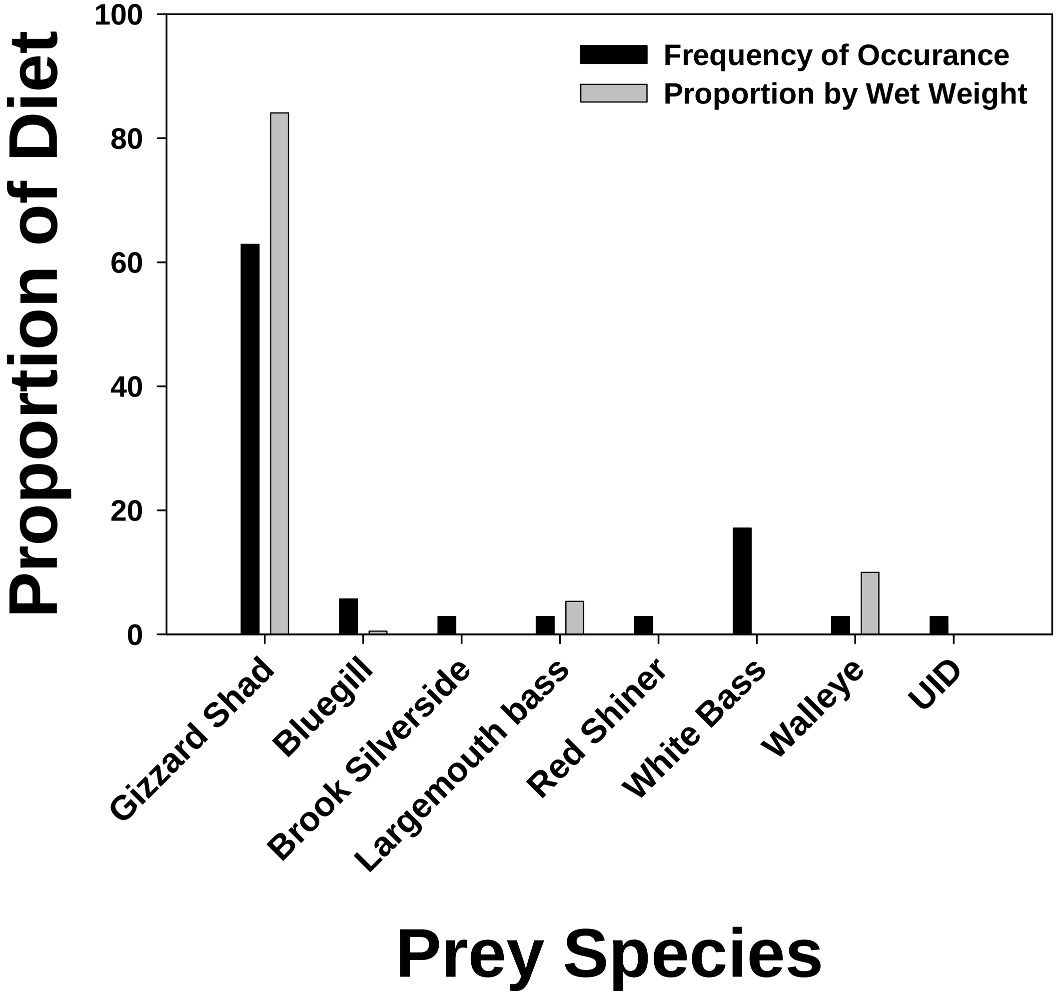

Figure 11. Diet composition of muskellunge sampled in Lake Shelbyville via shoreline electrofishing, May 2007 – May 2012. Data are pooled across samples from each season (Spring-Fall) and year. Proportions of diet by wet weight and frequency are transformed to percentages by multiplying by 100.

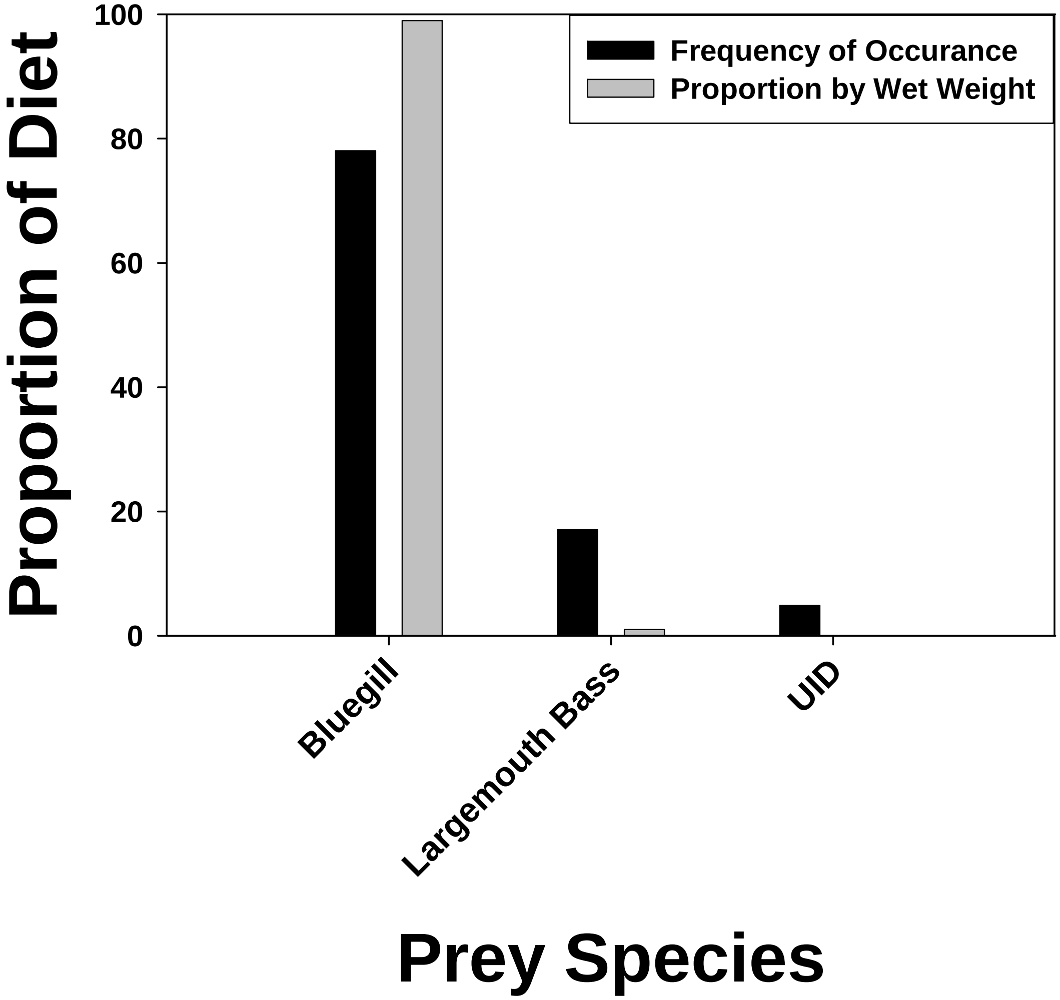

Figure 12. Diet composition of muskellunge sampled in Ridge Lake via shoreline electrofishing, modified fyke netting, and angler creel, May 2007 – May 2012. Data are pooled across samples from each season (Spring-Fall) and year. Proportions of diet by wet weight and frequency are transformed to percentages by multiplying by 100.

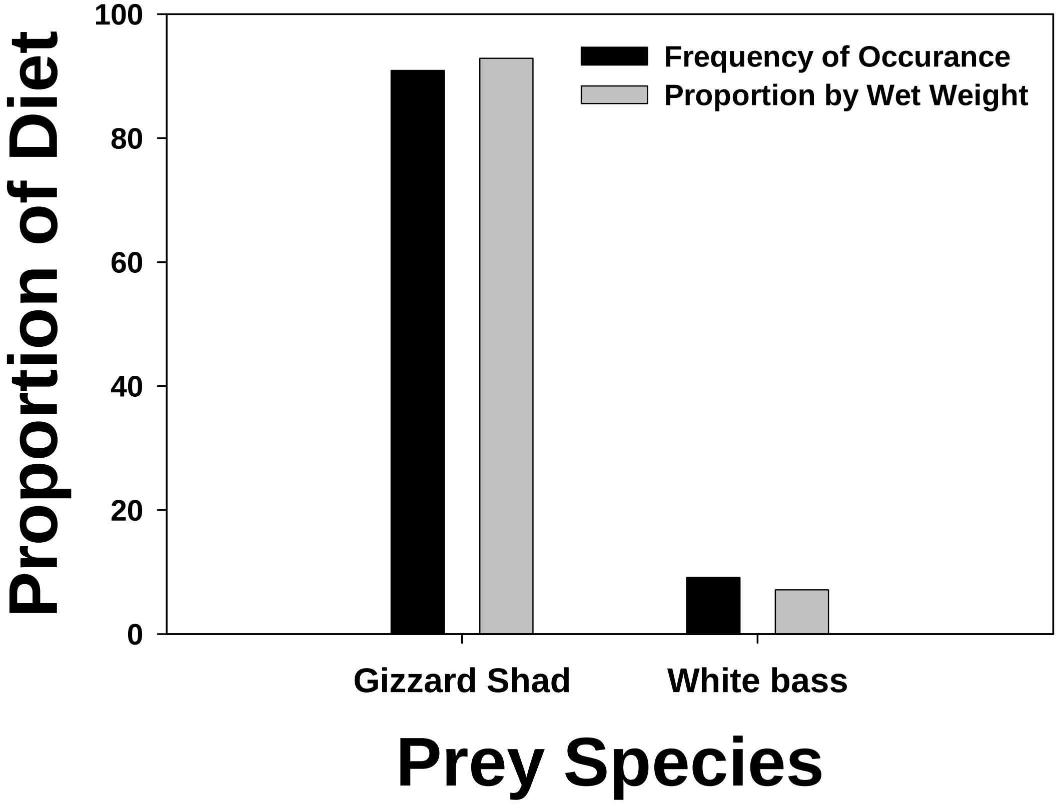

Figure 13. Diet composition of muskellunge sampled in Otter Lake via shoreline electrofishing, modified fyke netting, and angler creel, May 2007 – May 2012. Data are pooled across samples from each season (Spring-Fall) and year. Proportions of diet by wet weight and frequency are transformed to percentages by multiplying by 100.

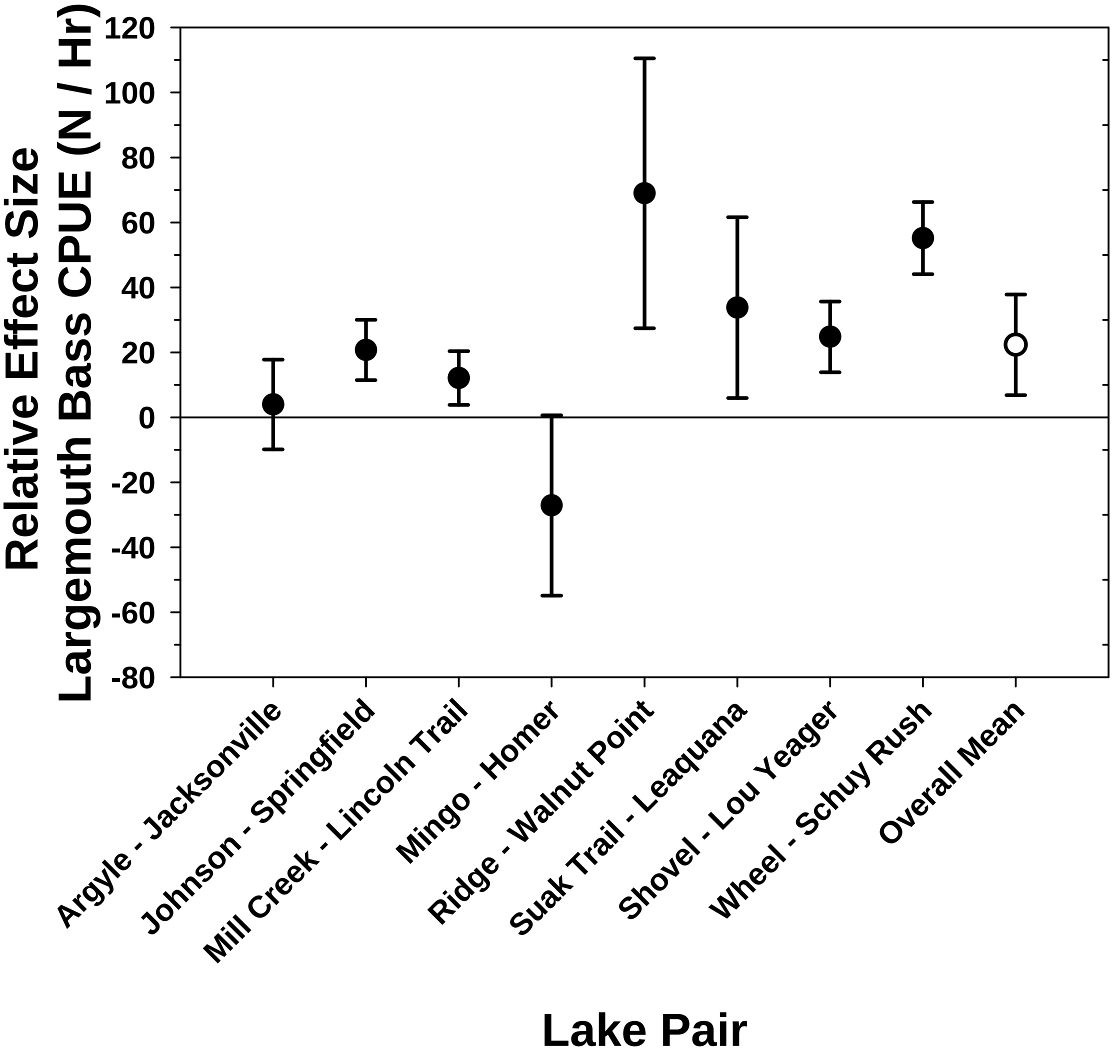

Figure 14. Relative effect sizes for number of largemouth bass collected per hour during standardized fall electrofishing surveys in Illinois lakes (N = 8) receiving muskellunge introductions relative to their spatially paired control lakes (N = 8). Error bars represent standard errors of effect sizes for each lake pair (solid circles) whereas error bars for overall effect size (open circle) indicate the 95% confidence interval. See methods for details on calculation of relative effect sizes.

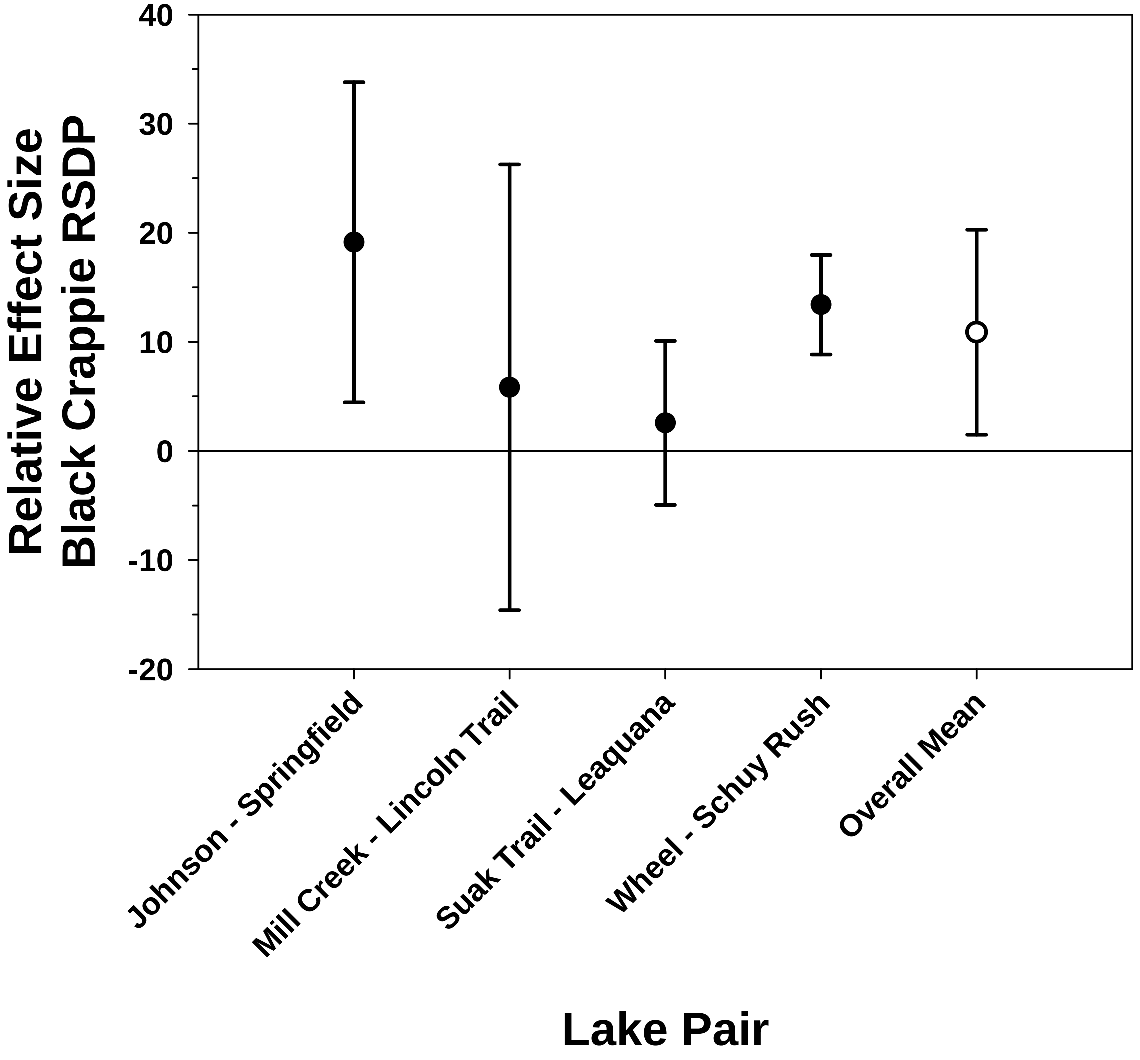

Figure 15. Relative effect sizes for relative stock distribution of preferred length black crappie collected during standardized fall electrofishing surveys in Illinois lakes (N = 4) receiving muskellunge introductions relative to their spatially paired control lakes (N = 4). Error bars represent standard errors of effect sizes for each lake pair (solid circles) whereas error bars for overall effect size (open circle) indicate the 95% confidence interval. See methods for details on calculation of relative effect sizes.

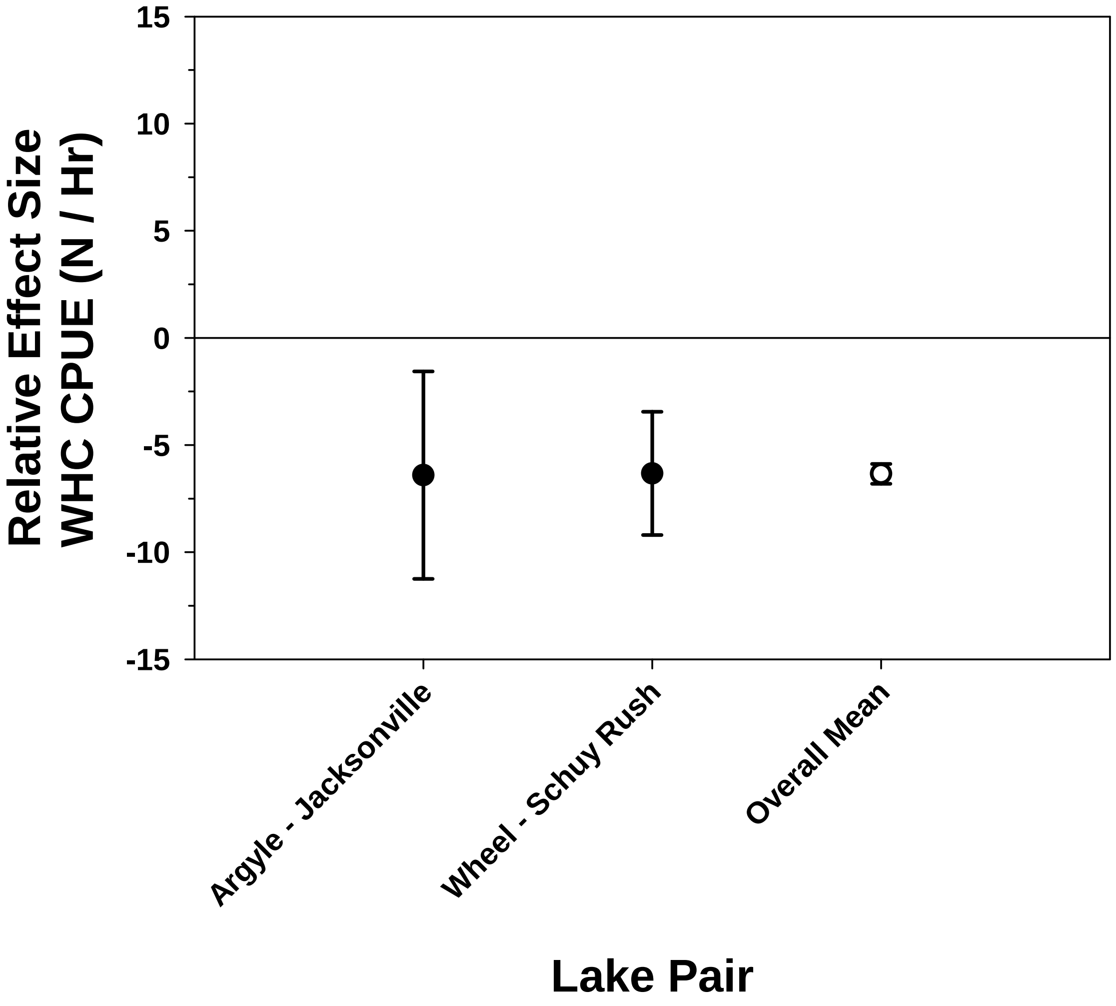

Figure 16. Relative effect sizes for number of white crappie collected per hour during standardized fall electrofishing surveys in Illinois lakes (N = 2) receiving muskellunge introductions relative to their spatially paired control lakes (N = 2). Error bars represent standard errors of effect sizes for each lake pair (solid circles) whereas error bars for overall effect size (open circle) indicate the 95% confidence interval. See methods for details on calculation of relative effect sizes.