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

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EXECUTIVE SUMMARY: Muskellunge *Esox masquinongy* are an important and increasingly popular sportfish that are commonly stocked throughout Illinois and much of the Midwestern United States. Stocking has become the primary management tool for establishing and maintaining muskellunge populations in Illinois and across the Midwestern United States. Great demand for these fish and the high costs associated with producing them create the need for efficient management practices. 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 and geographic 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 populations. Genetically distinct stocks are quickly becoming the new operational unit in fisheries management 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 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 is needed on differences in growth and survival among stocks in waters at varying latitudes in Illinois before management recommendations can be made on which stock is most appropriate. The first two jobs of this study examine 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. 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 a rigorous evaluation of the diet and community effects of muskellunge across a number of Illinois lakes in order to inform managers about the potential effects of muskellunge introductions.

During segment nine, all activities outlined in the annual work plan were accomplished and were completed within the specified budget. During this segment, two jobs related to muskellunge stock evaluation and one job related to food habits and effects of muskellunge introduction were continued. In previous segments of the study, we compared initial 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. In this segment population sampling by electrofishing was conducted during fall 2010 and spring 2011. These data were combined with modified fyke net surveys during spring 2011. Across years and lakes, the Ohio River drainage stock and the Illinois population generally appear to have similar growth rates through age-1. Through adulthood growth of the Upper Mississippi River drainage stock appears to be somewhat higher based on limited samples thus far that need to continue to be expanded in the future. Analysis of body morphology indicates that fish from the Upper Mississippi River drainage are consistently more lean than those of the other stocks. Results thus far from lake introductions suggest that after the first summer following stocking, the Ohio River drainage stock and Illinois population typically have similar survival and both 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. These introductions will need to be monitored over additional years to further assess potential differences in long-term growth, maximum length, and survival differences among stocks.

Muskellunge diet samples were collected from fish across 7 Illinois lakes from fall 2007 to spring 2011. 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 thus far from diet analysis indicate 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 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.

In the current segment we continued two sets of analyses focused on the community and fishery effects of muskellunge introductions. The first analysis expands a previously reported community analysis incorporating a data set collected as part of previous Federal Aid in Sport Fish Restoration Projects (F-135-R, Factors influencing largemouth bass recruitment and stocking and F-128-R, Quality management of bluegill populations). Data from multiple trophic levels including fish communities, zooplankton, nutrients, larval fish and benthic macroinvertebrate densities have previously been compared between lakes Mingo and Ridge and two reference lakes. In this segement we included data on larval fish and macroinvertebrate density from 2010. Lake Mingo has received muskellunge since fall of 2002 and Ridge Lake has been stocked since fall 2006. Data from Mingo and Ridge Lake is being compared to reference lakes before and after muskellunge introduction to determine if these stockings cause any changes in the aquatic communities of these two lakes. Preliminary results indicate that muskellunge stocking in Lake Mingo or Ridge Lake has not negatively affected largemouth bass and bluegill abundance and no significant effects on other parts of the aquatic food web have been detected.

The second set of analyses on effects of muskellunge stocking will involve a larger sample of lakes taken from the state Fishery Analysis System (FAS) database. Examination of muskellunge stocking records has identified a series of lakes that received concurrent initial stockings of muskellunge. To ensure that lakes selected for analysis have substantial muskellunge populations, we are selecting lakes where stockings have been successful based on both standardized electrofishing and spring trap netting surveys. This analysis will focus specifically on fish communities comparing trends before and after muskellunge introduction with a series of reference lakes. Reference lakes have been selected, which have similar geographic, physiochemical, morphometric and fishery characteristics to lakes receiving muskellunge stockings. This analysis will provide a more rigorous examination of muskellunge effects on existing fisheries due to a larger number of replicate lakes. Our results suggest that across 8 lakes in a time series ranging from 3-10 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.

In future years we will continue to monitor populations of muskellunge in lakes Mingo, Pierce and Sam Dale to evaluate long-term growth and survival differences between stocks and populations. The results obtained from initial years 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 will be used to develop guidelines for future muskellunge stockings that maximize growth, survival, and angler satisfaction in lakes throughout Illinois. As the management of muskellunge fisheries improves due to increased understanding of intraspecific variation, the effects of these highly predacious fishes on the existing aquatic community also needs to be considered. In future segments we will continue to examine the food habits and effects of muskellunge on existing fish populations. This information, combined with an increased understanding of appropriate stocks, will 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 Wisconsin glacier 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 this higher growth rate 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 (Minnesota's Leech Lake population) to exhibit higher growth rates at low temperatures and muskellunge from low latitudes (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 job, we investigate stock differentiation in growth for muskellunge in the field through adulthood. Long-term growth of muskellunge will be 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: In previous annual reports we compared growth rates between different stocks and populations of muskellunge through age-1 by year class in both ponds and lakes including Lake Mingo (Vermillion County), Pierce Lake (Winnebago County), and Sam Dale Lake (Wayne County). Comparison of age-1 growth has been completed and the results presented in previous annual reports. In this segment we focus on a global analysis of pooled year classes to examine general patterns for older age classes, and begin to examine growth patterns into adulthood for fish from Sam Dale Lake. Due to difficulty with mortality and availability of hatchery muskellunge, stockings were delayed in Sam Dale Lake so sampling of adult age classes is still in an earlier stage than Lakes Mingo and Pierce.

Stockings from various source populations (Table 1) representing each stock have been 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 2). 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 since 2002. 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:

Modified Fyke Net Surveys

In Lake Mingo a total of 53 muskellunge were captured during 19 nights of modified fyke net sampling (total of 211 net-nights) during March and April 2011. Catch rates averaged approximately 0.25 fish per net-night. Of the 53 muskellunge captured, 11 were Ohio River drainage stock, 41 were Illinois stock and 1 was Upper Mississippi River drainage stock. The smallest muskellunge captured was 803 mm and the largest was 1,050 mm; weights ranged from 4,070 g to 9,330 g. Twenty-five muskellunge were age-4, 19 were age-5, 9 were age-6. Of the 53 fish sampled 45% were male and 55% were female.

A total of 183 muskellunge were captured during the 7 nights of modified fyke net sampling (70 net-nights) in Pierce Lake during March and April 2011, yielding an average of 2.61 fish per net-night. Of the 183 muskellunge sampled, 28 were Ohio drainage stock, 152 were Illinois stock and 3 were Upper Mississippi River drainage stock. The smallest muskellunge captured was 677 mm and the largest was 1,023 mm; weights ranged from 2160g to 10,200g. Eighty-seven age-4, 55 age-5, 36 age-6, and 5 age-7 fish were sampled. Males represented 67% of the sampled muskellunge and females the other 33%.

A total of 107 muskellunge were captured during 24 nights of modified fyke net sampling (total of 214 net-nights) in Sam Dale Lake during February and March 2011. Catch rates averaged approximately 0.5 fish per net-night. Of the 107 muskellunge sampled 40 were Ohio stock, 64 were Illinois stock, and 3 were Upper Mississippi stock. The smallest muskellunge captured was 666 mm and the largest was 964; weights ranged from 2,020 g to 7,140 g. Sixty-five age-3, and 42 age-4 fish were sampled. Males represented 49% of the sampled muskellunge and females the other 51%.

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

Juvenile Growth Rate

In previous reports we compared relative daily growth rates (RDGR, standardized by weight) for age-1 muskellunge in Lakes Mingo, Pierce, and Sam Dale stratified by stocking year class. In Lakes Mingo and Pierce the Upper Mississippi river drainage stock exhibited a significantly lower overwinter RDGR in 4 of the 8 year classes examined. In Lake Sam Dale one of two year classes showed the Illinois population having a higher RDGR than the Upper Mississippi River drainage stock overwinter. Overwinter growth for the Upper Mississippi River drainage fish in all lakes for all other year classes were similar to the other two stocks.

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.

From 2003-2007 only two Upper Mississippi River drainage muskellunge were sampled at age-1 in Mingo and Pierce Lakes. 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 5 muskellunge from the Illinois stock, 5 muskellunge from the Ohio stock, and 2 muskellunge from the Upper Mississippi stock were sampled during fall 2009 electrofishing. The 2008 year class showed significantly higher growth for Upper Mississippi stock fish at age-1 than Ohio stock and Illinois stock fish. 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 with the exception of the 2008 year class in Lake Sam Dale.

Adult Size-at-Age

In Lake Mingo mean length-at-age was significantly different among stocks (ANOVA, $P < 0.01$, Table 3). 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 have been sampled thus far limiting our ability to make comparisons between stocks (Table 3). 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 3).

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 3). 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 4, Figure 1). Female muskellunge showed similar growth trajectories between stocks with nearly identical asymptotic lengths and growth coefficients (Table 4, Figure 2). 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 4, Figure 2). 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 $P = 0.02$,

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Table 5). However, at age-5 there were no statistically significant differences between stocks. At age-6 there is limited evidence that Upper Mississippi River drainage males may be longer than the other stocks (Table 5), although sample size is small. 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=6) 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 weights 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 5). 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 4, Figure 3). The growth trajectory of female muskellunge in Pierce Lake was generally also similar among stocks (Figure 4). No differences in asymptotic length or growth coefficients were found between stocks (Table 4, 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 4, Figure 4)

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 6). 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 were significantly longer than Illinois females at age-4 with Ohio River drainage females being intermediate (Table 6).

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 6). 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.

Previous studies have found morphological differences between Leech Lake Minnesota stocks when compared to other populations (Margenau and Hanson 1996). We pooled data from Sam Dale Lake, Lake Mingo, and Pierce Lake to describe the length weight relationships of Ohio River drainage, Upper Mississippi River drainage, and Illinois muskellunge. Upper Mississippi River drainage fish were consistently more lean, weighing less than Ohio or Illinois fish at similar lengths (ANCOVA, $P = 0.02$, Figure 5). In future segments, we will sample

additional fish from each stock, specifically the Upper Mississippi stock, to better describe these relationship and identify any morphological differences between stocks.

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. The inclusion of additional individuals into our long term dataset has muted previously described differences in growth trajectories of these stocks. 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 however 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.

Differences in the allometric length-weight relationship between stocks were present across lakes. Upper Mississippi River drainage muskellunge were found to be more lean than Ohio River drainage and Illinois muskellunge. Poor condition could explain patterns of both poor growth and survival of these stocks.

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

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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 (Cassellman 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. 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+). Assessment of juvenile survival rates was also conducted in replicated pond experiments and

reported in previous annual reports. The assessment of juvenile survival rates has been completed for all lakes and these findings are summarized in this report.

We continued a global analysis of adult survival rates in lakes Mingo and Pierce using data collected during the current segment. These analyses have been made possible by the establishment of multiple age classes in Lakes Mingo and Pierce combined with multiple years of catch data from spring modified fyke net surveys. In Lake Sam Dale two year classes (2006 and 2007) 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 annual survival and evaluate potential differences between stocks we utilized CPUE data from spring fyke net samples collected during 2007-2010 (Lake Mingo), 2008-2010 (Pierce Lake) and 2010-2011 (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 in 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.

FINDINGS:

Juvenile Survival Summary

In past reports we compared relative survival rates based on adjusted CPUE (adjusted for stocking related mortality) through age-1 of introduced muskellunge in Lakes Mingo and Pierce stratified by stocking year class. The analysis of juvenile survival on these lakes is complete and has been reported in previous segments. In summary, there was a pattern of similar survival between the Illinois population and the Ohio River drainage stock in Lakes Mingo and Pierce both through overwinter and to age-1 in most year classes. Upper Mississippi River drainage fish showed similar survival through overwinter but had significantly lower survival to age-1 than to the other stocks in several year classes.

Year classes of muskellunge were introduced into Sam Dale Lake each year from 2005-2008 (Table 2). 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. 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. In the fall of 2009 comparison of survival to age-1 between

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stocks was not possible due to low numbers of recaptured muskellunge. The 2008 year class was sampled 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. We will continue spring modified fyke net sampling on this lake to assess survival to adulthood of these year classes.

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

     Adjusted CPUE of adult muskellunge in Lake Mingo was higher for Illinois population muskellunge (mean ± 95% CI = 0.18 ±0.07) compared to the Upper Mississippi River stock (mean ± 95% CI = 0.02 ±0.07) with the Ohio River drainage stock (mean ± 95% CI = 0.09 ±0.07) being intermediate (ANOVA, P = 0.01). Upper Mississippi River drainage stock muskellunge were captured in lower abundance in Pierce lake (mean ± 95% CI = 0.07 ±0.79) than the Illinois population (mean ± 95% CI = 1.71 ±0.79), while the Ohio River drainage stock was intermediate (mean ± 95% CI = 0.60 ±0.79, ANOVA, P = 0.02). In Lake Sam Dale the Illinois population and Ohio River drainage stock muskellunge showed higher survival (mean ± 95% CI = 0.37 ±0.12) and 0.29 ±0.11) than the Upper Mississippi river drainage fish (mean ± 95% CI = 0.02 ± 0.12), ANOVA, P = <0.001).

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 7, 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 and Pierce allowed estimation of annual survival rates for adult muskellunge ages 3-6+ in both lakes (Table 8-9). 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. 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 several instances CPUE increased within a year class from one sampling year to the next (See Table 8 for examples). This may be a result of these fish not being fully recruited to the gear at age-2 or the increased number of net nights in the spring of 2010 and 2011. 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). Average annual survival estimates for adult Illinois population muskellunge in Lake Mingo was 54% for the period from 2007-2011 (Table 8). 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 2008-2011. The average annual survival estimate for the Illinois population from 2008-2011 was 64%. The Ohio River drainage stock had 56% mean annual survival across the same timespan (Table 9). Adult Upper Mississippi River drainage fish

were only captured in two sampling seasons and 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 = -0.40; P = 0.37).

Annual survival estimates for all three stocks in Lake Sam Dale between 2010 and 2011 were calculated (Table 10). Additional sampling will be required to allow for statistical comparisons of survival in Lake Sam Dale. Future years of data will allow for greater precision and comparisons of survival in all study lakes.

RECOMENDATIONS: Thus far results from 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 are consistently represented at similar levels in catches. In contrast a few Upper Mississippi River drainage muskellunge have been sampled beyond age-1 in Lake Mingo and Pierce Lake. The recapture rate of Upper Mississippi River drainage stock muskellunge has been too low to allow quantitative comparisons with the other stocks and survival of this stock in Mingo and Pierce is negligible.

Further fall and spring monitoring of introduced muskellunge will be conducted in each of the three lakes. Survival of these stocks in Sam Dale Lake which is the southernmost lake in the study is of particular interest. Once compiled, results from these lakes may reveal latitudinal differences in survival within the state among the introduced stocks. In future years we will continue spring fyke net surveys on Sam Dale Lake and increase spring netting efforts in Lakes Mingo and Pierce. Capturing additional year classes during these spring nettings will be vital for a more powerful assessment of differences between stocks. This long-term data set will allow us to detect any biologically significant differences in longevity or survival between the distinct stocks of muskellunge in Illinois lakes. There are strong indications in our sample lakes that summer is crucial in determining the long-term survival of stocked muskellunge. Failure to cope with adversely high summer temperatures may be an important source of mortality and could be different between stocks that have adapted to differing thermal regimes. Work remains to be done in identifying differences in thermal stress response between stocks of muskellunge.

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

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

INTRODUCTION: Muskellunge introductions in lakes Mingo, Pierce and Sam Dale have been successful and high density muskellunge fisheries have been developed in the study lakes. The establishment or enhancement of muskellunge fisheries requires not only an understanding of the appropriate source stock, but also the potential effects on the recipient aquatic community. There are a limited number of studies that have examined diet composition of introduced predators and even fewer have considered potential interactions between stocked game species and other piscivorous top predators (Eby et al. 2006). Species introductions can have strong ecological effects and therefore there exists a great need for research to inform management

decisions regarding introductions (Lodge et al. 1998; García-Berthou et al. 2005; Keller et al. 2007). 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). These concerns combined with a paucity of available information have motivated some angler groups targeting other species to develop antagonistic attitudes towards introduced muskellunge populations. 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.

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). Several studies exist in the gray literature including a recent 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 (including bluegills) before and after muskellunge introduction and found no consistent pattern of significant declines in relative abundances after muskellunge introduction (Knapp et al. 2008). 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. 2008) 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 segment 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 2010 and May 2011 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 2007-2010). 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).   In previous segments we sacrificed and later dissected 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 3 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 11). Lakes were selected if at any time within the post introduction period (3-7 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 11). Each selected muskellunge lake was paired with a nearby control lake that was not stocked with muskellunge (Figure 12). Control lakes were selected primarily on the basis of geographic distance and data availability however care was taken to select lakes of similar size, depth and fish communities where possible.

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.

Community Effects of Muskellunge Stocking

The study sites for evaluation of community effects of muskellunge introduction include Lake Mingo, and Ridge Lake (Coles County), with reference waters including Homer Lake (Champaign County), and Walnut Point Lake (Douglas County). These lakes have been monitored since fall of 1998 as part of ongoing or previous Federal Aid in Sport Fish Restoration Projects (F-135-R, Factors influencing largemouth bass recruitment and stocking and F-128-R, Quality management of bluegill populations). Data have been collected on relative abundance and size structure of juvenile and adult fish, larval fish density, benthic macroinvertebrate density and size structure, zooplankton density and size structure, chlorophyll a concentration, water clarity, total phosphorous, temperature and dissolved oxygen using standard methodologies (for specific sampling details see Diana et al. 2009). Lake Mingo was initially stocked with muskellunge in 2002 and Ridge Lake was initially stocked in 2005. Each lake has received annual stockings of 8-10 inch muskellunge each fall since the initial stockings. Changes to community parameters in Lakes Mingo and Ridge were analyzed using a paired before-after control-impact design (BACIP, Underwood 1994).

In past reports we presented results for a number of community parameters including relative abundance of largemouth bass and bluegill, zooplankton density and size structure, algal biomass, and total phosphorous concentration utilizing data from 1998-2009 on Ridge Lake and 1998-2005 on Lake Mingo. In this segment we update the analyses of these parameters and include additional data on larval fish and benthic macroinvertebrate density incorporating data from 2010. Adult fish response metrics from these lakes were also combined with those from a larger set of lakes receiving muskellunge stockings for the purpose of drawing more general conclusions and are presented in the following section (fishery effects of muskellunge stocking). Data from fall (September-November, electrofishing CPUE, seine fish density) or summer (June-August, zooplankton, chlorophyll, total phosphorous, and larval fish) sampling dates were averaged to produce a single measurement for each year. Data were analyzed using a paired BACI design suited to a repeated measures analysis of variance (Keough and Mapstone 1995) to test for impacts on each parameter in separate analyses.

FINDINGS:

Muskellunge Food Habits

Stomach contents of 525 muskellunge from seven Illinois lakes were sampled between May 2010 and May 2011 yielding 115 diet items (410 fish had empty stomachs). Diet samples collected during this segment were pooled with data from previous 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 6), Pierce (Figure 7), Sam Dale (Figure 8), Shelbyville (Figure 9), and Otter (Figure 11), Bluegill were the dominant diet item in Ridge Lake (Figure 10). Bluegill 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 at this time. 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), and yellow perch (Pierce). Of all muskellunge captured, 80% had empty stomachs at the time of sampling. Bluegill appear to be a more important diet item in the spring compared to the fall in Pierce Lake (Figure 7), but Sam Dale and Mingo showed similar diet patterns between seasons (Figure 6, Figure 8). Gizzard shad were the most frequent prey item in 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 10).

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 12; Figure 13). 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 3).

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 12).

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 12).

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 12).

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 12).

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 12, Figure 14). 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 12, Figure 15).

Community Effects of Muskellunge Stocking

Introduction and establishment of significant adult populations of muskellunge in both Ridge Lake and Lake Mingo has had little effect on major components of the aquatic community (Table 13). In Ridge Lake we found no significant effects of muskellunge introduction on any of the observed parameters (Table 13). Similarly our analysis indicated few changes in Lake Mingo although there were some marginally significant changes in zooplankton metrics. Further examination of trends in average cladoceran density in Lake Mingo indicated a marginally significant decrease in abundance of these zooplankters that was not present in the control system. Marginally significant effects of muskellunge introduction on average cladoceran size

structure were also evident but were driven by a slight increase in the size of zooplankters in the control system (Homer Lake) while cladoceran size remained unchanged in Lake Mingo.

RECOMENDATIONS: Muskellunge diet information has continued to show a consistent pattern of little predation on largemouth bass or other game species. 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. 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).

Among the strongest of our results was the positive response of largemouth bass relative abundance to muskellunge introduction where 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. While 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 two 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 *in press*). 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 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. 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.

Our results suggest that muskellunge introduction has had minimal negative effects on several ecologically and recreationally important fish species in Illinois lakes over time periods from four to seven years after introduction. In addition muskellunge seem to have little effect on other aspects of the aquatic community. We found evidence for a potentially strong 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. 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. 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 begin developing guidelines regarding appropriate muskellunge populations for stocking throughout

Illinois. In future segments, recommendations will be made that will allow hatchery and management biologists to make decisions that will maximize benefits for the muskellunge program in Illinois.

BUDGET TABLE:

Project Segment 9

Job	Proposed Cost	Actual Cost
Job 101.1	$37,856	$37,856
Job 101.2	$37,856	$37,856
Job 101.3	$28,087	$28,087
Job 101.4	$18,317	$18,317

LITERATURE CITED

Anderson, R.O., Neumann, R.M. 1996. Length, weight and associated structural indices. Pages 447-482 *in* B.R. Murphy and D.W. Willis, editors. Fisheries techniques, 2nd edition. American Fisheries Society, Bethesda, Maryland

Angilletta, M. J., T. D. Steury, and M. W. Sears. 2004 Temperature, growth rate, and body size in ectotherms: fitting pieces of a life-history puzzle. Integrative and Comparative Biology 44:498-509.

Altukhov, Y.P. 1981. The stock concept from the viewpoint of population genetics. Canadian Journal of Fisheries and Aquatic Sciences 38: 1523-1538.

Bayley, P. B., and D. J. Austen. 2002. Capture efficiency of a boat electrofisher. Transactions of the American Fisheries Society. 131:435-451.

Bayley, P. B., S. T. Sobaski, and D. J. Austen. 1990. The fishery analysis system (FAS): creel survey and lake analyses. INHS Center for Aquatic Ecology. Aquatic Ecology Technical Report 90/12.

Becker, G.C. 1983. Fishes of Wisconsin. University of Wisconsin Press, Madison, Wisconsin.

Begg, G.A., K.D. Friedland, and J.B. Pearce. 1999. Stock identification and its role in stock assessment and fisheries management: an overview. Fisheries Research 43: 1-8.

Belk, M.C., J.B. Johnson, K.W. Wilson, M.E. Smith, and D.D. Houston. 2005. Variation in intrinsic individual growth rate among populations of leatherside chub (*Snyderichthys copei* Jordan & Gilbert): adaptation to temperature or length of growing season? Ecology of Freshwater Fish 14: 177-184.

Bevelhimer, M.R., R.A. Stein, and R.F. Carline. 1985. Assessing significance of physiological differences among three esocids with a bioenergetics model. Canadian Journal of Fisheries and Aquatic Sciences 42: 57-69.

Beverton, R..J.H. and S.J. Holt. 1957. On the dynamics of exploited fish populations. Fishery Invest. Lond. Ser. 2. 19: 533 pp.

Bonar, S. A., W. A. Hubert, and D. W. Willis. Editors. 2010. Standard Methods for Sampling North American Freshwater Fishes. American Fisheries Society, Bethesda, Maryland.

Boxrucker, J. 2002. Improved growth of a white crappie population following stocking of saugeyes (sauger × walleye): a top-down, density-dependent growth response. North American Journal of Fisheries Management 22:1425-1437.

Boxrucker, J.C. 1982. Mass marking of fingerling largemouth bass by fin-clipping followed by freeze-cauterization of the wound. North American Journal of Fisheries Management 2: 94-96.

Blackburn, T.M., K.J. Gaston, and N. Loder. 1999. Geographic gradients in body size: a clarification of Bergmann's rule. Div. Distrib. 5:165-174.

Bozek, M.A., T.M. Burri, and R.V. Frie. 1999. Diets of muskellunge in northern Wisconsin lakes. North American Journal of Fisheries Management 19:258-270.

Brenden, T.O., E.M. Hallerman, and B.R. Murphy. 2004. Predatory impact of muskellunge on New River, Virginia, smallmouth bass. Proceedings of the Southeastern Association of Fish and Wildlife Agencies 58:12-22.

Brenden, T.O., E.M. Hallerman, B.R. Murphy, J.R. Copeland, and J.A. Williams. 2007. The New River, Virginia, muskellunge fishery: population dynamics, harvest regulation modeling, and angler attitudes. Environmental Biology of Fishes 79:1-2, 11-25.

Carey, M.P. and D.H. Wahl. 2010. Interactions of multiple predators with different foraging modes in an aquatic food web. Oecologia: 162: 443-452.

Carey, M. P. and D. H. Wahl. 2011. Foraging modes of predators and behaviors of prey determine the outcome of multiple predator interactions. Transactions of the American Fisheries Society *In Press*.

Carline, R.F., R.A. Stein, and L.M. Riley. 1986. Effects of size at stocking, season, largemouth bass predation, and forage abundance on survival of tiger muskellunge, Pages 151-167 *in* G. E. Hall, editor. Managing Muskies. American Fisheries Society, Special Publication 15, Bethesda, Maryland, USA.

Carpenter S.R. 1989. Replication and treatment strength in whole-lake experiments. Ecology 70(2): 453-463.

Casselman, J.M. and E.J. Crossman. 1986. Size, age, and growth of trophy muskellunge and muskellunge-northern pike hybrids—the cleithrum project, 1979-1983. American Fisheries Society Special Publication 15:93-110.

Clapp, D.F., Y. Bhagwat, and D.H. Wahl. 1997. The effect of thermal stress on walleye fry and fingerling mortality. North American Journal of Fisheries Management 17: 429-437.

Clapp, D.F. and D.H. Wahl. 1996. Comparison of food consumption, growth, and metabolism among muskellunge – an investigation of population differentiation. Transactions of the American Fisheries Society 125: 402-410.

Conner M.M., Miller, M.W., Ebinger, M.R., and K.P. Burnham. 2007. A Meta-BACI approach for evaluating management intervention on chronic wasting disease in mule deer. Ecological Applications. 17: 140-153.

Conover, D.O. and T.M.C. Present. 1990. Countergradient variation in growth rate: compensation for length of the growing season among Atlantic silversides from different latitudes. Oecologia 83: 316-324.

Conover, D.O., J.J. Brown, and A. Ehtisham. 1997. Countergradient variation in growth of young striped bass (*Morone saxatilis*) from different latitudes. Canadian Journal of Fisheries and Aquatic Sciences 54: 2401-2409.

Crossman, E.J. 1978. Taxonomy and distribution of North American esocids. Pages 13-26 *in* R.L. Kendall, editor. Selected coolwater fishes of North America. American Fisheries Society, Special Publication 11, Washington, D.C., USA.

Crossman, E.J. 1986. The noble muskellunge: a review. Pages 1-13 *in* G.E. Hall, editor. Managing Muskies. American Fisheries Society, Special Publication 15, Bethesda, Maryland, USA.

Curry, A.R., 2007. Using movements and diet analyses to assess effects of introd muskellunge (*Esox masquinongy)* on Atlantic salmon *(Salmo salar)* in the Saint John River, New Brunswick. Environmental Biology of Fish 79:49-60.

DiMichele, L. and M.E. Westerman. 1997. Geographic variation in development rate between populations of the teleost *Fundulus heteroclitus*. Marine Biology 128: 1-7.

Downes, B. J., L. A. Barmuta, P. G. Fairweather, D. P. Faith, M. J. Keough, P. S. Lake, B. D. Mapstone, and G. P. Quinn. 2002. Monitoring Ecological Impacts Concepts and Practice in Flowing Waters. Cambridge University Press, Cambridge, UK.

Eby, L.A., W.J. Roach, L.B. Crowder, J.A. Stanford. 2006. Effects of stocking up freshwater food webs. Trends in Ecology and Evolution 21(10): 576-584.

Eklov, P. and T. VanKooten. 2001. Facilitation among piscivorous predators: effects of prey habitat use. Ecology 82: 2486-2494.

Fedriani, J.M., Fuller, T.K., Sauvajot, R.M., and York, E.C. 2000. Competition and intraguild predation among three sympatric carnivores. Oecologia, 125: 258–270.

Ferguson, G.W., and L.G. Talent. 1993. Life-history traits of the lizard *Sceloporus undulates* from two populations raised in a common laboratory environment. Oecologia 93:88-94.

Foster, J.R. 1977. Pulsed gastric lavage - efficient method of removing the stomach contents of live fish. The Progressive Fish-Culturist 39:166-169.

Gabelhouse, D. W.1984.An assessment of crappie stocks in small Midwestern private impoundments.North American Journal of Fisheries Management 4:371-384.

Galarowicz, T.L. and D.H. Wahl. 2003. Differences in growth, consumption, and metabolism among walleyes from different latitudes. Transactions of the American Fisheries Society 132: 425-437.

Galinet, G. F., D. W. Willis, B. G. Blackwell, and M. J. Hubers. 2002. Influence of a saugeye (sauger x walleye) introduction program on the black crappie population in Richmond Lake, South Dakota. .North American Journal of Fisheries Management 22:1416-1424.

García-Berthou, E., Alcaraz, C., Pou-Rovira, Q., Zamora, L., Coenders, G. and Feo, C. 2005. Introduction pathways and establishment rates of invasive aquatic species in Europe. Canadian Journal of Fisheries and Aquatic Sciences 65: 453-463.

Gotthard, K., S. Nylin, and C. Wiklund. 1994. Adaptive variation in growth rate: life history costs and consequences in the speckled wood butterfly, *Pararge aegeria*. Oecologia 99:281-289.

Gurevitch, J. and L.V. Hedges. 2001. Meta-analysis – combining the results of independent experiments. Pages 347-369 *in* S. M. Scheiner and J. Gurevitch, editors. Design and Analysis of Ecological Experiments. Oxford University Press New York, New York 2001.

Hanson, D.A. 1986. Population characteristics and angler use of muskellunge in eight northern Wisconsin lakes. American Fisheries Society Special Publication 15:238-248.

Henderson, P.A., R.H.A. Holmes, and R.N. Bamber. 1988. Size-selective overwintering mortality in the sand smelt, *Atherina boyeri* Risso, and its role in population regulation. Journal of Fish Biology 33:221-233.

Holker, F., and coauthors. 2007. Species-specific responses of planktivorous fish to the introduction of a new piscivore: implications for prey fitness. Freshwater Biology 52(9):1793-1806.

Hubbs, C.L. and K.F. Lagler. 1958. Fishes of the Great Lakes region. Cranbrook Institute of Science Bulletin 26.

Hutchinson, G.E. 1958. Concluding remarks. Cold Spring Harbor Symposia on Quantitative Biology 22:415-427.

Ihssen, P.E., D.O. Evans, W.J. Christie, J.A. Reckahn, and R.L. DesJardine. 1981. Life history, morphology, and electrophoretic characteristics of five allopatric stocks of lake whitefish *Coregonus clupeaformis* in the Great Lakes region. Canadian Journal of Fisheries and Aquatic Sciences 38: 1790-1807.

Jonassen, T.M., A.K. Imsland, R. Fitzgerald, S.W. Bonga, E.V. Ham, G. Naevdal, M.O. Stefansson, and S.O. Stefansson. 2000. Geographic variation in growth and food consumption efficiency of juvenile Atlantic halibut related to latitude. Journal of Fish Biology 56: 279-294.

Keast, A. and M. G. Fox.1992. Space use and feeding patterns in an offshore fish assemblage in a shallow mesotrophic lake. Environmental Biology of Fishes 34:159-170.

Keller, R.P., Lodge, D.M. and D.C. Finnoff. 2007. Risk assessment for invasive species produces net bioeconomic benefits. Proceedings of the National Academy of Sciences of the United States of America 104: 203-207.

Keough, M.J. and B.D. Mapstone. 1995. Protocols for designing marine ecological monitoring programs associated with BEK Mills. National Pulp Mills Research Program Technical Report no. 11. Canberra, ACT: CSIRO.

Keough, M.J. and G. P. Quinn. 2000. Legislative vs. practical protection of an Intertidal shoreline in southeastern Australia. Ecological Applications 10:871-881.

Koppelman, J.B. and D.P. Philipp. 1986. Genetic applications in muskellunge management Pages 111-121 *in* G.E. Hall, editor. Managing Muskies. American Fisheries Society, SpecialPublication 15, Bethesda, Maryland, USA.

Knapp, M. L., S. W. Mero, D. J. Bohlander, and D. F. Staples. 2008. Fish community responses to the introduction of muskellunge in Minnesota lakes. Minnesota Department of Natural Resources, Special Publication 166.

Krska, R.J. Jr., and R.L. Applegate. 1982. Food of young muskellunge in a power plant cooling reservoir. The Progressive Fish Culturist 44: 172-173.

Leitner, J., and Bulak, J. 2008. Performance differences between two endemic stocks of Largemouth Bass in South Carolina. North American Journal of Fisheries Management 28: 516-522.

Levinton, J.S. 1983. The latitudinal compensation hypothesis: growth data and a model of latitudinal growth differentiation based upon energy budgets. I. interspecific comparison of *Ophryotrocha* (Polychaeta: Dorvilleidae). Biological Bulletin (Woods Hole) 165: 686-698.

Levinton, J.S. and R.K. Monahan. 1983. The latitudinal compensation hypothesis: growth data and a model of latitudinal growth differentiation based upon energy budgets. II. intraspecific comparisons between subspecies of *Ophryotrocha puerilis* (Polychaeta: Dorvilleidae). Biological Bulletin (Woods Hole) 165: 699-707.

Lodge, D.M., Stein, R.A., Brown, K.M., Covich, A.P., Bronmark, C., Garvey, J.E. and S.P. Klosiewski. 1998. Predicting impact of freshwater exotic species on native biodiversity: challenges in spatial scaling. Australian Journal of Ecology 23: 53-67.

Lonsdale, D.J. and J.S. Levinton. 1985. Latitudinal differentiation in copepod growth: an adaptation to temperature. Ecology 66: 1397-1407.

Luey, J.E. and I.R. Adelman. 1984. Stock structure of rainbow smelt in western Lake Superior: population characteristics. Transactions of the American Fisheries Society 113: 709-715.

MacLean, J.A. and D.O. Evans. 1981. The stock concept, discreteness of fish stocks, and fisheries management. Canadian Journal of Fisheries and Aquatic Sciences 38: 1889 1898.

MacLean, J.A., D.O. Evans, N.V. Martin, and R.L. DesJardine. 1981. Survival, growth, spawning distribution, and movements of introduced and native lake trout *Salvelinus namaycush* in two inland Ontario Lakes. Canadian Journal of Fisheries and Aquatic Sciences 38: 1685-1700.

Margenau, T.L. and S.P. AveLallemant. 2000. Effects of a 40-inch minimum length limit on muskellunge in Wisconsin. North American Journal of Fisheries Management 10:986 993.

Margenau, T.L. and D.A. Hanson. 1996. Survival and growth of stocked muskellunge: effects of genetic and environmental factors. Wisconsin Department of Natural Resources Research Report 172 172: 1-11.

McClane, A.J. 1974. McClane's field guide to freshwater fishes of North America. Holt, Rinehart, and Winston, New York, NY, USA.

McNeil, F.I. and E.J. Crossman. 1979. Fin clips in the evaluation of stocking programs for muskellunge *Esox masquinongy*. Transactions of the American Fisheries Society 108: 335-343.

Midwest Regional Climate Center (MRCC). 2004. http://mcc.sws.uiuc.edu/

Mitzner, L. M. 1984.Crappie management: problems and solutions. North American Journal of Fisheries Management 4:339-340.

National Oceanic and Atmospheric Administration (NOAA). 2004. http://www.noaa.gov/

New York State Climate Office (NYSCO). 2004. http://nysc.eas.cornell.edu/

Nicieza, A.G., F.G. Reyes-Gavilan, and F. Brana. 1994. Differentiation in juvenile growth and bimodality patterns between northern and southern populations of Atlantic salmon (*Salmo salar* L.). Canadian Journal of Zoology 72: 1603-1610.

Oates, D.W., L.M. Krings, and K.L. Ditz. 1993. Field manual for identification of selected North American freshwater fish by fillets and scales. Nebraska Game and Parks Commission, Nebraska Technical Series 19, Lincoln.

Pennsylvania State Climatologist (PSC). 2004. http://pasc.met.psu.edu/PA_Climatologist/index.php

Philipp, D.P. and J.E. Claussen. 1995. Fitness and performance differences between two stocks of largemouth bass from different river drainages within Illinois. American Fisheries Society Symposium 15: 236-243.

Post, J.R., and D.O. Evans. 1989. Size-dependent over-winter mortality of young-of-the-year yellow perch (*Perca flavescens*): laboratory, in situ enclosure, and field experiments. Canadian Journal of Fisheries and Aquatic Sciences 46:1958-1968.

Riha, V.F., and K.A. Berven. 1991. An analysis of latitudinal variation in the larval development of the Wood Frog (*Rana sylvatica*). Copeia 1991:209-221.

Ricker, W.E. 1975. Computation and interpretation of biological statistics of fish populations. Bulletin of the Fisheries Research Board of Canada 191. 382 pp.

Shaklee, J. B., and K. P. Currens. 2003. Genetic stock identification and risk assessment. Pages 291–328 in E. M. Hallerman, editor. Population genetics: principles and applications for fisheries scientists. American Fisheries Society, Bethesda, Maryland.

Schultz, E.T., K.E. Reynolds, and D.O. Conover. 1996. Countergradient variation in growth among newly hatched *Fundulus heteroclitus*: geographic differences revealed by common-environment experiments. Functional Ecology 10: 366-374.

Schulze, T., and coauthors. 2006. Response of the residential piscivorous fish community to introduction of a new predator type in a mesotrophic lake. Canadian Journal of Fisheries and Aquatic Sciences 63(10):2202-2212.

Siler, D. H. and G. B. Beyerle. 1986. Introduction and management of northern muskellunge in Iron Lake, Michigan. American Fisheries Society Special Publication 15: 257-262.

Smith, P.W. 1979. The fishes of Illinois. University of Illinois Press, Urbana, Illinois, USA.

Thornton, K. W. 1990. Perspectives on reservoir limnology. Pages 1-13 in K. W. Thornton, B. L. Kimmel, and F. E. Payne, editors. Reservoir limnology: ecological perspectives. John Wiley & Sons Inc.

Underwood, A. J. 1994. On beyond BACI: Sampling designs that might reliably detect environmental disturbances. Ecological Applications 4(1):3-15.

Vander Zanden, M.J., T. E. Essington, and Y. Vadeboncoeur. 2005. Is pelagic top-down control in lakes augmented by benthic energy pathways? Canadian Journal of Fisheries and Aquatic Sciences 62: 1422-1431.

Wagner, C.P., M.J. Jennings, J.M. Kampa, and D.H. Wahl. 2007. Survival, growth, and tag retention in age-0 muskellunge implanted with passive integrated transponders. North American Journal of Fisheries Management 27: 873-877.

Wagner, C.P., L.M. Einfalt, A. Scimone, and D.H. Wahl. 2009. Effects of fin-clipping on the foraging behavior and growth of age-0 muskellunge. North American Journal of Fisheries Management. In Press.

Wahl, D.H. and Stein, R.A. 1991. Food consumption and growth of three esocids field tests of a bioenergetic model. Transactions of the American Fisheries Society 120: 230-246.

Wahl, D.H. and R.A. Stein. 1989. Comparative vulnerability of three esocids to largemouth bass *Micropterus salmoides* predation. Canadian Journal of Fisheries and Aquatic Sciences 46: 2095-2103.

Wahl, D.H., and R. A. Stein. 1988. Selective predation by three esocids: the role of prey behavior and morphology. Transactions of the American Fisheries Society 117(2): 142-151.

Werner, E.E., and Hall, D.J. 1977. Habitat partitioning in a freshwater fish community. Journal of the Fisheries Research Board of Canada 34: 360–370.

Willis, D. W., J. F. Smeltzer, and S. A. Flickinger.1984.Characteristics of a crappie population in an unfished small impoundment containing northern pike. North American Journal of Fisheries Management 4:385-389.

Wingate, P.J., and J.A. Younk. 2007. A program for successful muskellunge management -A Minnesota success story. Environmental Biology of Fishes 79: 163-169.

Yamahira, K. and D.O. Conover. 2002. Intra- vs. interspecific latitudinal variation in growth: adaptation to temperature or seasonality? Ecology 83: 1252-1262.

Younk, J.A. and R.F. Strand. 1992. Performance evaluation of four muskellunge *Esox masquinongy* strains in two Minnesota lakes. Minnesota Department of Natural Resources Section of Fisheries Investigational Report No. 418. pp 22.

Table 1. 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 2. 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 2. 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 2. Continued.

Lake	Stock	Population	Stocking Date	Number of Fish		Number per Hectare		Mean Length (mm)	Mean Weight (g)
				Stocked	Adjusted	Stocked	Adjusted		
			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 2. 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 3. 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 ($\pm$0)[a]	605 ($\pm$13)[b]	628 ($\pm$11)[b]	<0.01
Male	3	782 ($\pm$57)	756 ($\pm$10)	772 ($\pm$8)	0.05
	4	-	845 ($\pm$14)	840 ($\pm$12)	0.57
	5	-	910 ($\pm$17)[a]	883 ($\pm$17)[b]	0.02
	6	-	900 ($\pm$0)	921($\pm$38)	0.60
	7	-	945 ($\pm$38)	-	-
Female	3	-	790 ($\pm$29)	784 ($\pm$10)	0.77
	4	-	885 ($\pm$27)	882 ($\pm$17)	0.83
	5	909 ($\pm$0)	963 ($\pm$18)	962 ($\pm$14)	0.25
	6	962 ($\pm$0)	967 ($\pm$139)	1005 ($\pm$111)	0.75
	7	-	-	1068 ($\pm$0)	-
			Weight		
Combined	2	480 ($\pm$0)[a]	1519 ($\pm$112)[b]	1740 ($\pm$96)[b]	<0.01
Male	3	3680 ($\pm$762)	3283 ($\pm$162)	3428 ($\pm$128)	0.28
	4	-	4712 ($\pm$222)	4562 ($\pm$99)	0.32
	5	-	5941 ($\pm$362)	5424 ($\pm$387)	0.06
	6	-	6350 ($\pm$0)	5778 ($\pm$567)	0.37
	7	-	6150 ($\pm$225)	-	-
Female	3	-	3669 ($\pm$457)	3871 ($\pm$332)	0.47
	4	-	6033 ($\pm$475)	5634 ($\pm$274)	0.15
	5	5880 ($\pm$0)	7448 ($\pm$574)	7294 ($\pm$434)	0.32
	6	6190 ($\pm$0)	6940 ($\pm$2723)	8171 ($\pm$2424)	0.40
	7	-	-	9650 ($\pm$0)	-

Table 4. 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 2002-2011 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 5. 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 2003-2011. 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	-	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	855 (±0)	851 (±17)	874 (±10)	0.09
	6	942 (±0)	885 (±20)	886 (±16)	0.33
	7	-	-	-	-
Female	3	-	680 (±48)[a]	758 (±27)[b]	0.01
	4	-	871 (±31)	844 (±13)	0.11
	5	-	910 (±27)	928 (±16)	0.26
	6	-	934 (±36)	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 6. 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	-	832 (±16)[a]	786 (±19)[b]	<0.01
	5	-	-	-	-
Female	3	817 (±36)	793 (±15)	821 (±10)	0.05
	4	964 (±0)[a]	922 (±25)[ab]	891 (±40)[b]	0.03
	5	-	975 (±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	-	4512 (514)[a]	3200 (±591)[b]	<0.01
	5	-	-	-	-
Female	3	3750 (±1383)	3858 (±335)	4485(±227)	0.05
	4	7140 (±0)	6612 (±775)	5707 (±448)	0.07
	5	-	7750 (±0)	-	-

Table 7. 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	$0.05 (\pm0.05)^b$	$1.05 (\pm0.73)^a$	$0.88 (\pm0.21)^{ab}$	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 8. 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 9. 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 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
			Illinois Population				
3	1.28		0.34		0.72		
		0.41		1.00		1.00	
4	0.36		0.50		0.65		0.35
		0.44		0.46		1.00	
5	0.59		0.16		0.23		0.28
		0.31		0.13		1.00	
6+	-		0.18		0.02		0.55
		-					
Mean		0.32 (±0.35)		0.40 (±0.22)		1.00 (±0)	
			Ohio River Drainage				
3	0.36		-		0.13		
		0.75		-		1.00	
4	0.23		0.27		-		0.60
		0.30		1.00		-	
5	0.27		0.07		0.45		-
		0.42		1.00		1.00	
6+	-		0.11		0.09		0.60
Mean		0.19 (±0.17)		0.67 (±0.65)		1.00 (±0)	

Table 10. Catch-per-unit effort (number per net night) from spring fyke net surveys conducted 2010-2011 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
Illinois Population			
3	1.48		0.61
		0.26	
4			0.39
Mean		0.26 (±0)	
Ohio River Drainage			
3	0.73		0.58
		0.33	
4			0.24
Mean		0.33 (±0)	
Upper Mississippi Drainage			
3	0.14		0.04
		0.14	
4			0.02
Mean		0.14 (±0)	

Table 11. 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	Wheel Lake
Control Lake	Lake Jacksonville	Lake Springfield	Lincoln Trail Lake	Homer Lake	Walnut Point Lake	Lake Le-aqua-na	Lake Lou Yeager	Schuy - Rush Lake
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	1993-1996, 1998
Years After	2002, 2005-2007	2003-2007	1997,2001 2005,2007	2003-2008	2006-20010	2001-2007	2000,2002 2003,2006	2000,2003 2004,2006
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	1999,2000,2002-2003 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)	2.55 (2.47-3.18)
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)	1.73 (0.27-4.2)
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)	1.66(0.71-4.51)
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)	54.43 (0-80)

Table 12. 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

Table 13. Results of paired before-after control-impact analysis for 6 community parameters in response to muskellunge introduction in Ridge Lake and Lake Mingo.

Parameter	Stocked Before - After	Control Before - After	Difference(±SE)	P
		Ridge Lake		
Zooplankton Density (#/L)	-144.80	6.14	-150.94(198.19)	0.40
Cladoceran Length (mm)	0.04	-0.08	0.12(0.10)	0.31
Chlorophyll a (ug/L)	0.35	-3.99	4.34(9.13)	0.57
Total P (ug/L)	-40.4	-51.95	11.55(53.55)	0.71
Larval Fish Density (# /m^3)	6.84	29.01	6.84(24.10)	0.38
Benthos Density (#/m^2)	3094.55	898.22	2196.33(3188.19)	0.23
		Lake Mingo		
Cladoceran Density (#/L)	133.13	17.16	115.97(52.59)	0.08
Cladoceran Length (mm)	0.00	-0.19	-0.19(0.08)	0.07
Chlorophyll a (ug/L)	-2.07	-0.18	-1.89(5.77)	0.76
Total P (ug/L)	-45.83	-20.09	-25.74(50.47)	0.64
Larval Fish Density (# /m^3)	-1.82	28.31	30.13(39.41)	0.46
Benthos Density (#/m^2)	2656.17	1734.09	922.08(3013.99)	0.78
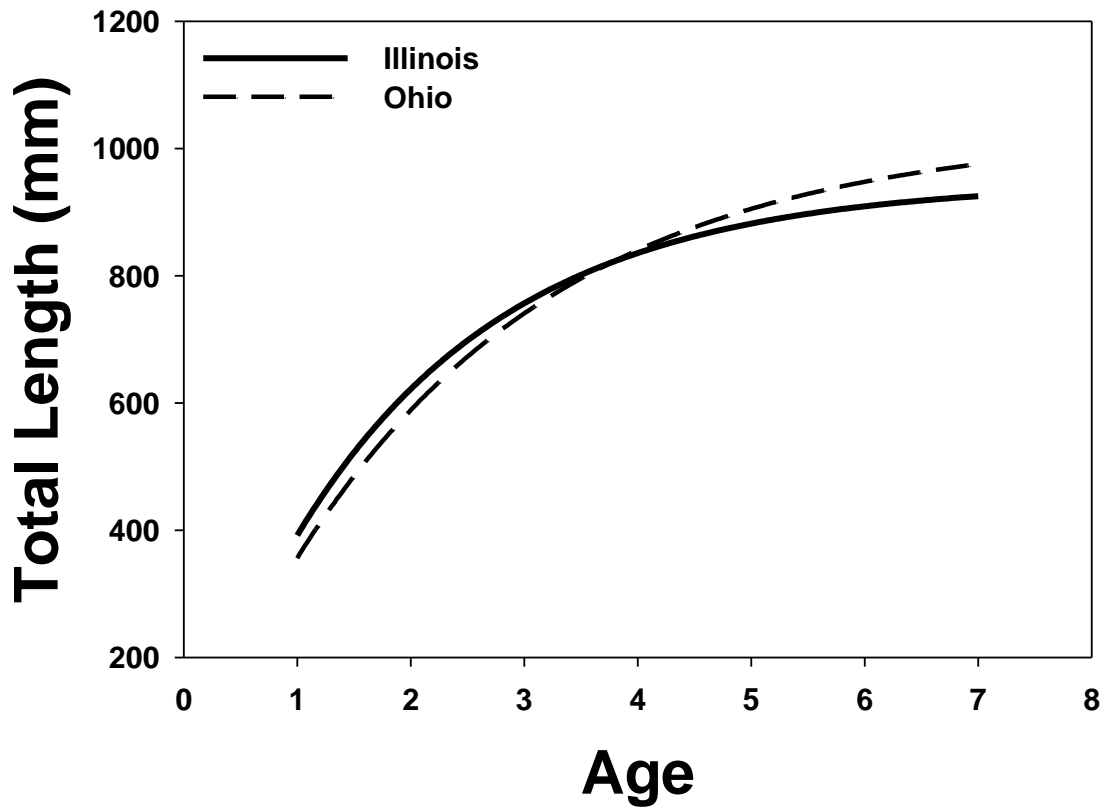
Figure 1. Fitted von Bertalanffy growth functions for male muskellunge from the Illinois population (solid line) and the Ohio River drainage stock (dashed line) sampled in Lake Mingo from fall 2003 through spring 2011.
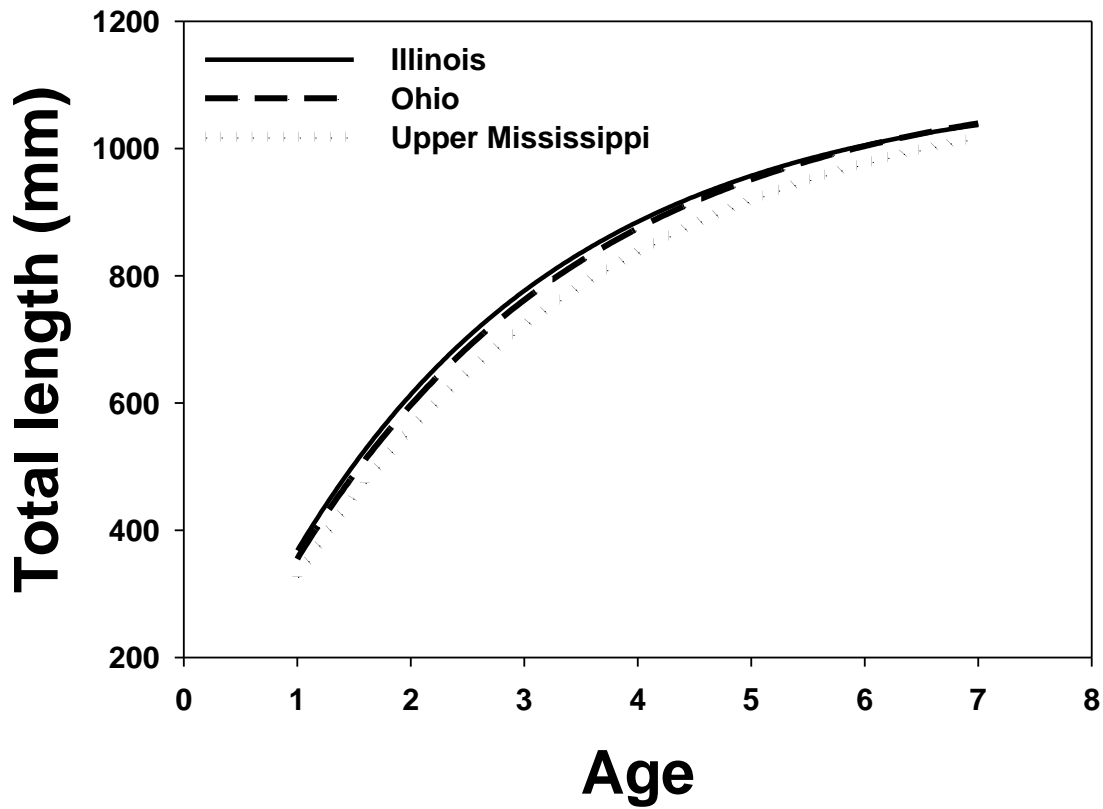
Figure 2. Fitted von Bertalanffy growth functions for female muskellunge from the Illinois population (solid line) the Ohio River drainage stock (long dashed line) and the Upper Mississippi River drainage stock sampled in Lake Mingo from fall 2003 through spring 2011. The growth function for the Upper Mississippi River drainage stock (short dashed line) was fit by pooling both genders due to low survival of this stock.
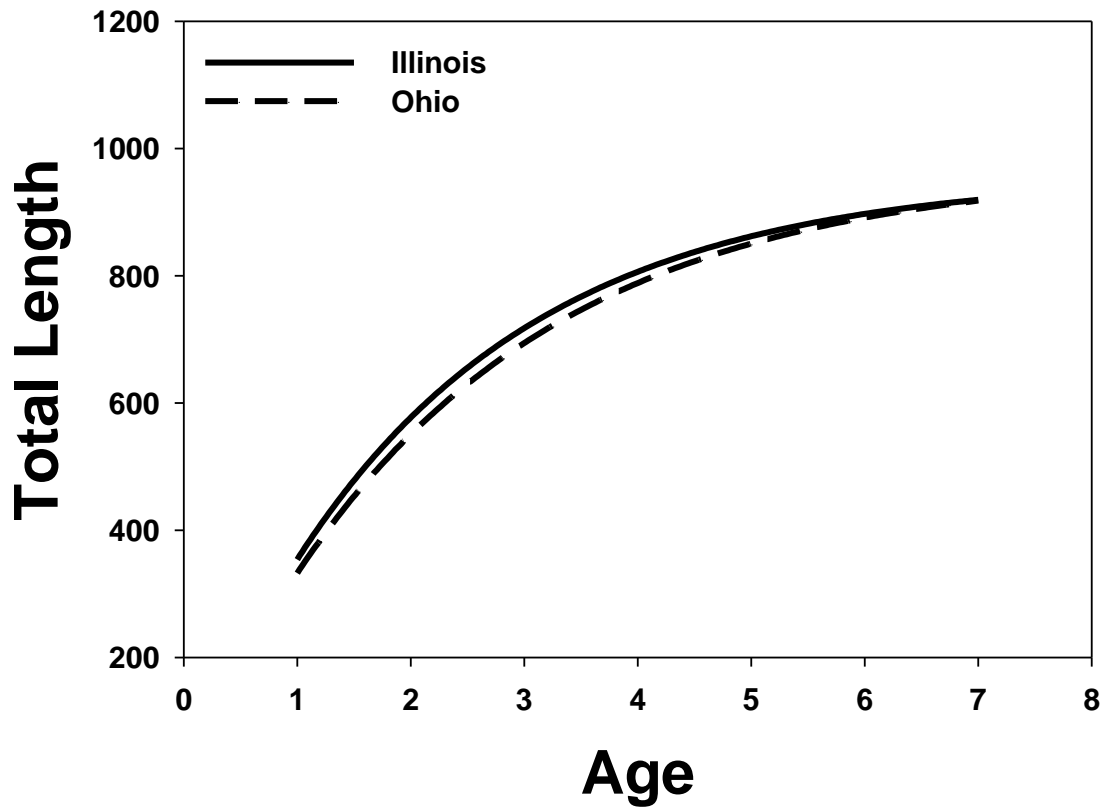
Figure 3. Fitted von Bertalanffy growth functions for male muskellunge from the Illinois population (solid line) and the Ohio River drainage stock (dashed line) sampled in Pierce Lake from fall 2004 through spring 2011.
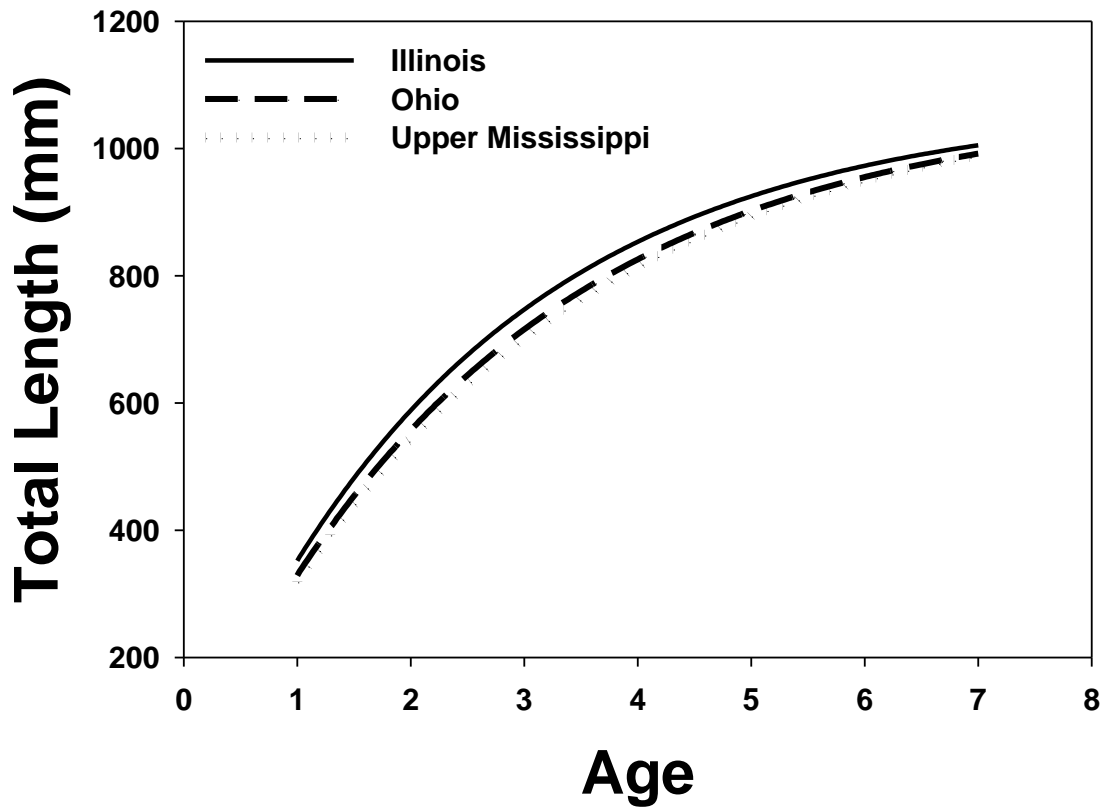
Figure 4. Fitted von Bertalanffy growth functions for female muskellunge from the Illinois population (solid line), the Ohio River drainage stock (long dashed line), and the Upper Mississippi river Drainage stock sampled in Pierce Lake from fall 2004 through spring 2011. The growth function for the Upper Mississippi River drainage stock (short dashed line) was fit by pooling both genders due to low survival of this stock.
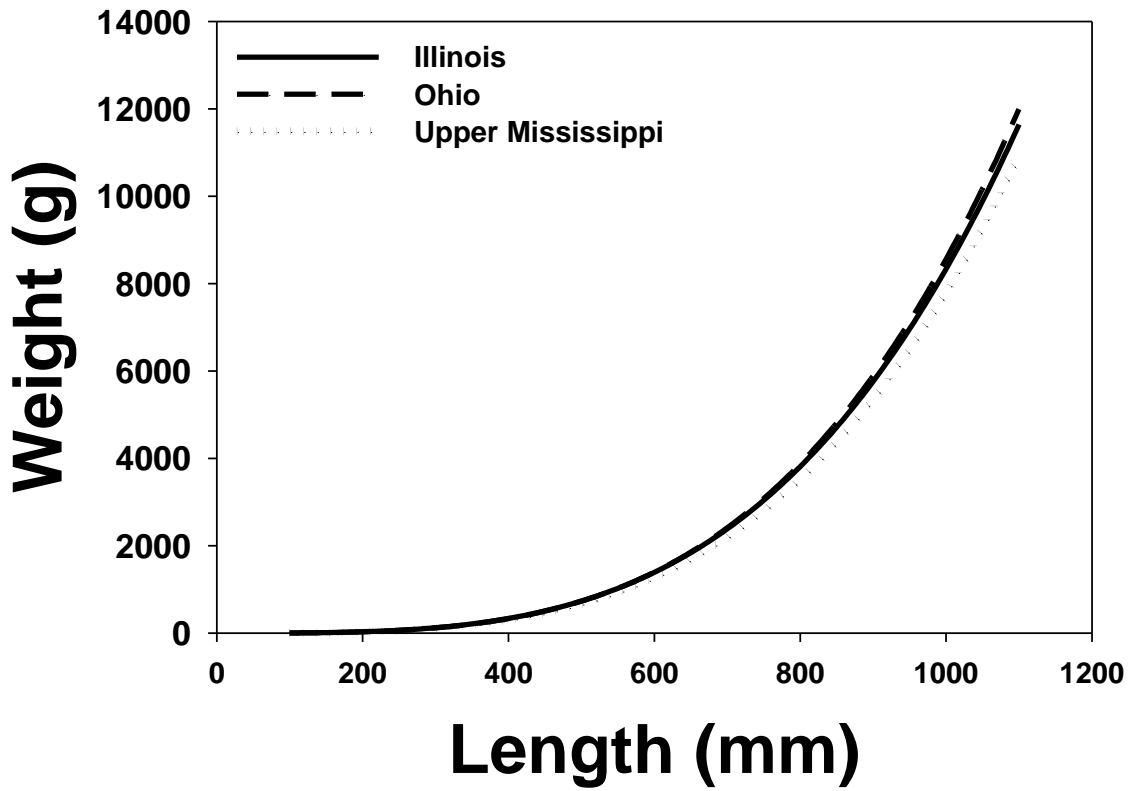
Figure 5. Length-weight relationships for muskellunge of the Illinois population (solid line), Ohio river drainage (long dashed line), and the Upper Mississippi River drainage (short dashed line) in three lakes (Lakes Mingo, Pierce, and Sam Dale) in Illinois.
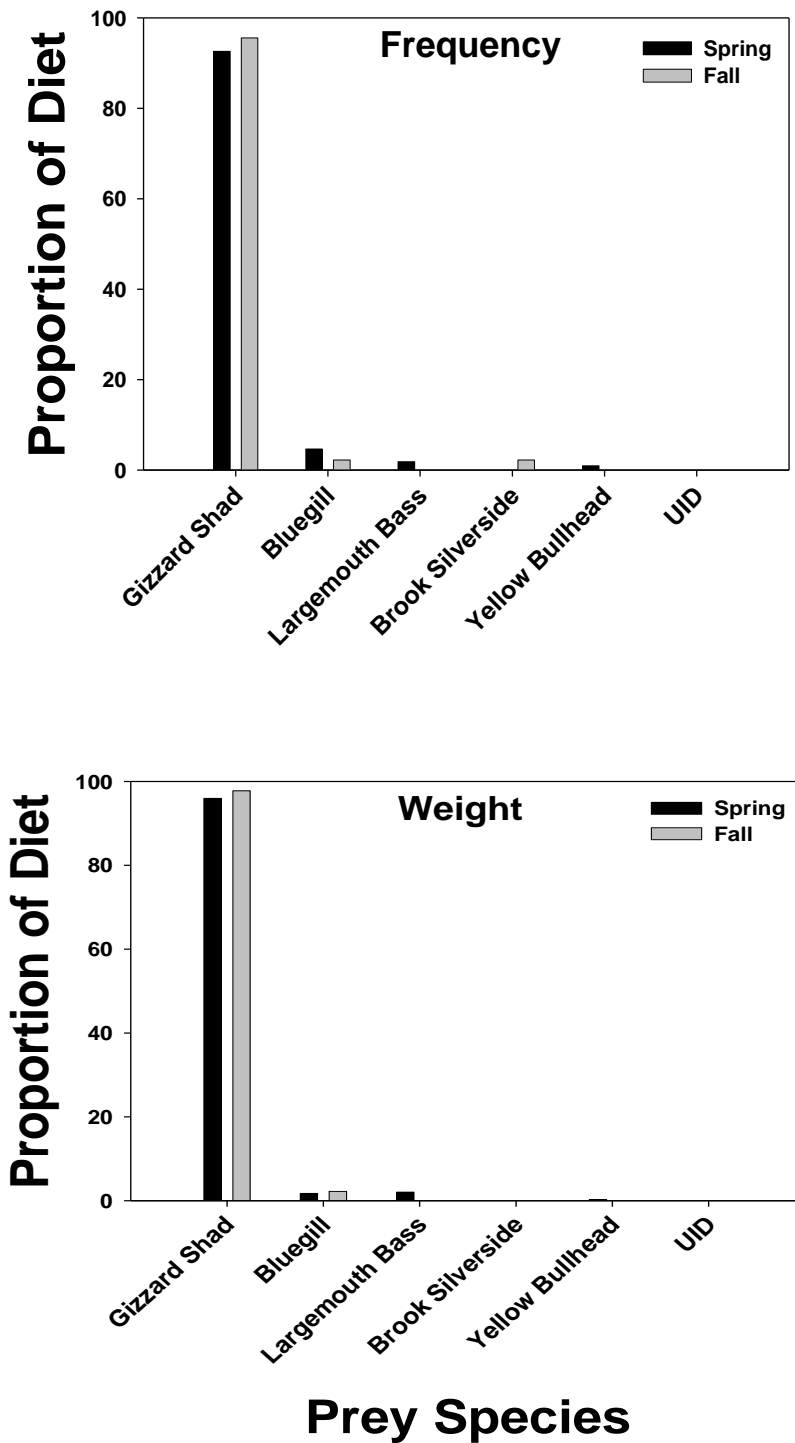
Figure 6. Diet composition of muskellunge sampled in Mingo Lake via trap netting and shoreline electrofishing, May 2007 – May 2011, by season. Spring is March, April, and May, while Fall is September, October, November. Data are pooled across years, upper panel shows diet by frequency of occurrence, lower shows proportion by wet weight. Proportions of diet by wet weight and frequency are transformed to percentages by multiplying by 100.
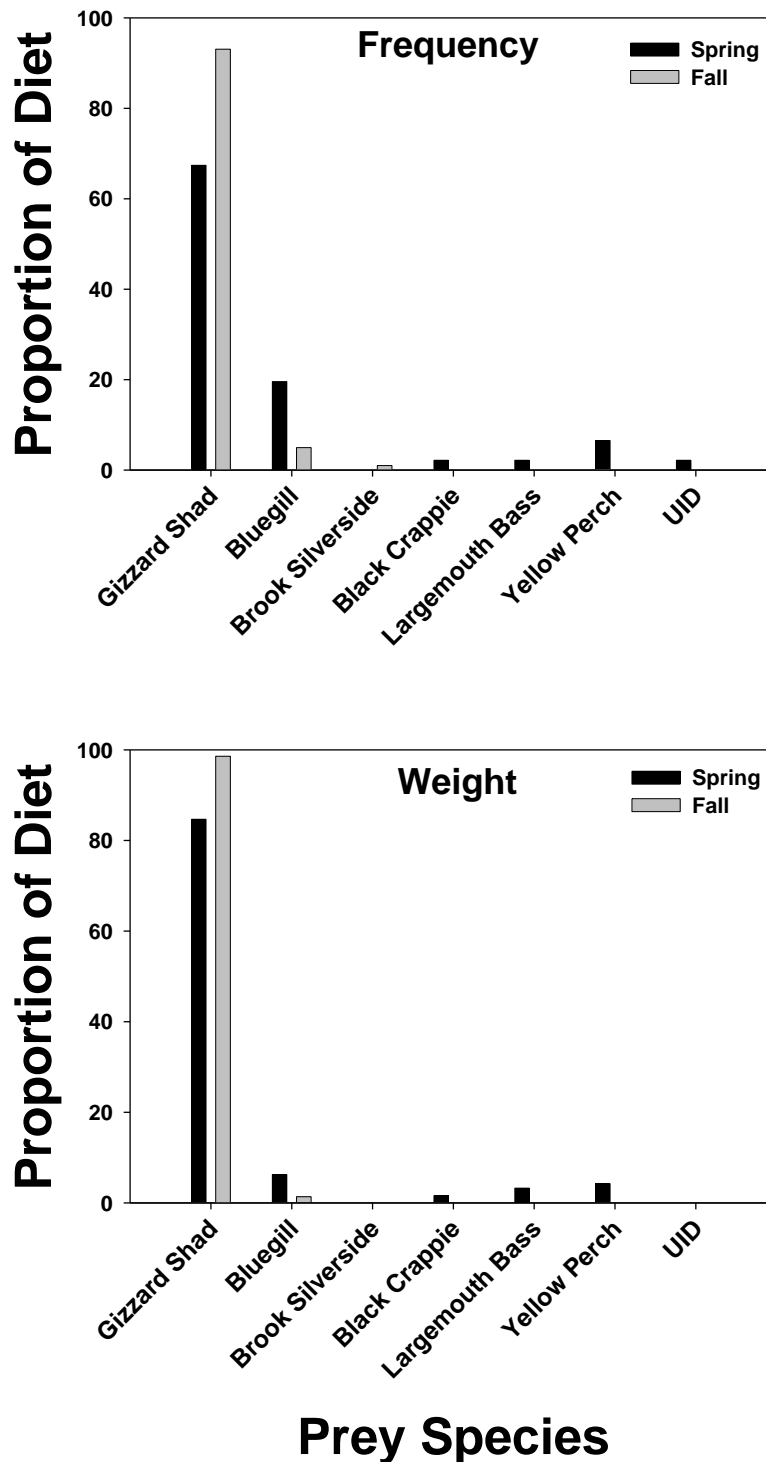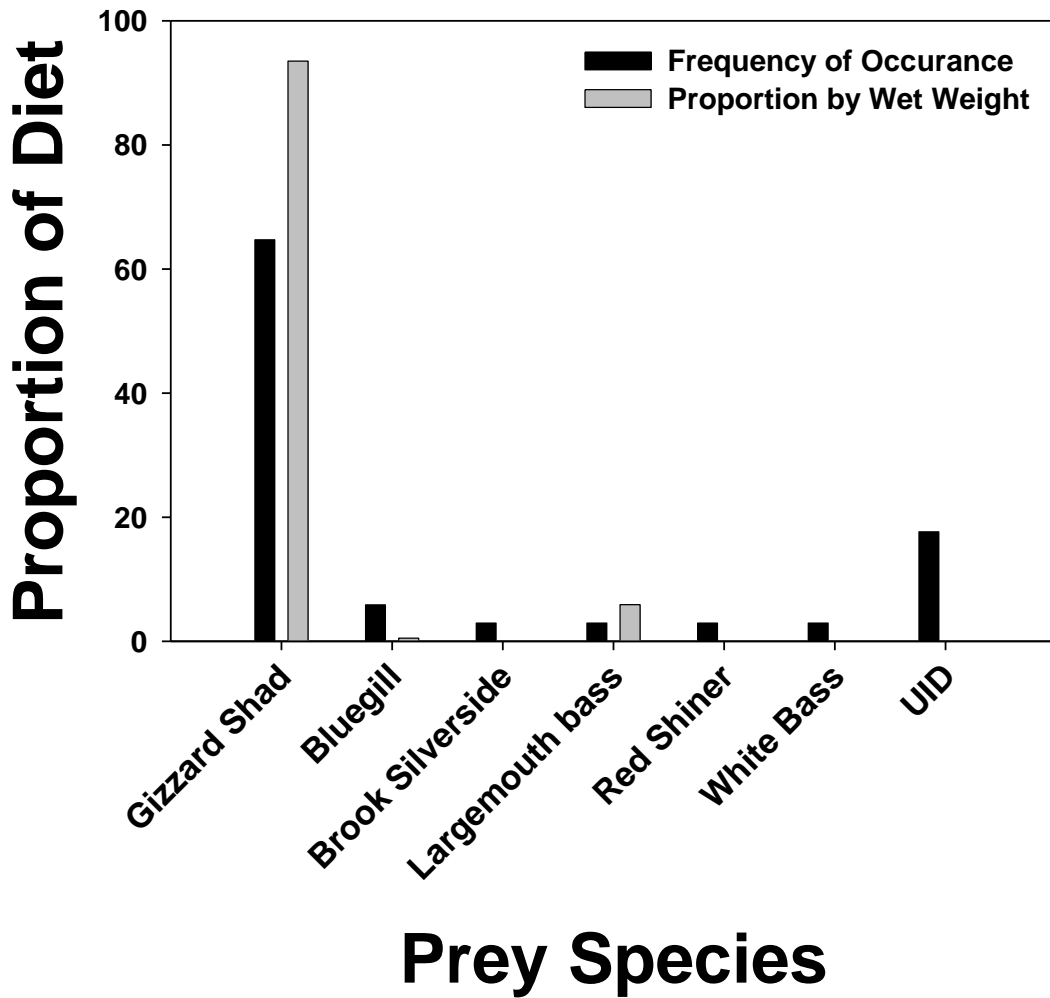
Figure 7. Diet composition of muskellunge sampled in Pierce Lake via trap netting and shoreline electrofishing, May 2007 – May 2011, by season. Spring is March, April, and May, while Fall is September, October, November. Data are pooled across years, upper panel shows diet by frequency of occurrence, lower shows proportion by wet weight. Proportions of diet by wet weight and frequency are transformed to percentages by multiplying by 100.
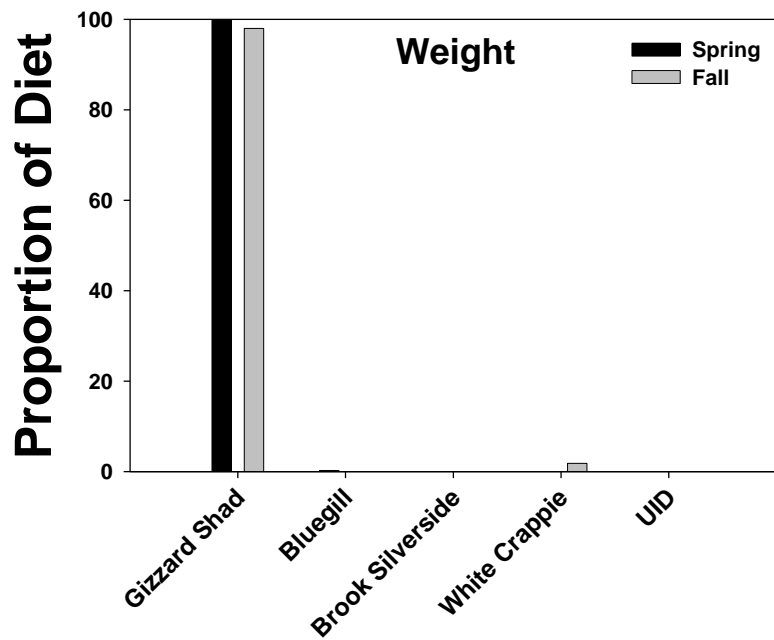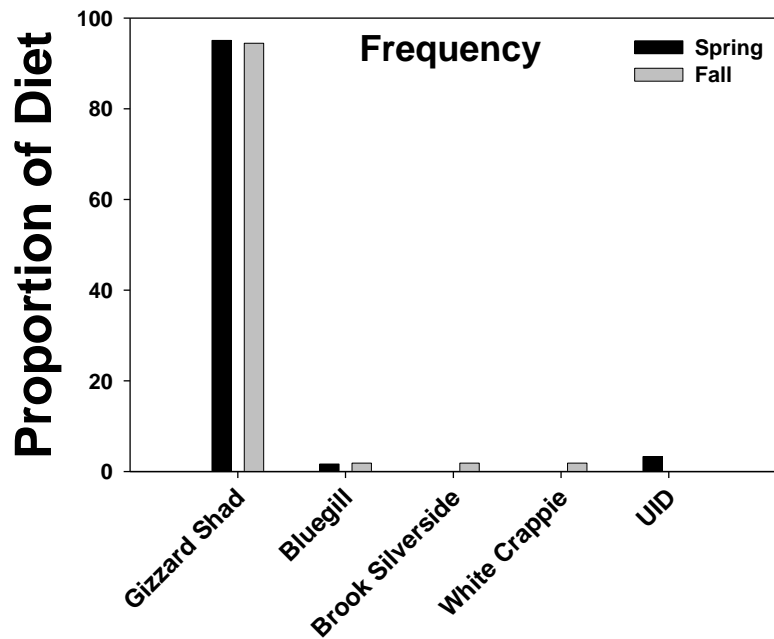
Figure 8. Diet composition of muskellunge sampled in Sam Dale Lake via trap netting and shoreline electrofishing, May 2007 – May 2011, by season. Spring is March, April, and May, while Fall is September, October, November. Data are pooled across years, upper panel shows diet by frequency of occurrence, 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 Lake Shelbyville via shoreline electrofishing, May 2007 – May 2011. 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.
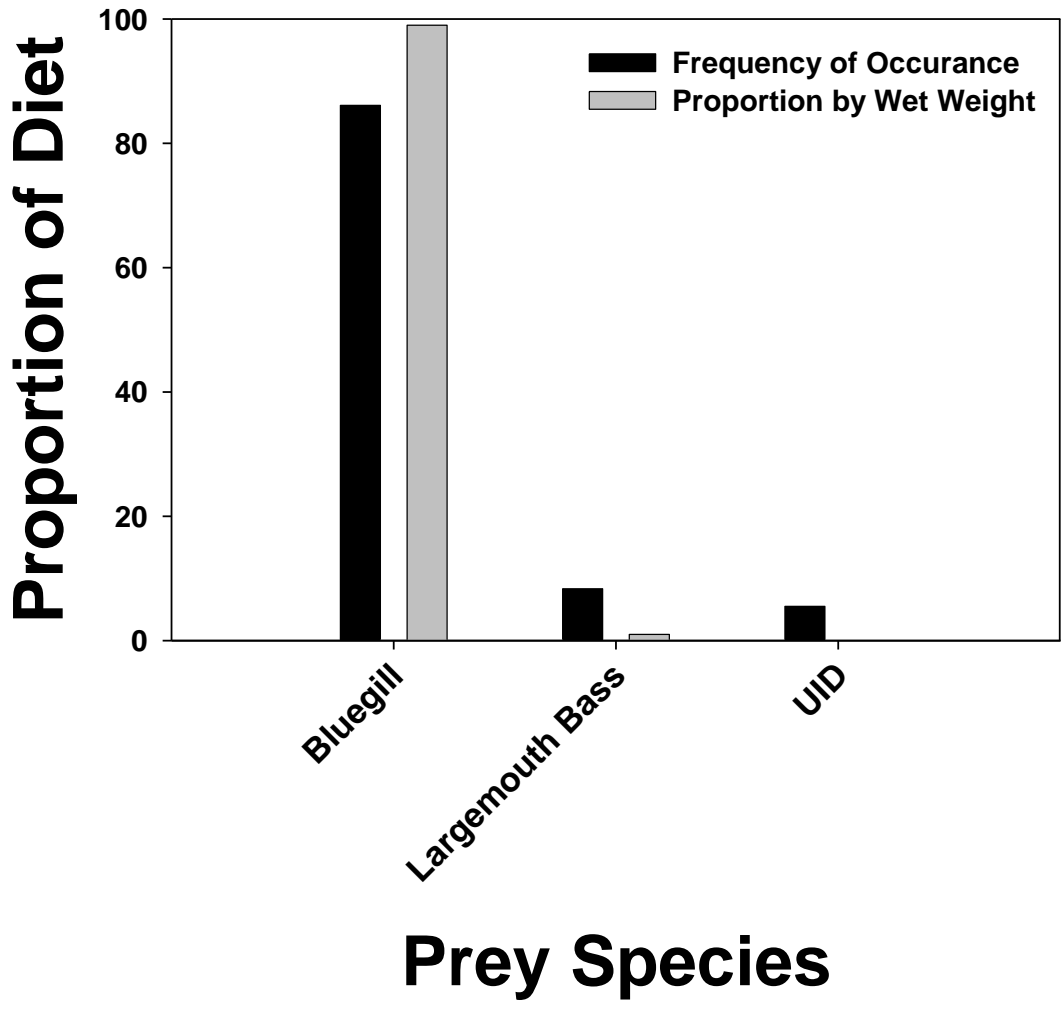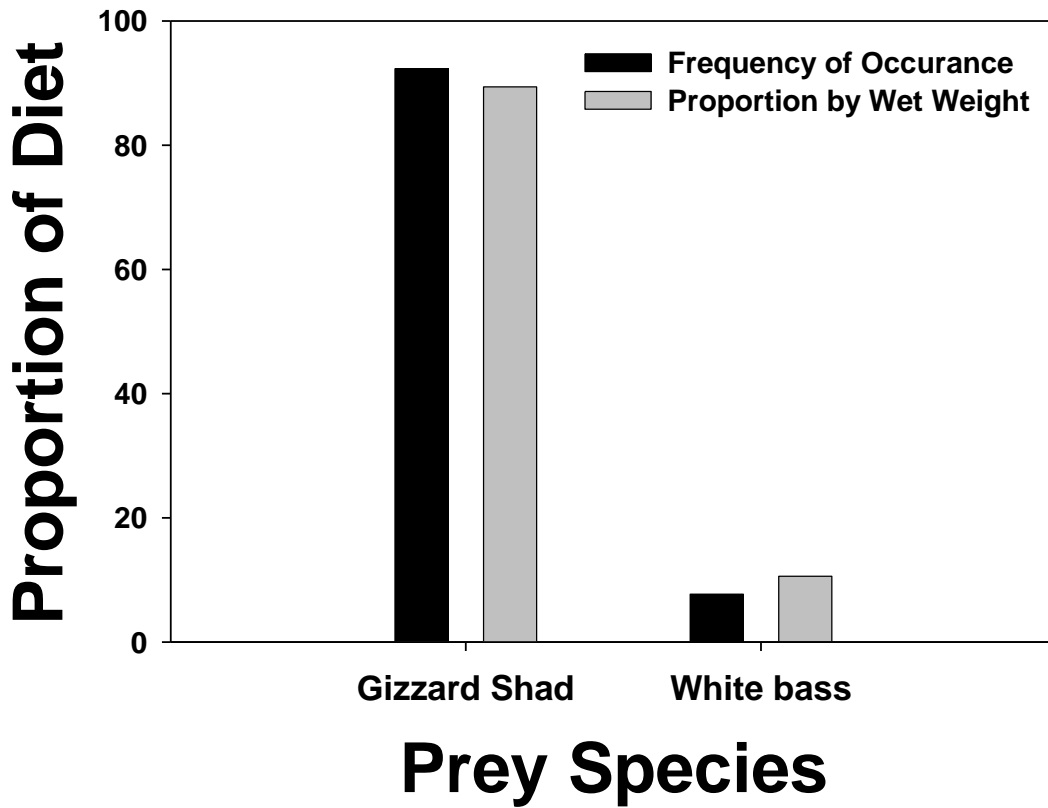
Figure 10. Diet composition of muskellunge sampled in Ridge Lake via shoreline electrofishing, modified fyke netting, and angler creel, May 2007 – May 2011. Data are pooled across samples from each season (Spring-Fall) and year. Proportions of diet by wet weight and frequency are transformed to percentages by multiplying by 100.
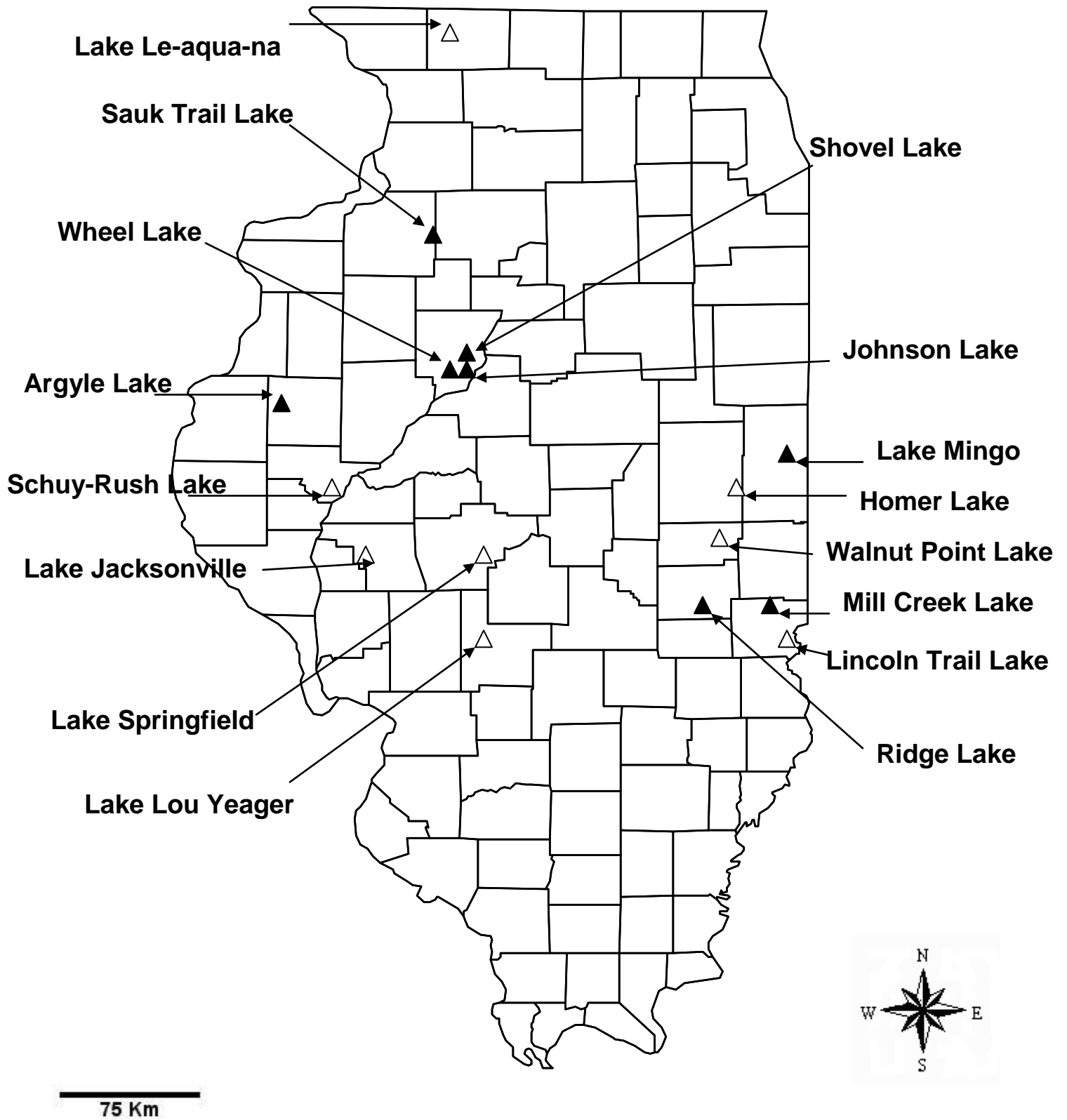
Figure 11. Diet composition of muskellunge sampled in Otter Lake via shoreline electrofishing, modified fyke netting, and angler creel, May 2007 – May 2011. Data are pooled across samples from each season (Spring-Fall) and year. Proportions of diet by wet weight and frequency are transformed to percentages by multiplying by 100.

Figure 12. Locations of 16 spatially paired Illinois lakes used to evaluate effects of muskellunge introduction on population characteristics of resident fishes. See table 1 for specific lake pairings.
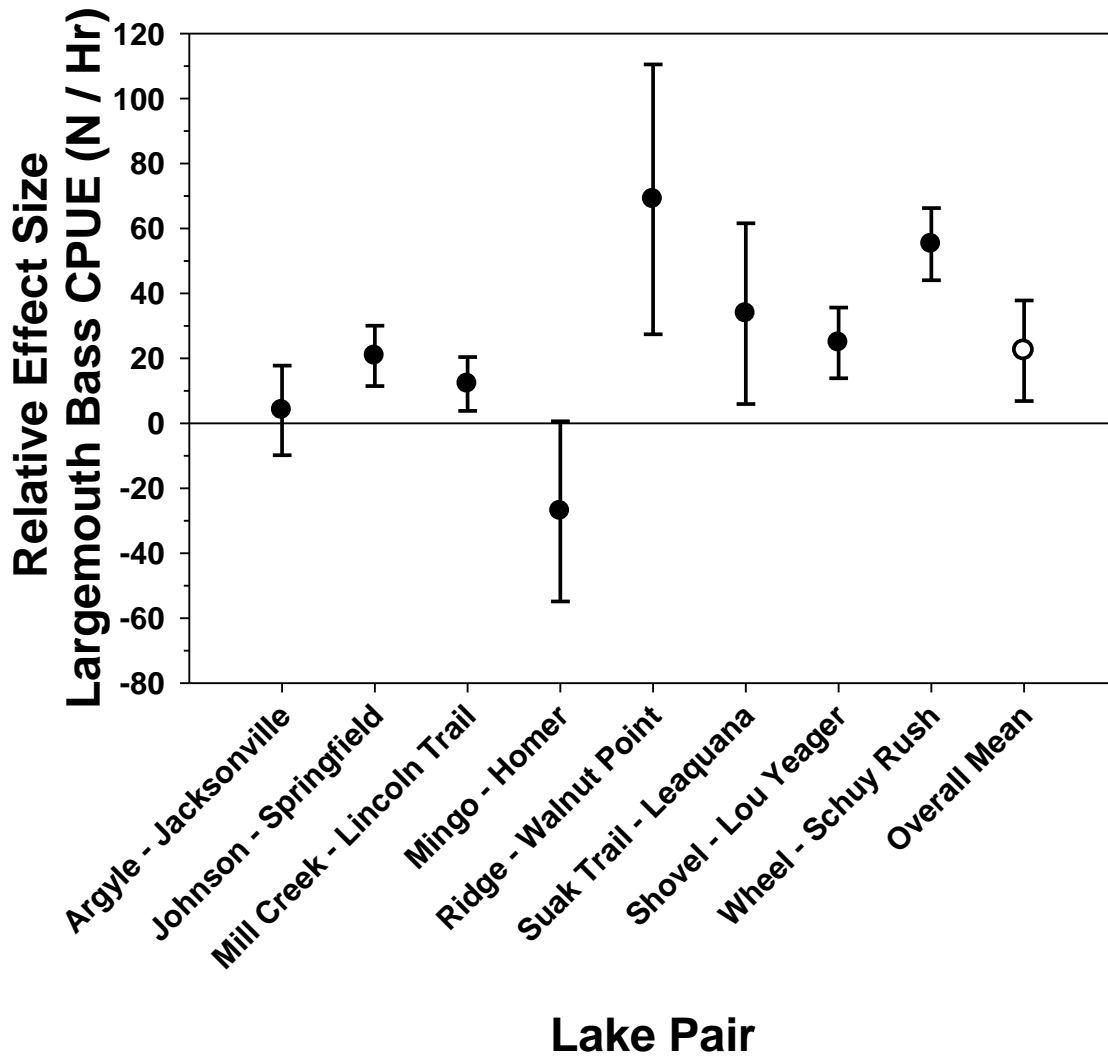
Figure 13. Relative effect sizes for number of largemouth bass collected per hour during standardized fall electrofishing surveys in Illinois lakes (N = 8) receiving muskellunge introductions relative to their spatially paired control lakes (N = 8). Error bars represent standard errors of effect sizes 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.
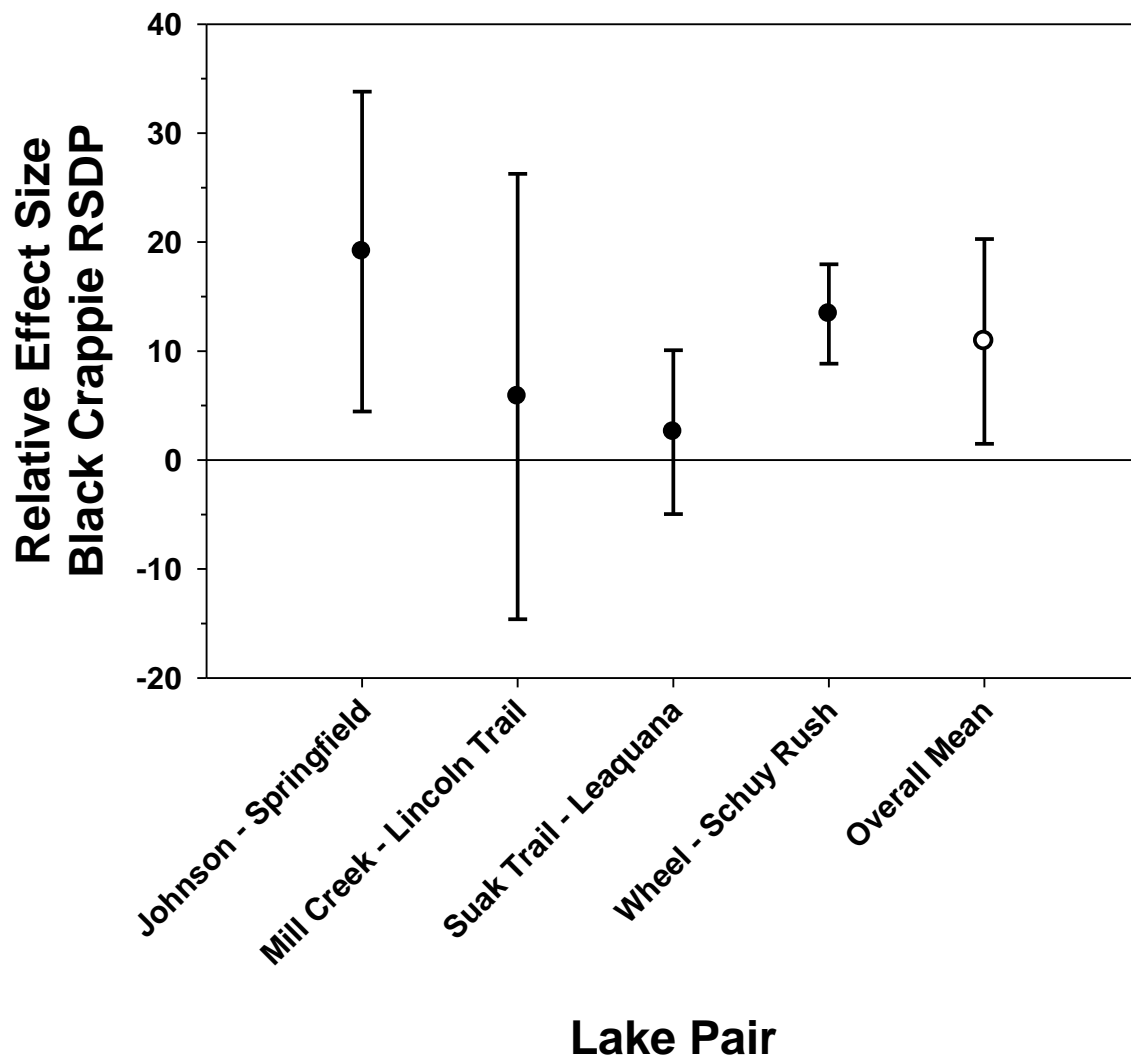
Figure 14. Relative effect sizes for relative stock distribution of preferred length black crappie collected during standardized fall electrofishing surveys in Illinois lakes (N = 4) receiving muskellunge introductions relative to their spatially paired control lakes (N = 4). Error bars represent standard 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.
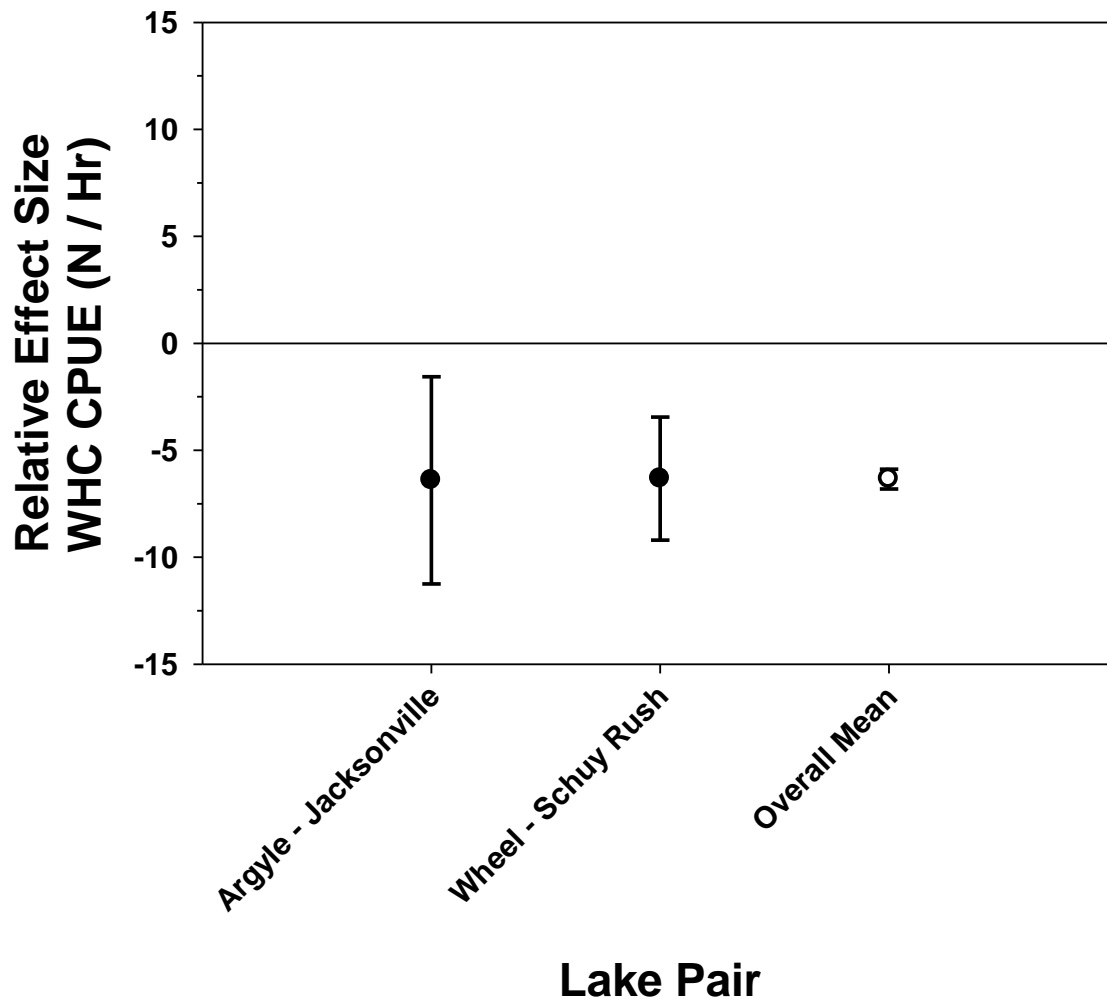
Figure 15. Relative effect sizes for number of white crappie collected per hour during standardized fall electrofishing surveys in Illinois lakes (N = 2) receiving muskellunge introductions relative to their spatially paired control lakes (N = 2). Error bars represent standard errors of effect sizes 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.