

EFFECT OF HARVEST MORTALITY ON MUSKELLUNGE SIZE STRUCTURE IN  
WISCONSIN'S CEDED TERRITORY

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## ABSTRACT

Muskellunge *Esox masquinongy* management is often aimed at producing large trophy individuals. However, muskellunge are a long-lived species that occurs naturally at low population densities, which makes them susceptible to the effects of harvest mortality. Muskellunge populations within Wisconsin's ceded territory are exposed to both angling and spearing fisheries. My objective was to determine the extent that harvest mortality affects muskellunge population size structure in Wisconsin's ceded territory. Cleithra were used to estimate age and to back-calculate growth histories of muskellunge to determine the scope for growth among a range of populations producing small-, medium-, and large-bodied fish in Wisconsin's ceded territory. Female muskellunge grew larger ( $L_{\infty} = 47.7$  in) than males ( $L_{\infty} = 40.2$  in). Small-bodied populations had a mean asymptotic length of 38.7 in, medium-bodied populations had a mean asymptotic length of 45.0 in, and large-bodied populations had a mean asymptotic length of 50.4 in. These results formed the basis of an individual-based simulation model that predicted the influence of varying levels of harvest mortality from recreational angling and tribal spearing fisheries on the size structure of muskellunge populations. Both angling and spearing fisheries caused a decline in muskellunge population size structure as harvest mortality associated with either fishery increased. Numbers of trophy length muskellunge ( $\geq 40, 45, \text{ or } 50$  in) decreased as harvest mortality from either fishery increased across all body types and regulations. Combinations of angling and spearing mortality were identified that reduced relative stock density of muskellunge greater than 38 in and 42 in below levels used by the Wisconsin Department of Natural Resources to define trophy fisheries. These results can be used to aid in management of muskellunge

populations in northern Wisconsin's ceded territory by providing a series of growth standards for muskellunge populations and by identifying levels of angling and spearing exploitation that influence the trophy potential of a muskellunge population.

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## INTRODUCTION

The muskellunge *Esox masquinongy* is an ecologically and economically important game fish across North America (Menz and Wilton 1983; Belusz and Witter 1986; Simonson and Hewett 1999). Muskellunge are a top-level predator that consume a wide variety of prey species (Scott and Crossman 1973; Bozek et al. 1999). The Wisconsin Department of Natural Resources (WDNR) estimated that anglers spend 5.3-million angler-days and \$425-million pursuing muskellunge annually (Simonson 2008). Muskellunge also support a culturally important tribal spearing fishery for members of Wisconsin's Chippewa tribes. Because many anglers value muskellunge as a trophy fish, a better understanding of how angling and spearing exploitation affect muskellunge population size structure in northern Wisconsin is needed.

In Wisconsin, muskellunge were originally limited to lakes and rivers within the drainages of the Amnicon, Chippewa, Wisconsin, and Mississippi rivers (Figure 1; Oehmcke et al. 1977). However, since the late 1890s muskellunge have been stocked throughout the state, which has led to the creation of over 400 new muskellunge waters (Nevin 1901; Kerr 2011). Currently, Wisconsin has 711 lakes and 83 river segments that are considered muskellunge waters, which are managed to provide trophy-, action-, and harvest-oriented fisheries (Simonson 2008). Most of Wisconsin's muskellunge waters (> 85%) are located within the northern portion of the state known as the ceded territory (Figure 2; Staggs et al. 1990).

### *Ceded territory and management implications*

Wisconsin's ceded territory was created as a result of the Treaties of 1837 and 1842, in which Chippewa tribes ceded their land to the United States government

(Erickson 2007). In ceding their land, the Chippewa reserved the right to hunt, fish, and gather within the ceded territory. In 1974, two members of the Lac Courte Oreilles band of Chippewa were arrested for spear fishing off their reservation within the ceded territory. Their arrest resulted in a series of court cases, in which the Lac Courte Oreilles, along with the Bad River, Lac du Flambeau, Sokaogon, Red Cliff and St. Croix bands of Chippewa sought relief from interference by the state of Wisconsin in their fishing rights guaranteed by the Treaties of 1837 and 1842. The resultant court rulings, known as the Voight decision, affirmed the Chippewa's treaty rights within the ceded territory and established a framework for the exercise of treaty rights (Erickson 2007).

Most tribal harvest occurs during spring, which is primarily aimed at spawning walleye *Sander vitreus*, although more than 5,000 muskellunge have been harvested since 1989 (US DOI 2010). The WDNR and the Great Lakes Indian Fish and Wildlife Commission (GLIFWC) jointly manage walleye and muskellunge fisheries in the ceded territory through harvest quotas, catch monitoring, and by adjusting bag and minimum size limits. Harvest quotas, termed "safe harvest levels", are set on individual lakes within the ceded territory so that the risk of exceeding maximum sustainable exploitation rates of 35% for walleye and 27% for muskellunge is less than 1-in-40 (Staggs et al. 1990; Hansen et al. 1991). Safe harvest levels are determined either by recent ( $\leq 2$  years old) mark-recapture population abundance estimates, or with a regression model that uses past mark-recapture estimates to predict adult abundance based on lake surface area (Hansen 1989; Staggs et al. 1990). Further, safe harvest levels incorporate a safety factor to account for year-to-year variation in adult abundance (Hansen et al. 1991).

Tribal spring spearing seasons were originally met with strong resistance from local and non-local opponents that sometimes resulted in violent, often racially motivated, protests at boat landings (US DOI 1991; McRoy and Bichler 2011). Muskellunge anglers still view spearing as a major problem facing Wisconsin's muskellunge fishery (Margenau and Petchenik 2004; Isermann et al. 2011). However, the Voight decision provided a legal framework to manage muskellunge populations for both recreational angling and subsistence tribal fisheries within the ceded territory.

### *Effects of angling*

Angling impacts aquatic ecosystems and fish communities (Rochet 1998; Post et al. 2002; Coleman et al. 2004; Cooke and Cowx 2004; Lewin et al. 2006; O'Toole et al. 2009). High exploitation and size selectivity associated with angling changes age and size structure, reduces genetic variability, alters trophic levels, and modifies habitat (Lewin et al. 2006). Angling is a popular activity in Wisconsin, with licensed anglers spending 22-million angler-days fishing and contributing over \$1-billion to the state's economy (WDNR 2007). Because of the large number of anglers and amount of time spent fishing Wisconsin's waters, the potential impact of angling on the state's fish populations must be understood.

Muskellunge are particularly susceptible to the impact of angling because they are a long-lived species that occur naturally at low population density (Hanson 1986; Frohnauer et al. 2007). Increases in annual mortality can cause a decrease in mean age of muskellunge, with as little as a 2% increase in annual mortality causing a reduction in mean age of muskellunge from 23 years to 21 years, which is comparable to a 70%

decline in recruitment (Casselman et al. 1996). Although 98% of all muskellunge anglers practice catch and release, muskellunge populations may still be negatively affected (Muoneke and Childress 1994; Margenau and Petchenik 2004). Esocid fisheries subjected to low harvest rates decline, which suggests significant post-release mortality (Newman and Storck 1986). Following capture via angling, muskellunge experience a reduction in blood pH, elevated levels of lactic acid and glucose, and a drop in total carbon dioxide and bicarbonate concentrations (Beggs et al. 1980; Landsman et al. 2011). Muskellunge caught using a single hook and live bait are subject to high levels of mortality because many fish are hooked in the stomach, which resulted in 22% of fish dying within 50 days of capture and 83% within one year of capture (Margenau 2007). Muskellunge captured by experienced, specialized anglers may experience low (< 5%) levels of post-release mortality (Strand 1986; Frohnauer et al. 2007; Landsman et al. 2011). However, Landsman et al. (2011) suggested that more studies are needed to address the possibility that post-release mortality rates may be higher for muskellunge captured by inexperienced, generalist anglers.

Anglers often preferentially remove the largest individuals (Gabelhouse Jr. and Willis 1986; Pierce et al. 1995; Miranda and Dorr 2000). This size selectivity can impact age and size structure of fish populations, which results in populations dominated by smaller, younger individuals (Goedde and Coble 1981; Rochet 1998). Changes in size structure associated with angling have been shown for several species found in Wisconsin waters (Coble 1988; Braña et al. 1992; Lyons et al. 1996; Miranda and Dorr 2000).

Within the ceded territory of northern Wisconsin, muskellunge are exposed to both angling and spearing exploitation. Because anglers value large muskellunge, the

effects of angling and spearing on muskellunge population size structure must be understood. Consequently, the WDNR would like to know how muskellunge population size structure responds to changes in harvest mortality, and more specifically, if trophy muskellunge fisheries can be sustained in lakes with consumptive fisheries.

### *Objective*

My objective was to determine the extent that harvest mortality affects muskellunge population size structure in Wisconsin's ceded territory. Cleithra were used to estimate age and to back-calculate growth histories of muskellunge to determine the scope for growth among a range of populations producing small-, medium-, and large-bodied fish in northern Wisconsin. Using these results, an individual-based, age-structured simulation model was built to predict how muskellunge population size structure responded to varying levels of harvest mortality from both angling and spearing fisheries.

## **METHODS**

### *Study area*

All data used to estimate muskellunge growth potential and construct the simulation model were collected by the WDNR and the GLIFWC within the ceded territory. Wisconsin's ceded territory encompasses 22,400 square miles and all or part of 30 counties in the northern third of the state (Figure 2; Staggs et al. 1990). Each year, roughly 25 lakes within the ceded territory were selected for monitoring during 1990–2011 (Hansen et al. 2000). Creel surveys were conducted from the first Saturday in May through early March of the following year, and corresponded to Wisconsin's open season

for game fish species. Creel surveys use a random stratified roving access design and were conducted on all weekends and holidays, and 2–3 randomly chosen weekdays per week (Rasmussen et al. 1998). Clerks count number of anglers, record effort, catch, and harvest, measure harvested fish, and examine fish for marks. Additionally, GLIFWC creel clerks were present at each lake during the open water spearing season to count all fish and measure a sample of speared fish (Staggs et al. 1990). Abundance of adult muskellunge was estimated by mark-recapture during 1999–2010. Muskellunge mark-recapture surveys were done over a two year period. In the first year, muskellunge were captured throughout the sampling season using fyke nets and electrofishing, and marked with a fin clip. The following year, muskellunge were recaptured with fyke nets in mid-May to coincide with the muskellunge spawning season. Abundance was estimated using Bailey's modification of the Lincoln-Petersen single-census mark-recapture estimator (Ricker 1975; Cornelius and Margenau 1999; Margenau and AveLallemant 2000).

#### *Estimation of age and growth potential*

Muskellunge age was estimated using the cleithrum, a bone in the fish's pectoral girdle, which more accurately records age and growth information throughout the life of a muskellunge than other structures such as scales or fin rays (Johnson 1971; Harrison and Hadley 1979; Casselman and Crossman 1986). Cleithra were collected by the WDNR and the GLIFWC during 1995–2011 from lakes within the ceded territory (Figure 3). Cleithra collected by the WDNR were from muskellunge captured in spring and fall fyke netting and electrofishing surveys, donated by taxidermists (angler caught), or found dead. All cleithra collected by the GLIFWC were taken from muskellunge harvested by tribal spearers during 2007–2011.

Prior to age estimation, cleithra with excess tissue were cleaned by either being submersed in near boiling water for a short period of time (< 30 seconds) and scrubbed or placed within a colony of dermestid beetles (*Dermestes* spp.) for a week. When estimating age, cleithra were placed in a black dish and immersed in water to improve visibility of annuli. Once immersed, cleithra were examined with the naked eye under ambient light.

I served as the primary reader for all muskellunge cleithra (reader 1). To detect any potential biases in and evaluate precision of my age estimates, two independent readers estimated muskellunge age using a subset of cleithra. Each reader had previous experience estimating esocid age using the cleithrum, and when estimating each fish's age, had no prior knowledge of that fish's gender or length at capture. Age-bias plots were constructed for each combination of readers (Campana et al. 1995). Each age-bias plot was visually interpreted with respect to a 1:1 equivalence line (reader X = reader Y), with age estimates of reader Y presented as the mean age and 95% confidence interval corresponding to each age class estimated by reader X (Campana et al. 1995). Precision between each readers' age estimates were compared by calculating the coefficient of variation (CV), which can be expressed as a ratio of the standard deviation to the mean (Campana et al. 1995).

Following age estimation, growth increments were measured along the anterior axis of the cleithrum from the origin to the outside edge of each annulus (Casselman and Crossman 1986). Growth increments were measured using a digital caliper ( $\pm 0.001$  in). Individual growth histories (length-at-age) were back-calculated using the biological-intercept model proposed by Campana (1990):

$$L_t = L_T + \frac{S_t - S_T}{S_T - S_0} (L_T - L_0)$$

where  $L_t$  is muskellunge length at time  $t$ ,  $L_T$  is muskellunge length at capture,  $S_t$  is cleithrum radius at time  $t$ ,  $S_T$  is cleithrum length at capture,  $S_0$  is cleithrum length at formation, and  $L_0$  is muskellunge length at time of cleithrum formation. The biological-intercept model is a linear method of back-calculation, and hinges on accurately defining a biological intercept. The biological-intercept is defined as the fish and structure length corresponding to initiation of proportionality between fish and structure growth, which often begins at hatching (Campana 1990). No information in the literature explicitly states when cleithrum formation begins in muskellunge. However, the cleithrum is visible at 11.6 mm for redbfin pickerel *E. americanus americanus*, a close relative of the muskellunge (Mansueti and Hardy 1967). At time of hatching, redbfin pickerel are 5–6 mm long, and grow an additional 5–6 mm before the cleithrum becomes visible (Fuiman 1982). Applying this to muskellunge, which at time of hatching have a mean length of 8.7 mm, the cleithrum should be visible after growing an additional 5–6 mm to ~15 mm total length (Fuiman 1982). The cleithrum grows at roughly 1/10 the rate of the total body length, so if the cleithrum is visible when a muskellunge reaches 15 mm in length ( $L_0$ ), the anterior cleithral radius should be approximately 1.5 mm ( $S_0$ ; Casselman and Crossman 1986).

The von Bertalanffy growth model was fit to each fish's back-calculated growth history:

$$L_t = L_\infty (1 - e^{-K(t-t_0)}) + \varepsilon$$

where  $L_t$  is muskellunge length at age  $t$ ,  $L_\infty$  is asymptotic length,  $K$  is the instantaneous rate at which  $L_t$  approaches  $L_\infty$ ,  $t$  is age,  $t_0$  is the hypothetical age that the muskellunge would have had zero length, and  $\varepsilon$  is additive process error (Ricker 1975; Quinn and Deriso 1999). Growth parameters (hereafter referred to as "parameters") were estimated by nonlinear regression. Not all estimates of growth potential were biologically reasonable. For example, some muskellunge had  $L_\infty$  estimates greater than 60 in, with a few exceeding 100 in. Unrealistic parameter estimates, likely caused by individuals that were young (sexually immature) or growing exceptionally fast (linear back-calculated length-at-age data), necessitated a need to objectively evaluate the "certainty" of each parameter estimate. Coefficient of variation served as a measure of how well each parameter was estimated. Each parameter had an accompanying estimate of asymptotic standard error, a term that can be used interchangeably with standard deviation (Motulsky and Christopoulos 2003). By treating each parameter estimate as a mean, coefficient of variation was calculated by dividing the parameter's asymptotic standard error by the parameter estimate. Estimates of  $L_\infty$  were used to evaluate precision of estimated growth potential. Muskellunge with a CV of  $L_\infty$  less than 20% were judged to have a well estimated growth potential. However, several fish ( $< 10$ ) had a CV less than 20%, but with unrealistically high estimates of  $L_\infty$  ( $> 70$  in). Over the last 40 years, very few muskellunge caught and reported by anglers have exceeded 60 in, which puts some doubt into whether muskellunge can attain such large sizes (Kerr 2007; J. Bunch, Muskies Inc, personal communication). Therefore, only muskellunge with a CV less than 20% and estimates of  $L_\infty$  less than 65 in were used in the present analysis. This length was chosen

arbitrarily to allow for some plasticity on the upper end of muskellunge growth potential, and is roughly 5 in longer than the current world record muskellunge.

Von Bertalanffy growth curves were constructed for each muskellunge that had a well estimated and biologically reasonable  $L_{\infty}$ . Muskellunge exhibit sexually dimorphic growth, with females attaining larger sizes than males (Casselman and Crossman 1986; Casselman et al. 1999). I constructed a likelihood-ratio test with models for each gender as the full model (6 parameters) and an overall model for both genders (3 parameters) as the reduced model to test for differences in growth between sexes (Kimura 1980; Bates and Watts 1988; Cerrato 1990).

Populations were classified based on mean  $L_{\infty}$  into three categories: small-, medium-, or large-bodied. Mean  $L_{\infty}$  was calculated for all populations with two or more muskellunge, and populations were designated as either small-, medium-, or large-bodied based on the 33<sup>rd</sup> and 67<sup>th</sup> percentiles. An inverse relationship exists between  $L_{\infty}$  and  $K$  (Ricker 1975). Populations with a mean  $L_{\infty}$  below the 33<sup>rd</sup> percentile were considered to be small-bodied and fast growing (low  $L_{\infty}$  and high  $K$ ), populations with a mean  $L_{\infty}$  above the 67<sup>th</sup> percentile were considered to be large-bodied and slow growing (high  $L_{\infty}$  and low  $K$ ), and populations with a mean  $L_{\infty}$  falling between the 33<sup>rd</sup> and 67<sup>th</sup> percentiles were considered to be medium-bodied and average growing (mean  $L_{\infty}$  and  $K$ ). Mean von Bertalanffy growth curves were then constructed for each body type. This classification was designed to estimate distributions (mean and standard deviation) of growth parameters of muskellunge populations across a range of growth types. These distributions formed the heart of my simulation model.

### *Muskellunge population size structure*

An individual-based simulation model was used to quantify the impact of harvest mortality on muskellunge population size structure in northern Wisconsin (Figure 4). This model assumed that muskellunge size structure is shaped by two factors: growth potential and mortality. For example, a muskellunge may have the potential to reach a record length, but if it lives in a population subject to a high mortality rate, that fish's chances of record length is low. The model required three inputs: growth potential (small-, medium-, or large-bodied), angling regulation (minimum length limit), and instantaneous harvest mortality. Based on these inputs, a virtual population composed of individual muskellunge, each with a unique set of growth parameters, was generated, allowed to grow, and subjected to a risk of mortality at each age.

Unique sets of von Bertalanffy growth parameters were generated for each muskellunge based on the relationship between  $K$  and the other two parameters,  $L_\infty$  and  $t_0$ . The parameter  $K$  was chosen as the basis for generating estimates of  $L_\infty$  and  $t_0$  because it was more highly correlated with  $t_0$  than  $L_\infty$ . Linear regression was used to generate values of  $L_\infty$  and  $t_0$  based on  $\log_e$ -transformed estimates of  $K$ . Values of  $K$  were transformed into natural logarithms to meet assumptions of linear regression (Sokal and Rohlf 2003).  $\log_e$ -transformed values of  $K$  were generated using the inverse of the lognormal cumulative distribution function of  $K$ , where  $\log_e$ -transformed values of  $K$  are normally distributed with a mean  $\bar{x}$  and standard deviation  $S$ . Therefore, all parameters generated were defined by the mean and standard deviation associated with each body type's  $\log_e$ -transformed value of  $K$ .

Once growth parameters had been generated for each muskellunge within the model, fish were allowed to grow and exposed to a risk of mortality at each age. Muskellunge were allowed to reach a maximum age of 30 years, which corresponds to the oldest muskellunge age on record (Casselman and Crossman 1986). Survival of individual fish from age  $j$  to age  $j + 1$  was a random process governed by annual survival rate:

$$S_j = e^{-Z_j}$$

where  $S_j$  is annual survival rate at age  $j$ , and  $Z_j$  is total instantaneous mortality at age  $j$  (Ricker 1975). Total instantaneous mortality  $Z_j$  for each age  $j$  was treated as a combination of instantaneous harvest mortality  $F_j$  for each age  $j$  and instantaneous natural mortality  $M$ :

$$Z_j = F_j + M$$

Total instantaneous harvest mortality  $F_j$  was composed of instantaneous angling mortality  $F_{angling}$  and instantaneous spearing mortality  $F_{spearing}$ :

$$F_j = F_{angling} + F_{spearing}$$

For each fishery, instantaneous harvest mortality  $F_j$  was simulated using a selectivity curve and a fully-selected instantaneous harvest mortality  $F$  specified as a model input:

$$F_j = s_j F$$

where  $s_j$  is the selectivity of the gear at age  $j$ , and  $F$  is a fully-selected instantaneous harvest mortality specified for the simulation. Five selectivity curves were constructed

for each body type: one for each minimum length limit (28-in, 40-in, 45-in, and 50-in) used to regulate muskellunge angling fisheries, and another for the spearing fishery. Selectivity was estimated for angling and spearing fisheries based on length-specific catches  $C_l$  recorded during WDNR creel surveys and GLIFWC creel census conducted during angling and spearing seasons during 1990–2010, and mean length-specific abundances  $N_l$  estimated using length-frequency data obtained during WDNR muskellunge mark-recapture population abundance estimates during 1990–2010:

$$s_j = \frac{C_l}{N_l}$$

Length-specific abundance was estimated using Bailey’s modification of the Lincoln-Petersen estimator for each 2-in length class by pooling length-frequency data for marked, captured, and recaptured muskellunge from mark-recapture population abundance estimates during 1990–2010 (Ricker 1975; Cornelius and Margenau 1999; Margenau and AveLallemant 2000). Relative selectivity  $S_j$  was then estimated as the length-specific selectivity divided by the maximum length-specific selectivity:

$$S_j = \frac{s_j}{\max(s_j)}$$

Relative selectivity for each fishery was modeled as:

$$S_j = \frac{1}{1 + e^{-\log_e 19 \left( \frac{j-j_{50}}{j_{95}-j_{50}} \right)}}$$

where  $j$  is age,  $j_{50}$  is age at 50% relative selectivity, and  $j_{95}$  is age at 95% relative selectivity (Haddon 2001). Because the above model required age-specific data, rather

than length-specific data from mark-recapture surveys, the von Bertalanffy growth model was rearranged to solve for age at a given length (each 2-in length class):

$$t = -\log_e \frac{1 - \frac{L_t}{L_\infty}}{K} + t_0$$

where  $t$  is the estimated age at a given length,  $L_t$  is length at age  $t$ ,  $L_\infty$  is the mean asymptotic length for a given body type,  $K$  is the mean instantaneous growth coefficient for a given body type, and  $t_0$  is the mean hypothetical age at which a muskellunge would have zero length for a given body type. Using this method, age can only be estimated for lengths less than or equal to each body type's mean  $L_\infty$ . Without an estimated age for a given length, the model fails to predict relative selectivity. Therefore, muskellunge with lengths greater than each body type's mean  $L_\infty$  were assumed to be fully vulnerable to capture ( $S_j = 1.0$ ). Additionally, because some body types had a mean  $L_\infty$  less than a given minimum length limit, selectivity could not be modeled and knife-edge selectivity was assumed (Quinn and Deriso 1999). In these cases, muskellunge smaller than a given minimum length limit were considered invulnerable to capture ( $S_j = 0.0$ ), while those larger than a given minimum length limit were fully vulnerable to capture ( $S_j = 1.0$ ).

Instantaneous natural mortality  $M$  was estimated using Pauly's (1980) equation:

$$\log_{10} M = -0.0066 - 0.279 \log_{10} L_\infty + 0.6543 \log_{10} K + 0.4634 \log_{10} T$$

where  $L_\infty$  and  $K$  are parameters from the von Bertalanffy growth model, and  $T$  is an estimate of the mean annual temperature at the position where the fish was caught ( $^{\circ}\text{C}$ ). Median values of  $L_\infty$  and  $K$  were used for each body type. Mean annual air temperature data collected during 1971–2000 from across the ceded territory were used as a proxy for

mean annual surface temperature (Pauly 1980; Wisconsin State Climatology Office 2011).

Because none of the parameters used in the simulation model are known with certainty, parameters  $K$  and  $M$  were allowed to vary based on their median value and sample standard deviation. Because values of  $K$  were used to predict corresponding values of  $L_\infty$  and  $t_0$ , all von Bertalanffy parameters varied at each simulation model iteration. Instantaneous natural mortality  $M$  varied by generating a random temperature  $T$  at each simulation model iteration.

Each body type was simulated under two different fisheries: angling-only and mixed (angling and spearing). A spearing-only fishery was not simulated because muskellunge populations in northern Wisconsin are likely always subjected to recreational angling exploitation (spearing would never be the sole source of exploitation). Four different minimum length limits are used to regulate muskellunge angling fisheries in Wisconsin: 28-in, 40-in, 45-in, and 50-in. Only regulations appropriate for a given body type were simulated (Table 1). For example, large-bodied muskellunge populations are not managed using a 28-in minimum length limit because this minimum-length limit would not adequately protect muskellunge from harvest long enough to allow growth to trophy sizes. For each combination of body type, fishery, and minimum length limit, either  $F_{angling}$  or  $F_{spearing}$  was simulated over a range from 0.0 to 0.5 in increments of 0.1. For simulating a mixed fishery, all combinations of  $F_{angling}$  and  $F_{spearing}$  were simulated over the range of 0.0 to 0.5 for each fishery. Additionally, each fishery was simulated at observed exploitation rates (average and 95<sup>th</sup> percentile) estimated from angling creel surveys and spearing creel censuses conducted by the

WDNR and GLIFWC. Each simulation began with 1,000 age-1 muskellunge, which were subjected to mortality and allowed to grow for a maximum of 30 years, and iterated 1,000 times.

To quantify how muskellunge size structure changed with harvest mortality, the number of muskellunge attaining trophy size at time of death was recorded after each iteration. Defining what constitutes a trophy muskellunge is difficult, and often varies with angler expectations and experience (Margenau and Petchenik 2004). To account for these differences, three different lengths were used in defining a trophy muskellunge: 40 in, 45 in, and 50 in. Relative stock density (RSD) indices are used by the WDNR to define and monitor trophy muskellunge fisheries. Relative stock density is defined as the percentage of stock length individuals that are also greater than a specified length:

$$RSD = \frac{\text{number of individuals} \geq \text{a specified length}}{\text{number of individuals} \geq \text{stock length}} \times 100$$

Trophy muskellunge fisheries in Wisconsin are defined as having a RSD-38  $\geq$  30 and RSD-42  $\geq$  17 (T. Simonson, Wisconsin Department of Natural Resources, personal communication). To allow calculation of RSD-38 and RSD-42, the number of muskellunge greater than or equal to stock length (30 in), 38 in, and 42 in were also recorded after each iteration. Median values ( $\pm$  95% confidence interval) were calculated for the number of muskellunge  $\geq$  40 in, 45 in, and 50 in, RSD-38, and RSD-42 for each simulated scenario.

## RESULTS

### *Estimation of age and growth potential*

For 306 muskellunge collected from across northern Wisconsin (Figure 3), length at capture averaged 36.9 in and ranged from 9.9 to 53.0 in (Figure 5). Reader 1 overestimated muskellunge age relative to the other two readers (Figure 6). Mean coefficient of variation was 7.3% between readers 1 and 2, 5.9% between readers 1 and 3, and 5.6% between readers 2 and 3. Across all muskellunge, mean age was 9.5 years and ranged 0–20 years (Figure 7). Residuals of the cleithrum-body length relationship confirmed linearity (Figure 8). The final sample consisted of 223 muskellunge after 83 fish were eliminated because of unreliable parameter estimates ( $CV > 20\%$  or  $L_{\infty} > 65$  in).

Muskellunge exhibited sexually dimorphic growth ( $F_{3,32} = 213.5$ ,  $P < 0.001$ ). Female muskellunge ( $L_{\infty} = 47.7$  in) grew larger than males ( $L_{\infty} = 40.2$  in; Figure 9). Small-bodied muskellunge reached a mean asymptotic length of 38.7 in (Figure 10). Medium-bodied muskellunge reached a mean asymptotic length of 45.0 in (Figure 10). Large-bodied muskellunge reached a mean asymptotic length of 50.4 in (Figure 10).

Relationships among von Bertalanffy growth parameters varied by muskellunge body type (Figure 11). Each relationship's associated linear regression line ( $\pm 95\%$  prediction interval) was used to generate unique von Bertalanffy growth curves for use in my simulation model (Figure 11).

### *Muskellunge population size structure*

Muskellunge population size structure declined as angling mortality increased. For small-, medium-, and large-bodied populations subjected to an angling-only fishery ( $F_{\text{angling}} = 0.0\text{--}0.5$ ) with various minimum-length limits, numbers of trophy muskellunge declined by an average of 56.7% and ranged 12.5–100.0% (Table 2, Figure 12). For small-, medium-, and large-bodied populations subjected an angling-only fishery ( $F_{\text{angling}} = 0.0\text{--}0.5$ ) with various minimum length limits, RSD-38 and RSD-42 declined by an average of 60.3% and ranged 33.8–86.6% (Table 3, Figure 13). For medium- and large-bodied populations with a 40-in minimum length limit, an instantaneous fishing mortality of 0.1 and  $> 0.5$  were required to cause RSD-42 to decline below 17 (Table 4). For small-, medium-, and large-bodied populations subjected to observed levels of angling mortality with various minimum length limits, numbers of trophy length muskellunge declined by an average of 19.6% and ranged 1.4–60.0% (Table 5). For small-, medium-, and large-bodied populations subjected to observed levels of angling mortality with various minimum length limits, RSD-38 and RSD-42 declined by an average of 20.1% and ranged 3.8–49.3% (Table 6). When simulated at observed levels of angling mortality, RSD-38 never declined below 30 and RSD-42 fell below 17 only for medium-bodied populations with a 40-in minimum length limit (Table 6).

Muskellunge population size structure declined as angling and spearing mortality increased. For small-, medium-, and large-bodied populations subjected to a mixed fishery ( $F_{\text{angling}} = 0.0\text{--}0.5$  and  $F_{\text{spearing}} = 0.0\text{--}0.5$ ) with various minimum length limits, numbers of trophy muskellunge declined by an average of 85.9% and ranged 61.9–100.0% (Table 7, Figures 14–16). For small-, medium-, and large-bodied populations subjected to a mixed fishery ( $F_{\text{angling}} = 0.0\text{--}0.5$  and  $F_{\text{spearing}} = 0.0\text{--}0.5$ ) with

various minimum length limits, RSD-38 and RSD-42 declined by an average of 62.8% and ranged 39.8–92.9% (Table 8, Figures 17–19). Several combinations of angling and spearing mortality were identified that reduced RSD-38 below 30 and RSD-42 below 17 (Table 9). For small-, medium-, and large-bodied populations subjected to observed levels of angling and spearing mortality with various minimum length limits, numbers of trophy muskellunge declined by an average of 26.2% and ranged 4.2–66.7% (Table 5). For small-, medium-, and large-bodied populations subjected to observed levels of angling and spearing mortality with various minimum length limits, RSD-38 and RSD-42 declined by an average of 13.4% and ranged 2.6–53.4% (Table 6). When simulated at observed levels of angling and spearing mortality, RSD-38 never declined below 30 and RSD-42 declined below 17 in four different scenarios (Table 6).

## DISCUSSION

### *Estimation of age and growth potential*

Muskellunge age estimates differed between readers, which was similar to another muskellunge age estimation study (Brenden 2005), but different from several other age estimation studies across a range of fish species and structures (Niewinski and Ferreri 1999; Howland et al. 2004; Robinson 2005). Thin-sectioned pelvic fin ray age estimates for muskellunge from the New River, Virginia differed between readers at several ages and was nonlinear for one set of readers (Brenden 2005). Dorsal fin spine, otolith and scale age estimates for yellow perch *Perca flavescens* from the Pymatuning Reservoir, Pennsylvania did not significantly differ between readers (Niewinski and Ferreri 1999). Similarly, inconnu *Stenodus leucichthys* age estimated using otoliths and

pectoral fin ray from the Artic Red River, Northwest Territories, Canada did not differ between readers (Howland et al. 2004). No bias was observed among readers estimating muskellunge age using cleithra from across North America archived by The Cleithrum Project (Robinson 2005).

Precision of age estimates among three readers for muskellunge cleithra from Wisconsin was similar to the average precision for a wide variety of fish species and structures (Campana 2001). No *a priori* value of precision can be set as a target level for age estimation studies because precision is influenced by both species and structure being used, along with the reader (Campana 2001). However, Campana (2001) reported a median CV of 7.6% based on 117 published precision values, and suggested that a CV of 5% can serve as a reference point for fishes of moderate longevity and reading complexity. While the mean CV of age estimates for my study was slightly higher than 5%, each value fell at or below the median value of 7.6% reviewed by Campana (2001). The mean CV of other esocid age estimation studies using cleithra was at or below 5% (Laine et al. 1991; Robinson 2005). Cleithral age estimates of northern pike *E. lucius* from Squeers Lake, Ontario had a mean CV of 1.2% (Laine et al. 1991). The mean CV of muskellunge cleithra from across North America archived by The Cleithrum Project was 5.4% (Robinson 2005).

The estimated age frequency for my sample of northern Wisconsin muskellunge was similar to other cleithrum- and scale-based muskellunge age and growth studies (Schoemer 1936; Carlander 1969; Johnson 1971; Casselman and Crossman 1986; Robinson 2005). My sample included no muskellunge older than age-20, and although muskellunge as old as age-30 have been documented, only 1% of all muskellunge from

the United States were older than age-20 (Casselman and Crossman 1986). The oldest muskellunge from Lac Vieux Desert and North Twin Lakes in northern Wisconsin were age-21 and age-25 (Robinson 2005). Scale age estimates for 351 muskellunge from northern Wisconsin resulted in a maximum observed age of 19 years (Schloemer 1936). Carlander (1969) compiled muskellunge scale age estimates from across North America, with fish ranging from age-0 to age-19. Documented known-age muskellunge have reached age-13 in northern Wisconsin, with one individual reportedly reaching age-26 (Johnson 1971; Johnson 1975). Because muskellunge scales only provide an accurate age estimate for young fish, the above scale age estimates are likely subject to structure bias (Fitzgerald et al. 1997).

The criteria used for eliminating muskellunge from my analysis resulted in a similar minimum age required to produce valid estimates of growth parameters as that recommended by previous studies (Casselman 2007). The minimum age to produce valid estimates of growth parameters for muskellunge is between age-8 and age-10 (Casselman 2007). The mean age of muskellunge not included in my final analysis (5.8 years) was much lower than the mean age of muskellunge included in the final sample (10.9 years).

Muskellunge in northern Wisconsin reached similar  $L_{\infty}$  as other North American populations (Casselman et al. 1999). On average, female and male muskellunge in northern Wisconsin were slightly smaller than those in Ontario (Table 10). Northern Wisconsin muskellunge populations classified as medium- and large-bodied fell within the lower range of  $L_{\infty}$  estimates for medium- and large-bodied populations in Ontario, but small-bodied muskellunge populations in northern Wisconsin fell outside the range of  $L_{\infty}$  estimates for small-bodied populations in Ontario (Table 10). Observed differences in

growth potential between northern Wisconsin and Ontario may have been due to several methodological and biological factors. The Cleithrum Project was designed to collect cleithra from trophy muskellunge donated by anglers and taxidermists from across North America, which may lead to an overestimation of mean length of individual age classes due to the size selective nature of angling (Ricker 1969; Gabelhouse Jr. and Willis 1986; Pierce et al. 1995; Casselman et al. 1999; Isermann et al. 2005; Arlinghaus et al. 2008). Casselman et al. (1999) concluded that  $L_{\infty}$  for female muskellunge is the most practical description of growth potential. My final sample contained a small number of female muskellunge with reliable estimates of  $L_{\infty}$  and when classifying populations by growth potential I used all available muskellunge (regardless of gender), which likely resulted in a lower mean  $L_{\infty}$  due to inclusion of smaller males (Casselman and Crossman 1986). Many of the Ontario muskellunge populations analyzed by Casselman et al. (1999) were from much larger waterbodies than those included in my analysis. Lake size is positively correlated with growth potential of several species of fish (Shuter et al. 1998; Purchase et al. 2005). A higher growth potential in large lakes may be caused by elevated levels of species richness, which may provide a broader range of forage sizes (Eadie et al. 1986; Matuszek and Beggs 1988; Post et al. 2000).

#### *Muskellunge population size structure*

Muskellunge population size structure declined as angling and spearing mortality increased, similar to other studies simulating the effects of exploitation on population size structure of various species of fish (Beamesderfer and North 1995; Quist et al. 2002; Holley et al. 2008; Makinster and Paukert 2008). As in my study, abundance of stock-length fish and proportional stock density declined for largemouth bass *Micropterus*

*salmoides* and smallmouth bass *M. dolomieu* as simulated exploitation increased on fisheries with varying minimum length limits and productivity (Beamesderfer and North 1995). Similarly, simulation modeling predicted that even low (< 10%) levels of exploitation may reduce numbers of large (> 24 in) speckled peacock bass *Cichla temensis* by 30–50% (Holley et al. 2008). Relative stock density of preferred-length shovelnose sturgeon *Scaphirhynchus platyrhynchus* was highly sensitive to exploitation (Quist et al. 2002) and proportional stock density of flathead catfish *Pylodictis olivaris* steadily declined under three different minimum length limits as exploitation increased (Makinster and Paukert 2008).

Based on my simulations, current levels of angling and spearing exploitation are likely influencing muskellunge size structure in some northern Wisconsin lakes. For example, large-bodied muskellunge populations with a 50-in minimum length limit simulated under a mixed fishery with average levels of angling and spearing exploitation experienced a decline of 13.2% in the numbers of muskellunge greater than 50 in. Such an example should be considered a "best case scenario", as larger declines were predicted for populations with lower minimum length limits or growth potential. Because spearing is not regulated by strict length limits (one fish any size, thereafter at least half the catch must be over 32 in), and my simulation model assumed no angling or hooking mortality for fish under the minimum length limit, spearing appeared to have a greater influence on size structure in mixed fishery simulations. My simulations predicted that relative stock density could potentially be reduced to levels below those used by the WDNR to define a trophy muskellunge fishery at observed levels of angling and spearing exploitation. However, the scenarios where this was observed (medium-bodied populations with

various minimum length limits) were borderline trophy fisheries prior to being subjected to any exploitation. Because any amount of harvest will reduce trophy potential, it is not surprising that low levels of exploitation reduced these fisheries' RSD-42 below trophy levels.

Despite release rates approaching 100% and high angler confidence (> 50%) that all released muskellunge survive, inexperienced anglers and certain angling practices likely lead to significant levels of mortality not accounted for in my simulation model (Newman and Storck 1986; Margenau 2007). Anglers not accustomed to handling large esocids resulted in 10% of all sublegal tiger muskellunge *E. masquinongy* x *E. lucius* caught to die as a result of the angling experience in a small Illinois impoundment (Newman and Storck 1986). Use of live bait is a common angling technique that can result in muskellunge being hooked in the stomach, which can cause high levels (> 80%) of post-release mortality within one year of capture (Margenau 2007). Handling and release techniques used by experienced muskellunge anglers may result in low levels of post-release mortality (< 5%), but inexperienced muskellunge anglers likely cause higher levels of post-release mortality (Landsman et al. 2011).

### *Management implications*

My study results aid muskellunge management in northern Wisconsin in two ways. First, previous age and growth estimates for muskellunge used scales or fin rays, which produce unreliable records of age and growth as fish reach older ages (Johnson 1971; Casselman 1983; Fitzgerald et al. 1997). By using cleithral estimates of age and growth to back-calculate growth histories, structure bias was reduced in my study to

provide a better understanding of muskellunge growth potential in northern Wisconsin. Further, my cleithra based growth curves can serve as a reference for muskellunge growth potential across northern Wisconsin. As more muskellunge cleithra are collected from northern Wisconsin lakes, von Bertalanffy growth curves can be constructed and compared with my growth curves to judge whether muskellunge growth potential in a given lake is higher or lower relative to those included in my study.

Second, results of my simulation modeling provided insight into how northern Wisconsin's muskellunge populations may respond to increased exploitation from angling and spearing fisheries. Increased mortality from either fishery resulted in reduced muskellunge population size structure. In some cases, relative stock densities declined below levels used by the WDNR to define trophy muskellunge fisheries. For most scenarios simulated, the level of angling or spearing mortality required to cause such declines were much higher than observed levels, particularly for spearing fisheries. However, simulations at observed levels of angling and spearing mortality demonstrated that current levels of exploitation are influencing muskellunge population size structure, and medium-bodied muskellunge populations are potentially at risk of falling below trophy RSD levels. Muskellunge populations suspected of being at or near such combinations of harvest mortality can be identified, which allows management goals or actions to be evaluated and perhaps revised. Angling regulations such as minimum length limits could be increased to reduce harvest mortality. Tribal quotas are currently set as litigated in the Voight decision to maintain a sustainable fishery. Because trophy muskellunge fisheries are not a conservation necessity, changes to the court-approved

tribal harvest regulation system to achieve trophy muskellunge fishery objectives can only be considered at the consent of the parties.

TABLE 1.—Combinations of muskellunge body type and minimum length limit used to regulate angling fisheries simulated under varying levels of harvest mortality.

Minimum Length Limit	Body Type		
	Small	Medium	Large
28-in	X		
40-in	X	X	X
45-in		X	X
50-in		X	X

TABLE 2.—Percent decline in number of trophy length muskellunge in small-, medium-, and large-bodied populations simulated under an angling-only fishery ( $F_{angling} = 0.0-0.5$ ) with various minimum length limits. Dash indicates that no fish reached a given length.

Body Type	Minimum Length Limit	Percent Decline in Trophy Length Muskellunge		
		≥ 40 in	≥ 45 in	≥ 50 in
Small-bodied	28-in	80.0	100.0	-
Small-bodied	40-in	37.1	100.0	-
Medium-bodied	40-in	14.8	64.5	100.0
Medium-bodied	45-in	0.0	12.5	60.0
Medium-bodied	50-in	0.0	0.0	40.0
Large-bodied	40-in	16.1	56.4	81.6
Large-bodied	45-in	0.0	19.3	68.4
Large-bodied	50-in	0.0	0.0	0.0

TABLE 3.—Percent decline in relative stock density of muskellunge greater than 38 in (RSD-38) and 42 in (RSD-42) in small-, medium-, and large-bodied populations simulated under an angling-only ( $F_{angling} = 0.0-0.5$ ) fishery with various minimum length limits.

Body Type	Minimum Length Limit	Percent Decline in	
		Relative Stock Density	
		RSD-38	RSD-42
Small-bodied	28-in	62.5	86.6
Small-bodied	40-in	0.0	78.8
Medium-bodied	40-in	0.0	39.6
Medium-bodied	45-in	0.0	0.0
Medium-bodied	50-in	0.0	0.0
Large-bodied	40-in	0.0	33.8
Large-bodied	45-in	0.0	0.0
Large-bodied	50-in	0.0	0.0

TABLE 4.—Instantaneous fishing mortality from an angling-only fishery required to cause relative stock density of muskellunge greater than 38 in (RSD-38) and 42 in (RSD-42) to fall below levels used by the Wisconsin Department of Natural Resources to define a trophy muskellunge fishery. None indicates that RSD values never reached trophy levels. Dash indicates that muskellunge were protected from harvest by minimum length limit and no declines could be observed given assumptions of simulation model.

<u>Body Type</u>	<u>Minimum Length Limit</u>	<u>RSD-38</u>	<u>RSD-42</u>
Small-bodied	28-in	None	None
Small-bodied	40-in	None	None
Medium-bodied	40-in	-	0.1
Medium-bodied	45-in	-	-
Medium-bodied	50-in	-	-
Large-bodied	40-in	-	> 0.5
Large-bodied	45-in	-	-
Large-bodied	50-in	-	-

TABLE 5.—Percent decline in number of trophy length muskellunge in small-, medium-, and large-bodied populations simulated under an angling-only or a mixed fishery with various minimum length limits at observed levels of exploitation in northern Wisconsin. Average corresponds to the instantaneous fishing mortality at the average observed exploitation rates for angling and spearing fisheries. 95% corresponds to the instantaneous fishing mortality at the 95<sup>th</sup> percentile of observed exploitation rates for angling and spearing fisheries. Dash indicates that no fish reached a given length.

Body Type	Minimum Length Limit	Fishery	F	Percent Decline in Numbers of Trophy Length Muskellunge		
				≥ 40 inches	≥ 45 inches	≥ 50 inches
Small-bodied	28-in	Angling	Average	16.7	33.3	-
Small-bodied	28-in	Angling	95%	41.7	50.0	-
Small-bodied	28-in	Mixed	Average	25.0	33.3	-
Small-bodied	28-in	Mixed	95%	50.0	66.7	-
Small-bodied	40-in	Angling	Average	8.3	16.7	-
Small-bodied	40-in	Angling	95%	13.9	40.0	-
Small-bodied	40-in	Mixed	Average	11.1	33.3	-
Small-bodied	40-in	Mixed	95%	27.8	66.7	-
Medium-bodied	40-in	Angling	Average	2.8	12.5	20.0
Medium-bodied	40-in	Angling	95%	5.5	31.3	60.0
Medium-bodied	40-in	Mixed	Average	8.3	21.9	40.0
Medium-bodied	40-in	Mixed	95%	18.3	46.9	60.0
Medium-bodied	45-in	Angling	Average	0.0	3.1	20.0
Medium-bodied	45-in	Angling	95%	0.0	6.3	20.0
Medium-bodied	45-in	Mixed	Average	6.4	12.5	20.0
Medium-bodied	45-in	Mixed	95%	15.6	28.1	60.0
Medium-bodied	50-in	Angling	Average	0.0	0.0	0.0
Medium-bodied	50-in	Angling	95%	0.0	0.0	20.0
Medium-bodied	50-in	Mixed	Average	6.4	12.5	20.0
Medium-bodied	50-in	Mixed	95%	14.7	25.0	40.0
Large-bodied	40-in	Angling	Average	1.4	7.3	15.8
Large-bodied	40-in	Angling	95%	3.2	22.0	42.1
Large-bodied	40-in	Mixed	Average	5.6	15.6	26.3
Large-bodied	40-in	Mixed	95%	15.5	37.6	60.5
Large-bodied	45-in	Angling	Average	0.0	2.8	10.5
Large-bodied	45-in	Angling	95%	0.0	6.4	34.2
Large-bodied	45-in	Mixed	Average	5.1	11.0	23.7
Large-bodied	45-in	Mixed	95%	10.6	25.7	52.6
Large-bodied	50-in	Angling	Average	0.0	0.0	0.0
Large-bodied	50-in	Angling	95%	0.0	0.0	0.0
Large-bodied	50-in	Mixed	Average	4.2	8.3	13.2
Large-bodied	50-in	Mixed	95%	11.6	21.1	34.2

TABLE 6.—Percent decline in relative stock density of muskellunge greater than 38 in (RSD-38) and 42 in (RSD-42) in small-, medium-, and large-bodied populations simulated under an angling-only or a mixed fishery with various minimum length limits at observed levels of exploitation in northern Wisconsin. Average corresponds to the instantaneous fishing mortality at the average observed exploitation rates for angling and spearing fisheries. 95% corresponds to the instantaneous fishing mortality at the 95<sup>th</sup> percentile of observed exploitation rates for angling and spearing fisheries. Dash indicates that no fish reached a given length. Asterisk indicates RSD declined below levels used by WDNR to define trophy muskellunge fisheries.

Body Type	Minimum Length Limit	Fishery	F	Percent Decline in Relative Stock Density	
				RSD-38	RSD-42
Small-bodied	28-in	Angling	Average	11.7	19.8
Small-bodied	28-in	Angling	95%	29.8	49.3
Small-bodied	28-in	Mixed	Average	14.7	23.3
Small-bodied	28-in	Mixed	95%	34.7	53.4
Small-bodied	40-in	Angling	Average	0.0	15.8
Small-bodied	40-in	Angling	95%	0.0	36.8
Small-bodied	40-in	Mixed	Average	4.2	20.4
Small-bodied	40-in	Mixed	95%	11.5	45.4
Medium-bodied	40-in	Angling	Average	0.0	7.0
Medium-bodied	40-in	Angling	95%	0.0	16.2*
Medium-bodied	40-in	Mixed	Average	3.5	11.7*
Medium-bodied	40-in	Mixed	95%	8.0	27.3*
Medium-bodied	45-in	Angling	Average	0.0	0.0
Medium-bodied	45-in	Angling	95%	0.0	0.0
Medium-bodied	45-in	Mixed	Average	4.1	6.0
Medium-bodied	45-in	Mixed	95%	9.0	17.1*
Medium-bodied	50-in	Angling	Average	0.0	0.0
Medium-bodied	50-in	Angling	95%	0.0	0.0
Medium-bodied	50-in	Mixed	Average	3.9	7.8
Medium-bodied	50-in	Mixed	95%	8.5	17.5*
Large-bodied	40-in	Angling	Average	0.0	3.8
Large-bodied	40-in	Angling	95%	0.0	11.2
Large-bodied	40-in	Mixed	Average	2.6	8.6
Large-bodied	40-in	Mixed	95%	6.3	22.5
Large-bodied	45-in	Angling	Average	0.0	0.0
Large-bodied	45-in	Angling	95%	0.0	0.0
Large-bodied	45-in	Mixed	Average	2.7	5.4
Large-bodied	45-in	Mixed	95%	6.3	13.7
Large-bodied	50-in	Angling	Average	0.0	0.0
Large-bodied	50-in	Angling	95%	0.0	0.0
Large-bodied	50-in	Mixed	Average	2.6	5.4
Large-bodied	50-in	Mixed	95%	6.9	13.5

TABLE 7.—Percent decline in number of trophy length muskellunge in small-, medium-, and large-bodied populations simulated under a mixed fishery ( $F_{angling} = 0.0-0.5$  and  $F_{spearing} = 0.0-0.5$ ) with various minimum length limits. Dash indicates that no fish reached a given length.

Body Type	Minimum Length Limit	Percent Decline in Trophy Length Muskellunge		
		≥ 40 in	≥ 45 in	≥ 50 in
Small-bodied	28-in	91.4	100.0	-
Small-bodied	40-in	85.7	100.0	-
Medium-bodied	40-in	71.3	90.3	100.0
Medium-bodied	45-in	69.7	87.5	100.0
Medium-bodied	50-in	69.4	87.1	100.0
Large-bodied	40-in	67.0	90.0	97.4
Large-bodied	45-in	62.4	85.3	97.4
Large-bodied	50-in	61.9	82.4	94.6

TABLE 8.—Percent decline in relative stock density of muskellunge greater than 38 in (RSD-38) and 42 in (RSD-42) in small-, medium-, and large-bodied populations simulated under a mixed fishery ( $F_{angling} = 0.0-0.5$  and  $F_{spearing} = 0.0-0.5$ ) with various minimum length limits.

Body Type	Minimum Length Limit	Percent Decline in Relative Stock Density	
		RSD-38	RSD-42
Small-bodied	28-in	75.9	91.4
Small-bodied	40-in	55.9	92.9
Medium-bodied	40-in	48.3	76.3
Medium-bodied	45-in	47.7	72.8
Medium-bodied	50-in	48.3	72.5
Large-bodied	40-in	39.8	73.7
Large-bodied	45-in	40.6	64.1
Large-bodied	50-in	40.4	64.0

TABLE 9.—Instantaneous fishing mortality ( $F_{angling}$  and  $F_{spearing}$ ) from a mixed fishery required to cause relative stock density of muskellunge greater than 38 in (RSD-38) and 42 in (RSD-42) to fall below levels used by the Wisconsin Department of Natural Resources to define a trophy muskellunge fishery. None indicates that RSD values never reached trophy levels. Dash indicates that muskellunge were protected from harvest by minimum length limit and no declines could be observed given assumptions of simulation model.

Body Type	Minimum Length Limit	RSD-38		RSD-42	
		$F_{angling}$	$F_{spearing}$	$F_{angling}$	$F_{spearing}$
Small-bodied	28-in	None	None	None	None
Small-bodied	40-in	None	None	None	None
Medium-bodied	40-in	-	0.3	0.1	0.1
Medium-bodied	45-in	-	0.3	-	0.1
Medium-bodied	50-in	-	0.3	-	0.1
Large-bodied	40-in	-	> 0.5	> 0.5	0.4
Large-bodied	45-in	-	> 0.5	-	0.4
Large-bodied	50-in	-	> 0.5	-	0.4

TABLE 10.—Average asymptotic length (inches) by gender and body type for muskellunge from northern Wisconsin and Ontario. Data for Ontario muskellunge from Casselman et al. (1999).

Gender or Body Type	Source	
	Wisconsin	Ontario
Female	47.7	49.3
Male	40.2	41.7
Small-bodied	38.7	40.0–45.0
Medium-bodied	45.0	45.0–50.0
Large-bodied	50.4	50.0–55.0



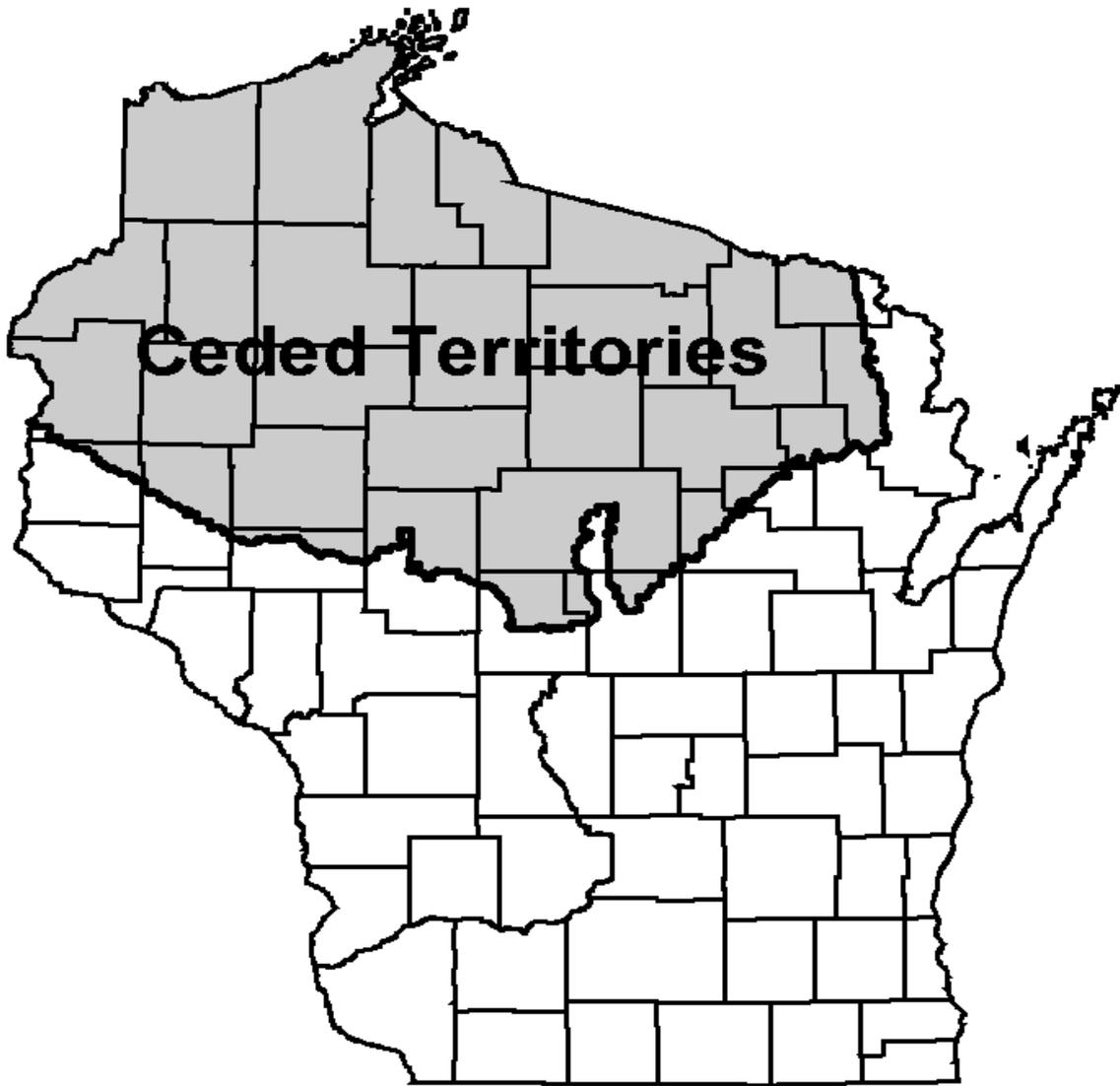


FIGURE 2.—Lands ceded by six bands of Chippewa in the Treaties of 1837 and 1842 encompassing all or part of 30 counties and 22,400 square miles in the northern third of Wisconsin. (Source: GLIFWC 2004.)



FIGURE 3.—Location of lakes in northern Wisconsin's ceded territory from which 306 muskellunge cleithra were collected during 1995–2011.

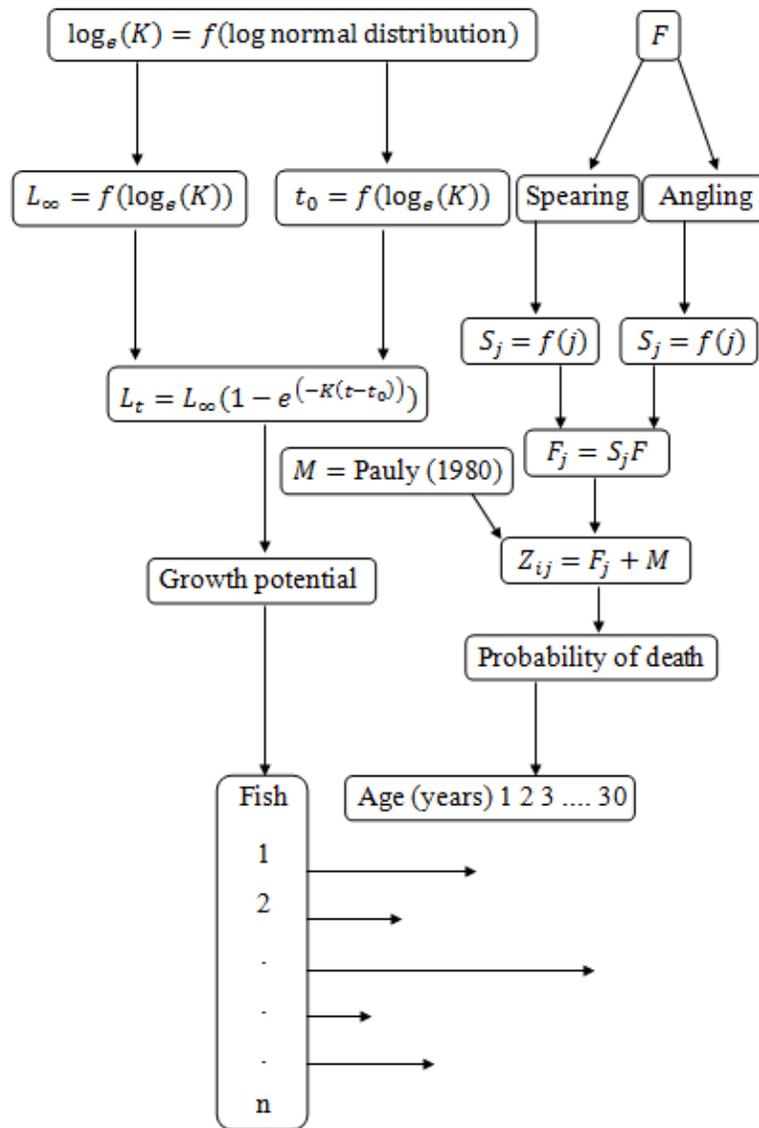


FIGURE 4.—Schematic diagram of a simulation model designed to predict muskellunge population size structure response to varying levels of angling and spearing mortality in northern Wisconsin, where  $j$  represents age and the inputs are an instantaneous angling or spearing mortality ( $F$ ), a body type (small-, medium-, or large-bodied), and a minimum length limit (28-, 40-, 45-, or 50-in). Remaining symbols are defined in Methods.

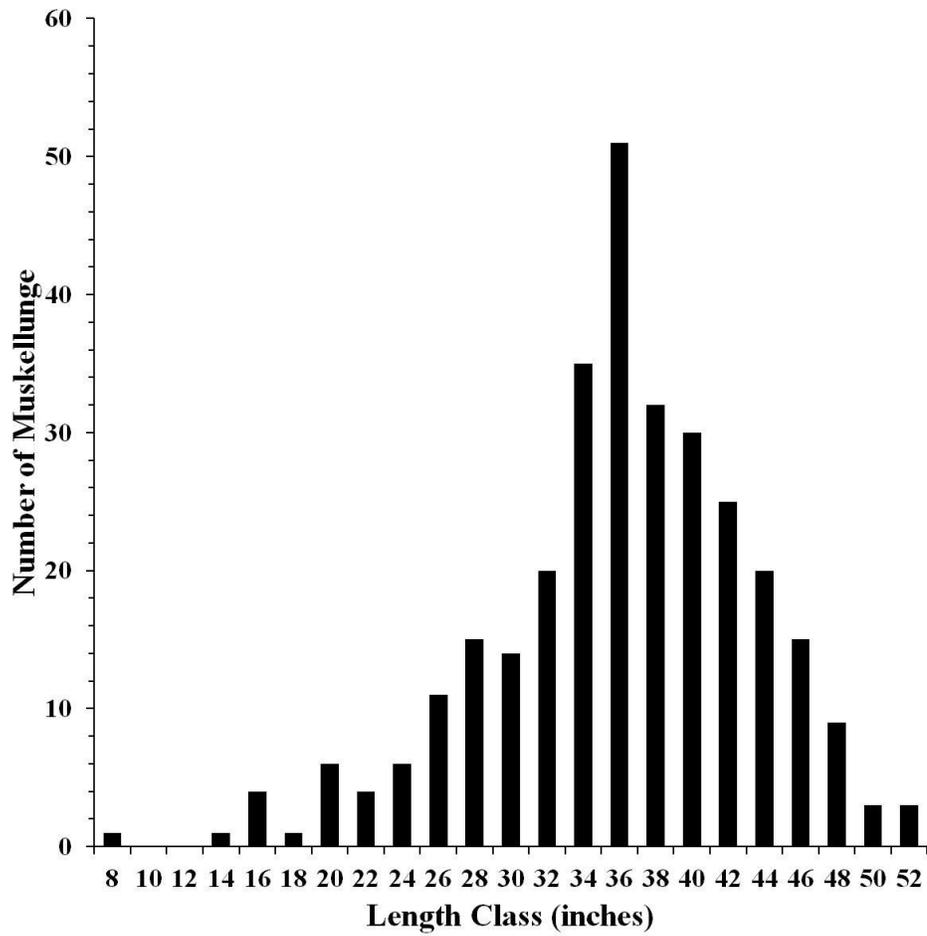


FIGURE 5.—Number of muskellunge (n = 306) by length class (inches) collected from northern Wisconsin during 1995–2011.

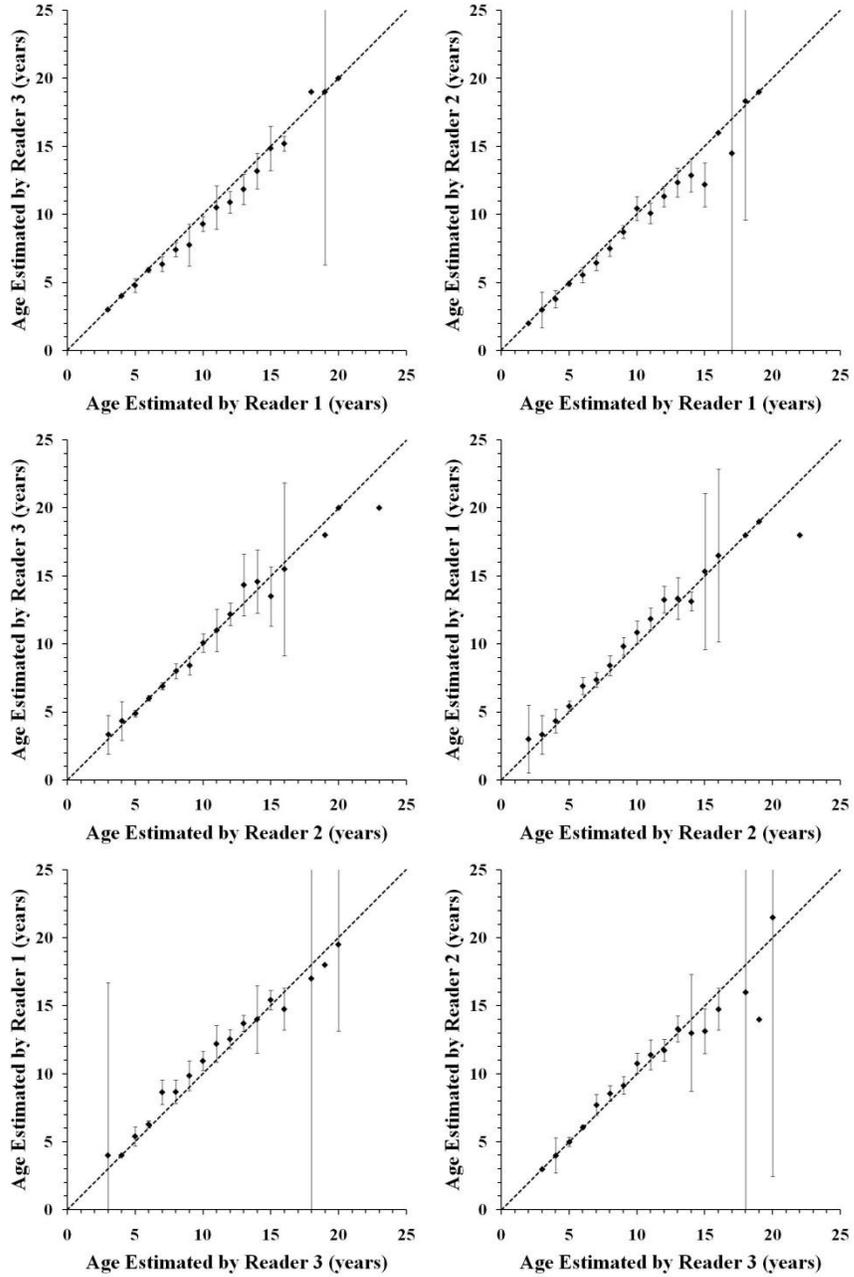


FIGURE 6.—Age-bias plots comparing muskellunge age estimates between three independent readers for muskellunge collected from northern Wisconsin during 2007–2011. Black diamonds represent mean values ( $\pm$  95% CI). Dashed line indicates 1:1 equivalence line.

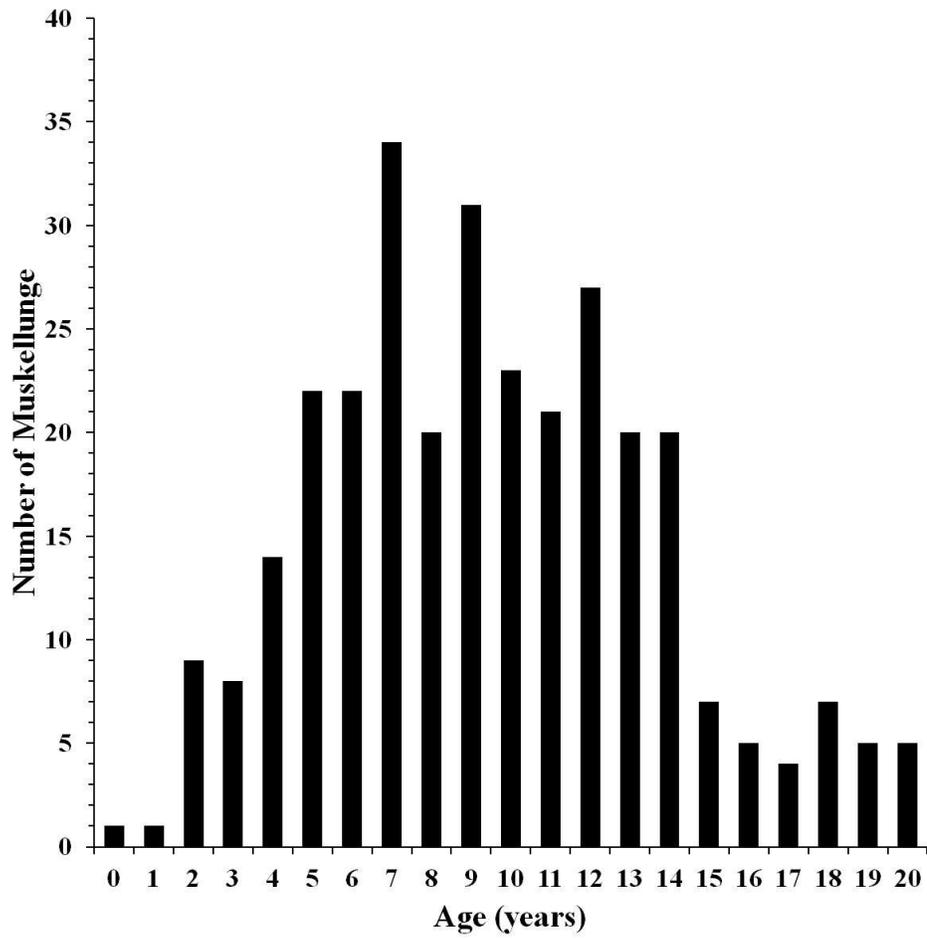


FIGURE 7.—Number of muskellunge (n = 306) by age (years) collected from northern Wisconsin during 1995–2011.

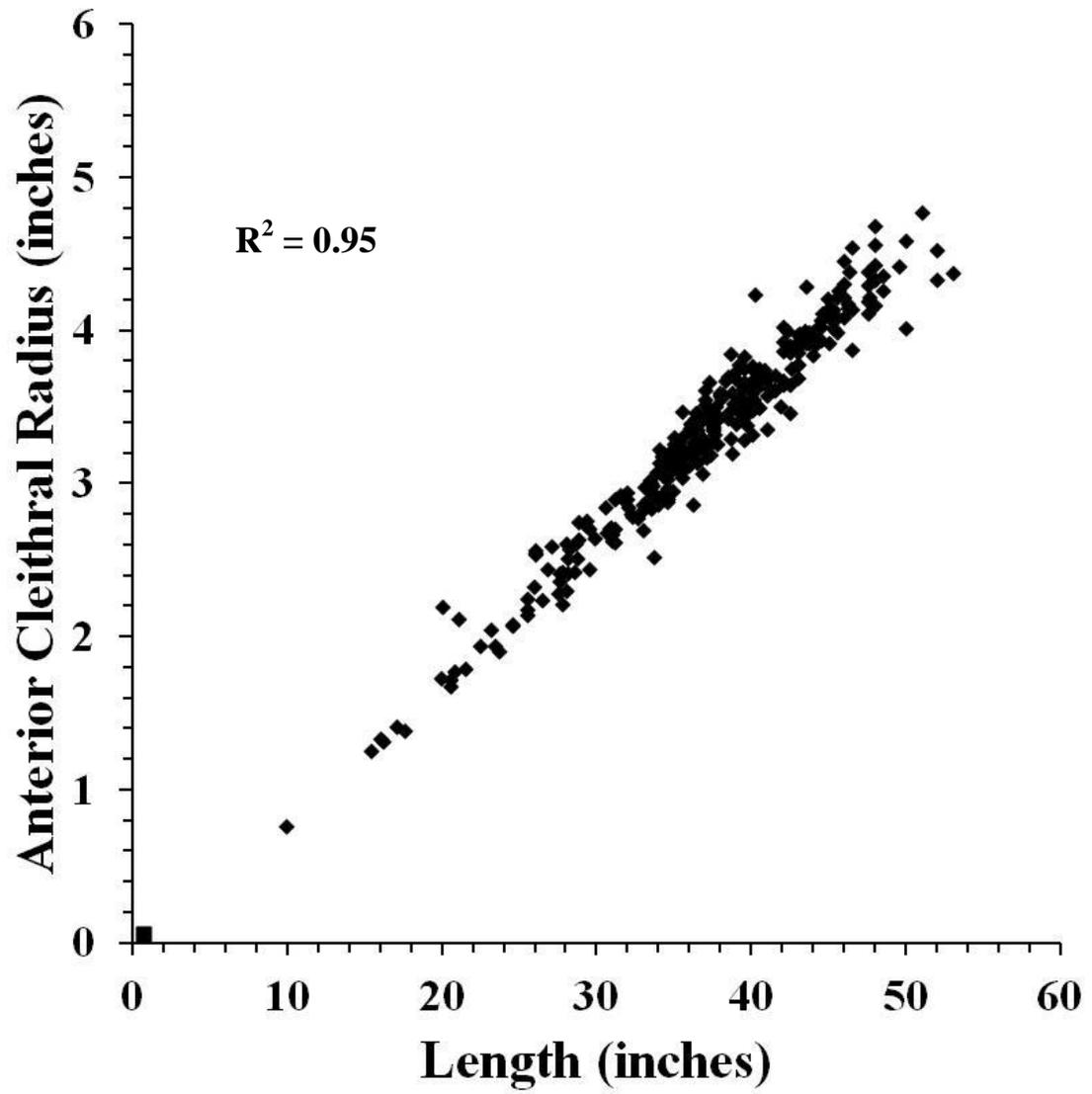


FIGURE 8.—Relationship between anterior cleithral radius (inches) and body length (inches) based on 306 muskellunge collected from northern Wisconsin during 1995–2011. Black square indicates biological intercept used in back-calculation of individual growth histories.

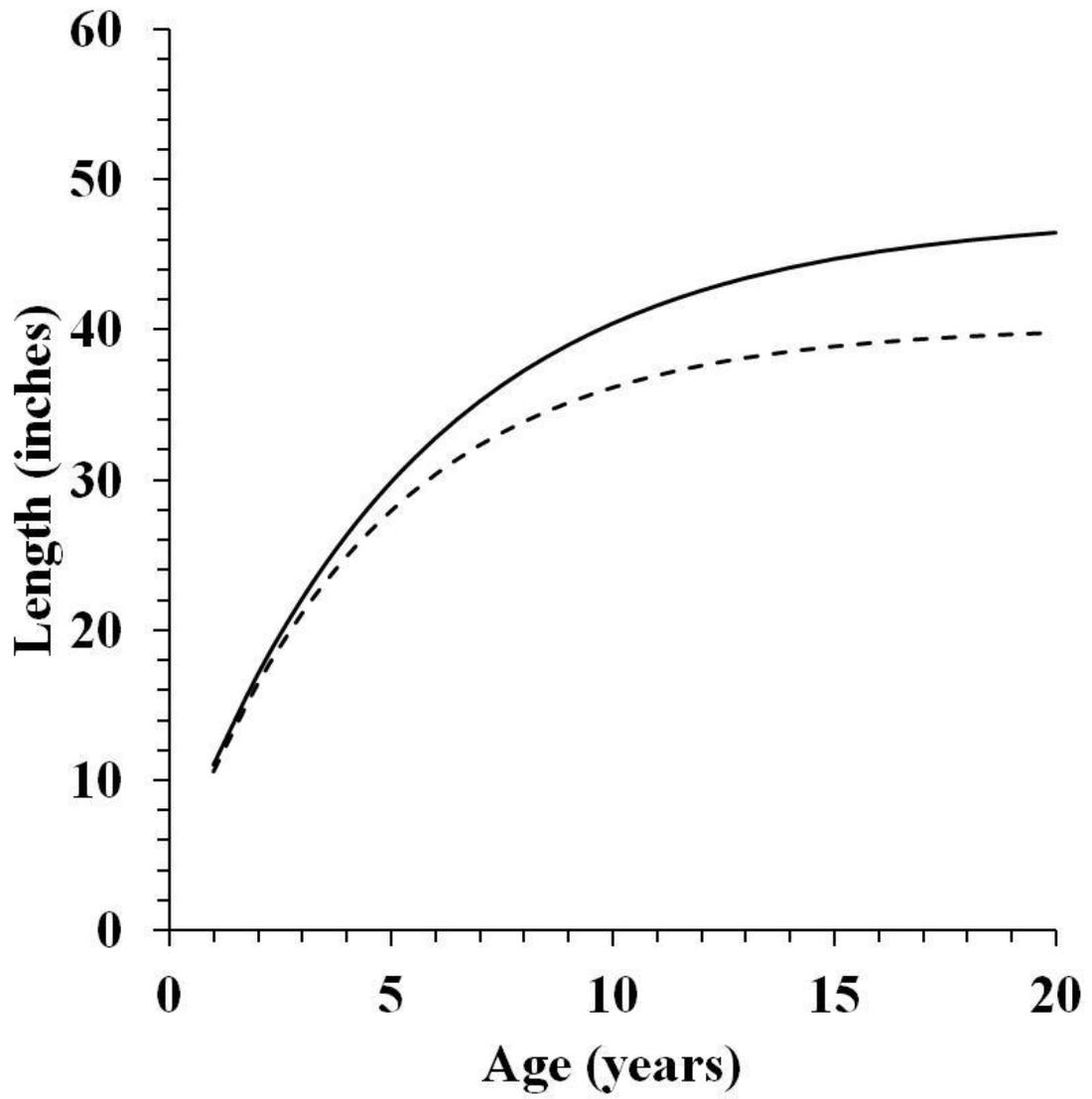


FIGURE 9.—Mean von Bertalanffy growth curves for female (solid) and male (dashed line) muskellunge based on 85 females and 105 males collected from northern Wisconsin during 1995–2011.

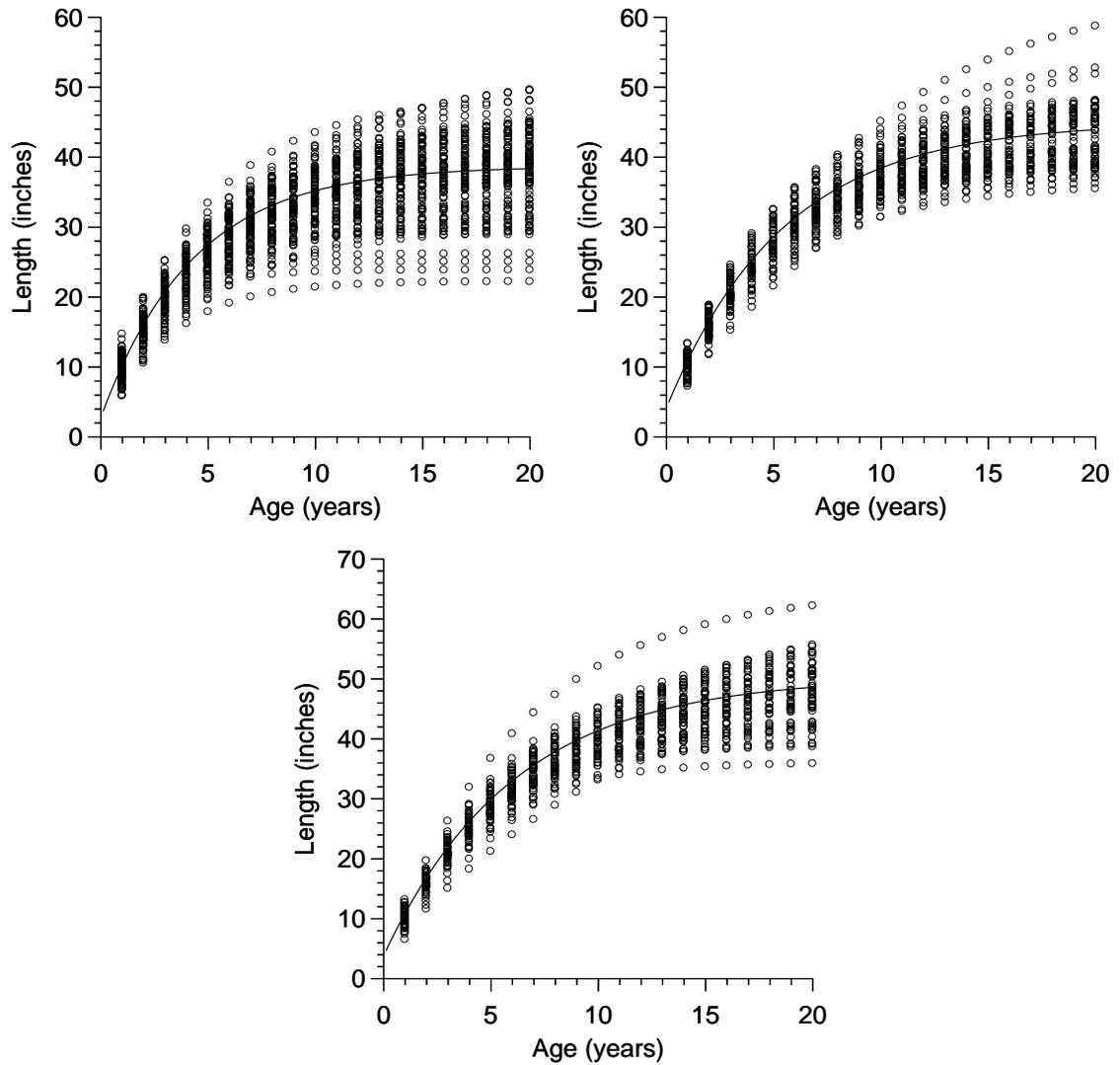


FIGURE 10.—Range of muskellunge growth potential for small-(upper left), medium-(upper right), and large-bodied (center) populations in northern Wisconsin based on 223 fish collected during 1995–2011. Circles indicate back-calculated length-at-age and black line indicates mean von Bertalanffy growth curve for each body type.

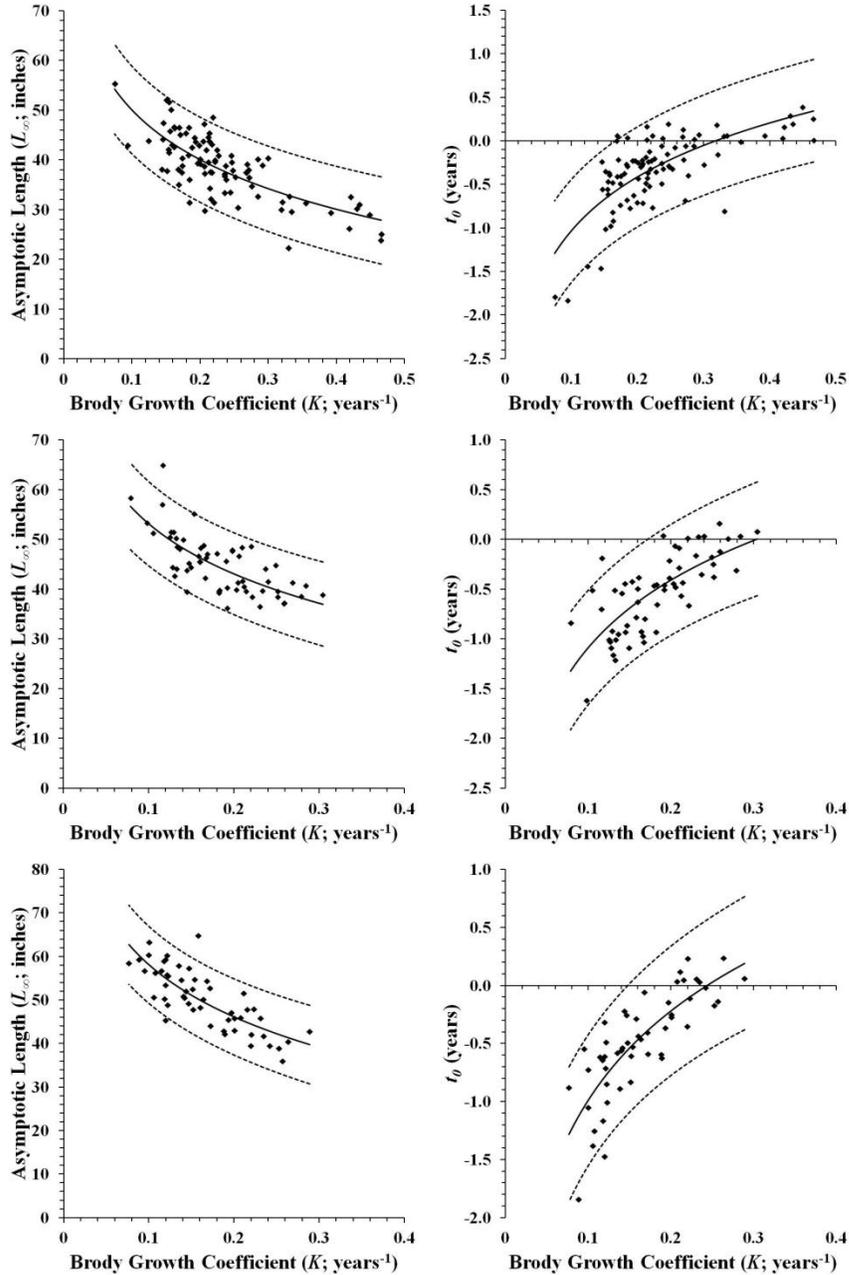


FIGURE 11.—Relationships among von Bertalanffy growth parameters for small-(top), medium-(middle), and large-bodied (lower) muskellunge populations in northern Wisconsin. Black diamonds indicate estimated parameters for individual fish. Solid line indicates regression line used to generate growth parameters for simulation model. Dashed lines indicate 95% prediction interval.

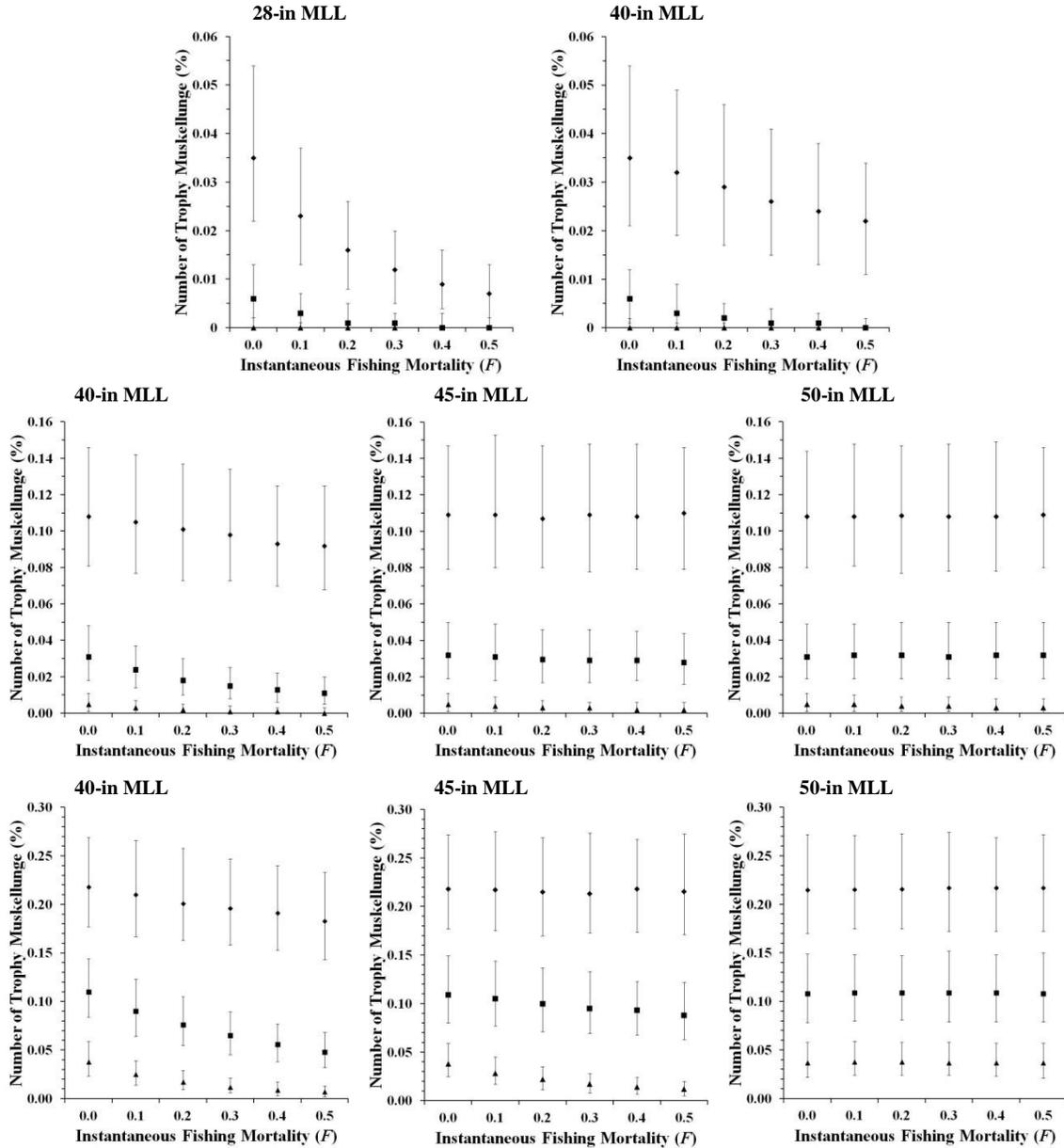


FIGURE 12.—Median number of muskellunge (%;  $\pm 95\%$  confidence interval) reaching trophy lengths for a small- (top), medium- (middle), and large-bodied (bottom) populations simulated under an angling-only fishery with various minimum length limits (MLL). Diamonds represent muskellunge  $\geq 40$  in, squares represent muskellunge  $\geq 45$  in, and triangles represent muskellunge  $\geq 50$  in.

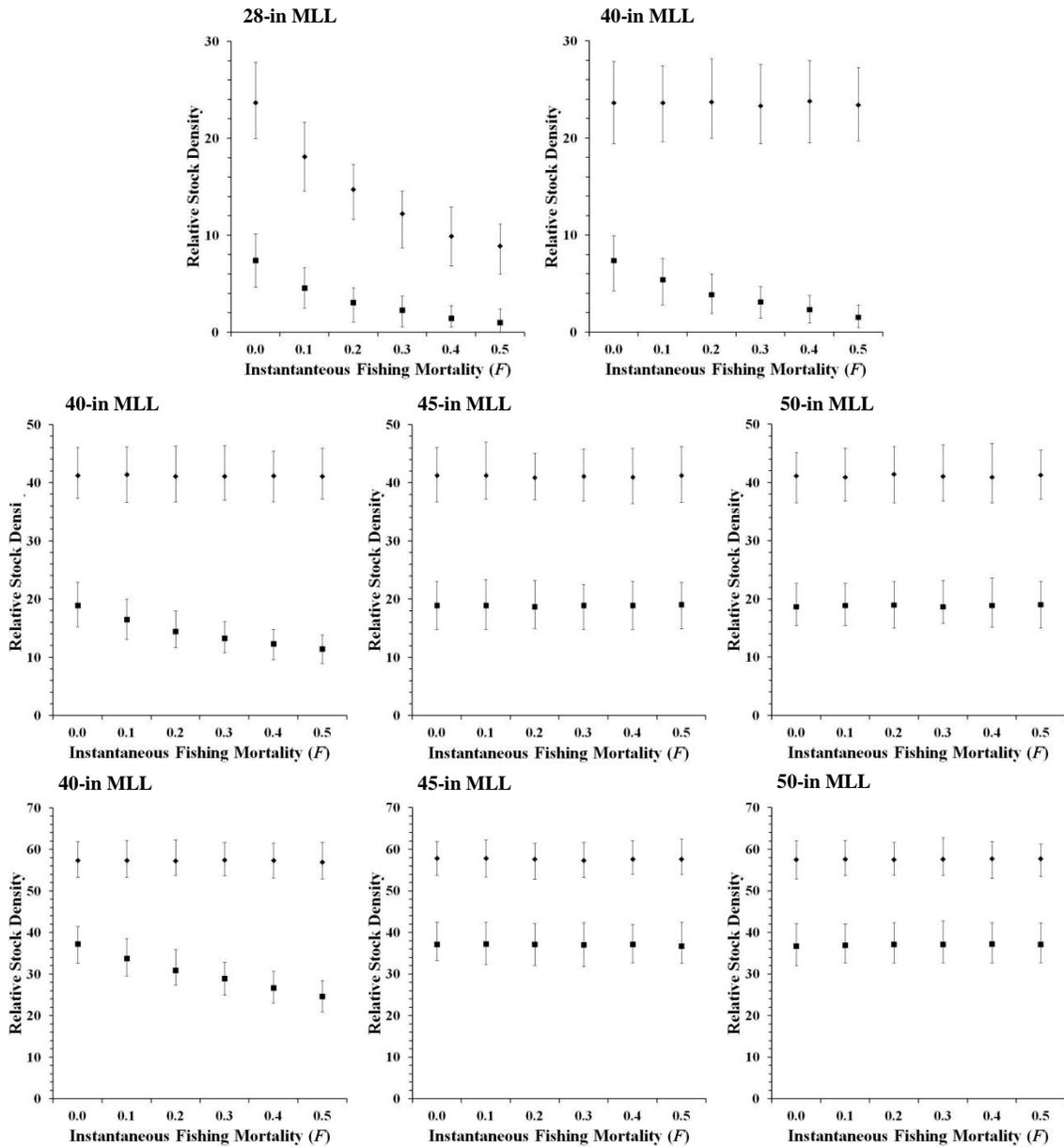


FIGURE 13.—Median relative stock density ( $\pm$  95% confidence interval) of muskellunge greater than 38 in (diamond) and 42 in (square) for a small- (top), medium- (middle), and large-bodied (bottom) populations simulated under an angling-only fishery with various minimum length limits (MLL).

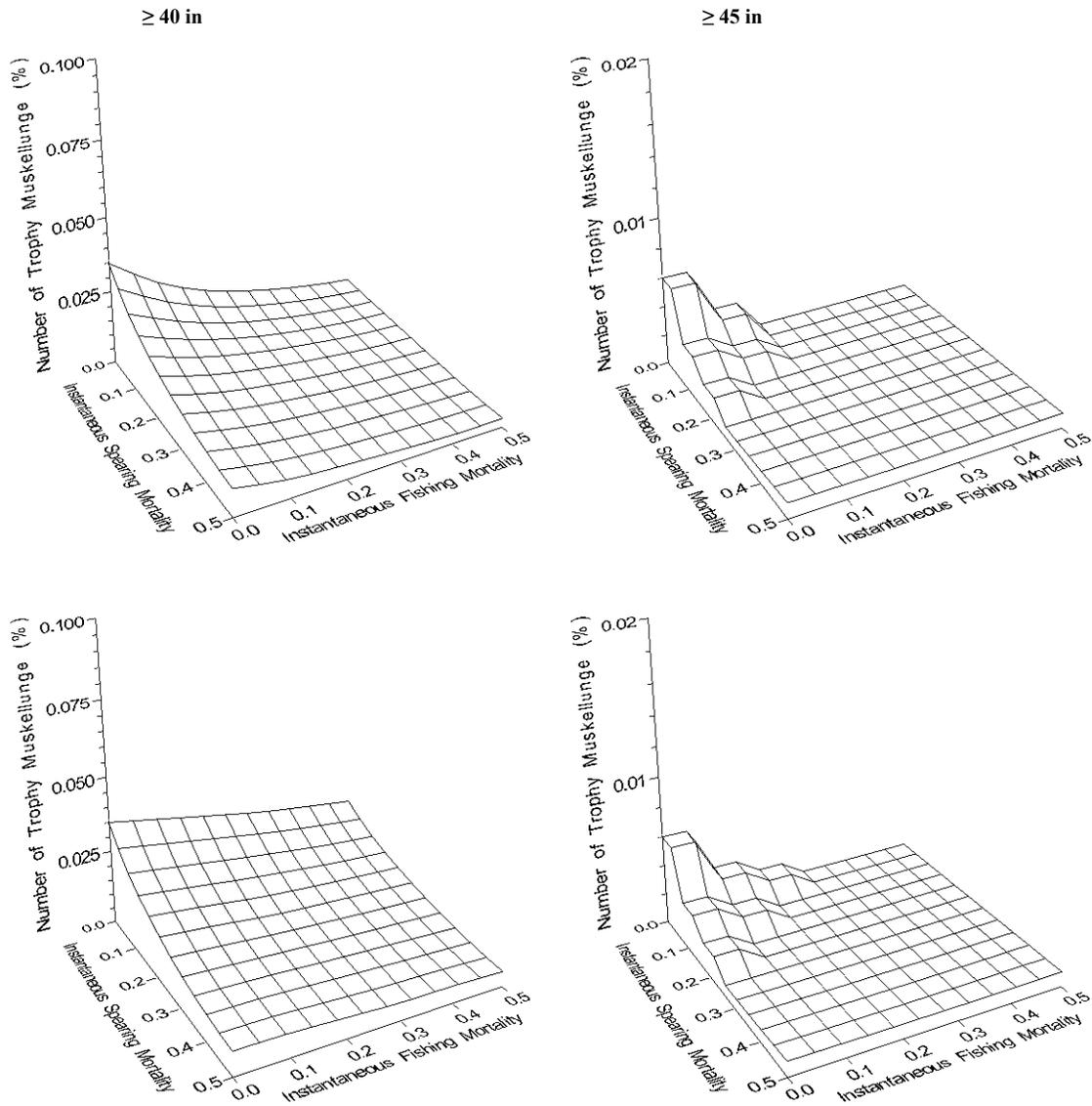


FIGURE 14.—Response surfaces illustrating relationship between number of muskellunge (%) greater than or equal to 40 in and 45 in and instantaneous spearing mortality ( $F_{spearing}$ ) and instantaneous fishing mortality ( $F_{angling}$ ) for a small-bodied population simulated under a mixed fishery with a 28-in minimum length limit (top) and a 40-in minimum length limit (bottom).

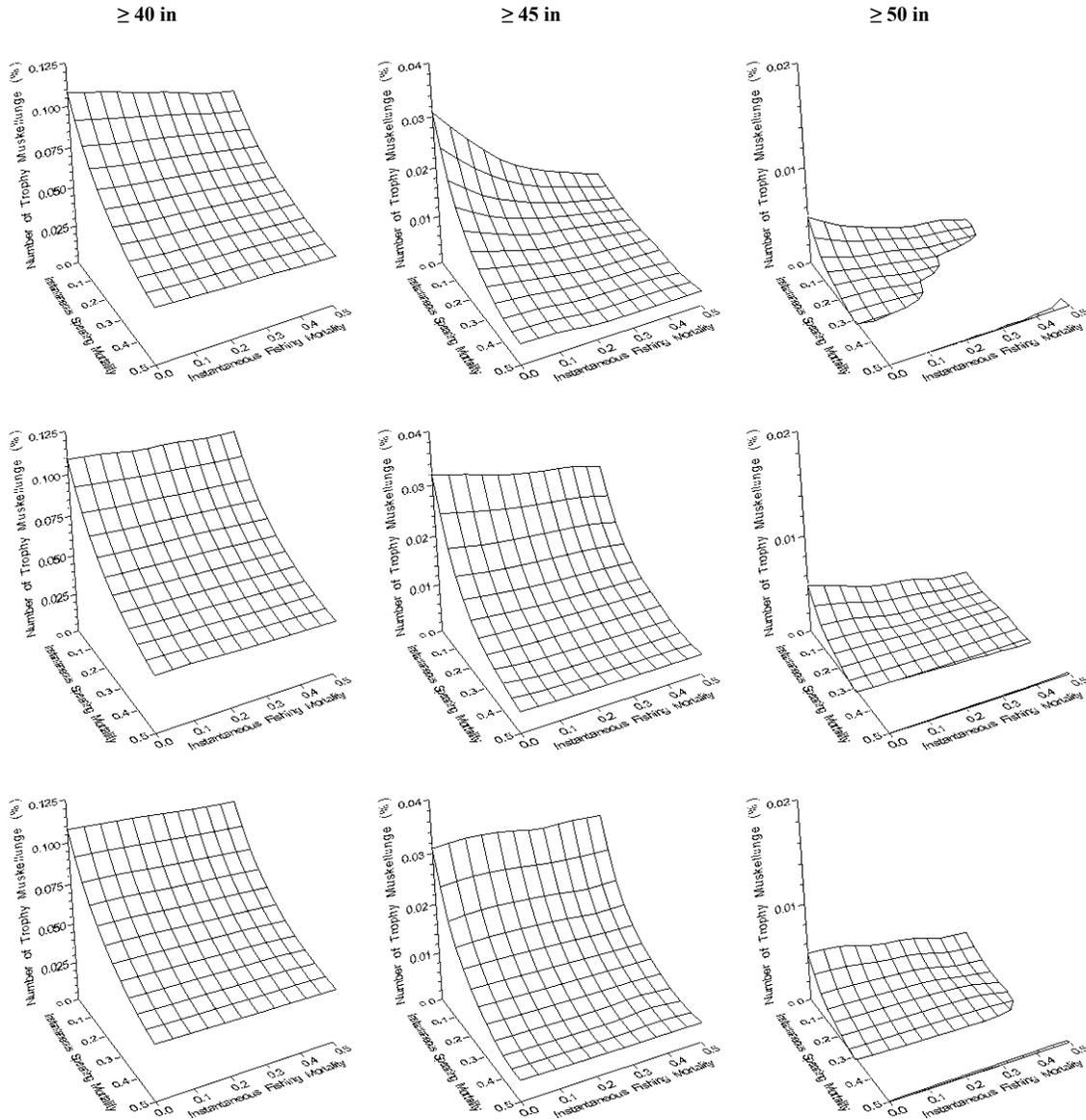


FIGURE 15.—Response surfaces illustrating relationship between number of muskellunge (%) greater than or equal to 40 in, 45 in, and 50 in, and instantaneous sparring mortality ( $F_{spearing}$ ) and instantaneous fishing mortality ( $F_{angling}$ ) for a medium-bodied population simulated under a mixed fishery with a 40-in (top), 45-in (middle), and 50-in (bottom) minimum length limit.

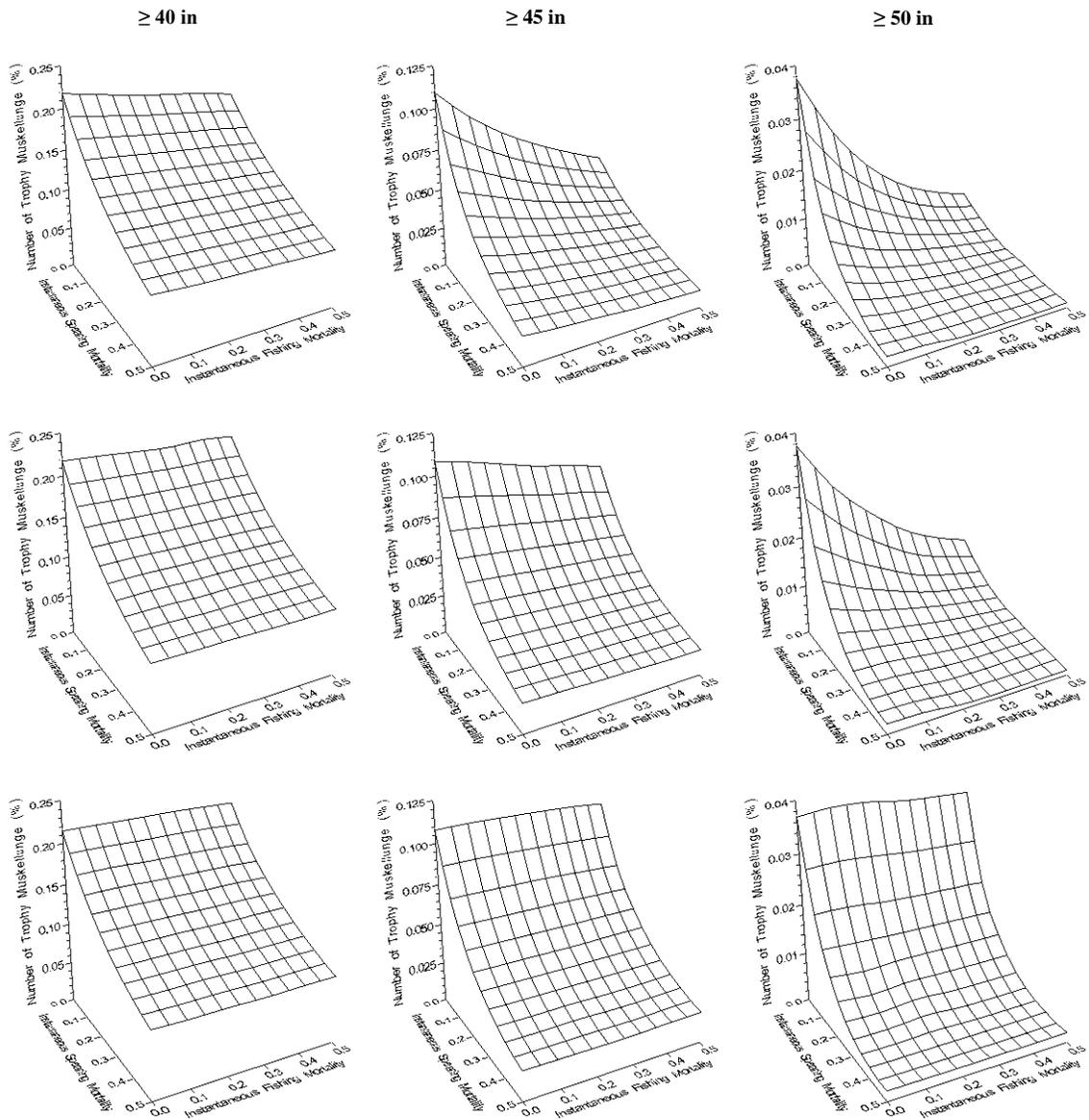


FIGURE 16.—Response surfaces illustrating relationship between number of muskellunge (%) greater than or equal to 40 in, 45 in, and 50 in and instantaneous spearing mortality ( $F_{spearing}$ ) and instantaneous fishing mortality ( $F_{angling}$ ) for a large-bodied population simulated under a mixed fishery with a 40-in (top), 45-in (middle), and 50-in (bottom) minimum length limit.

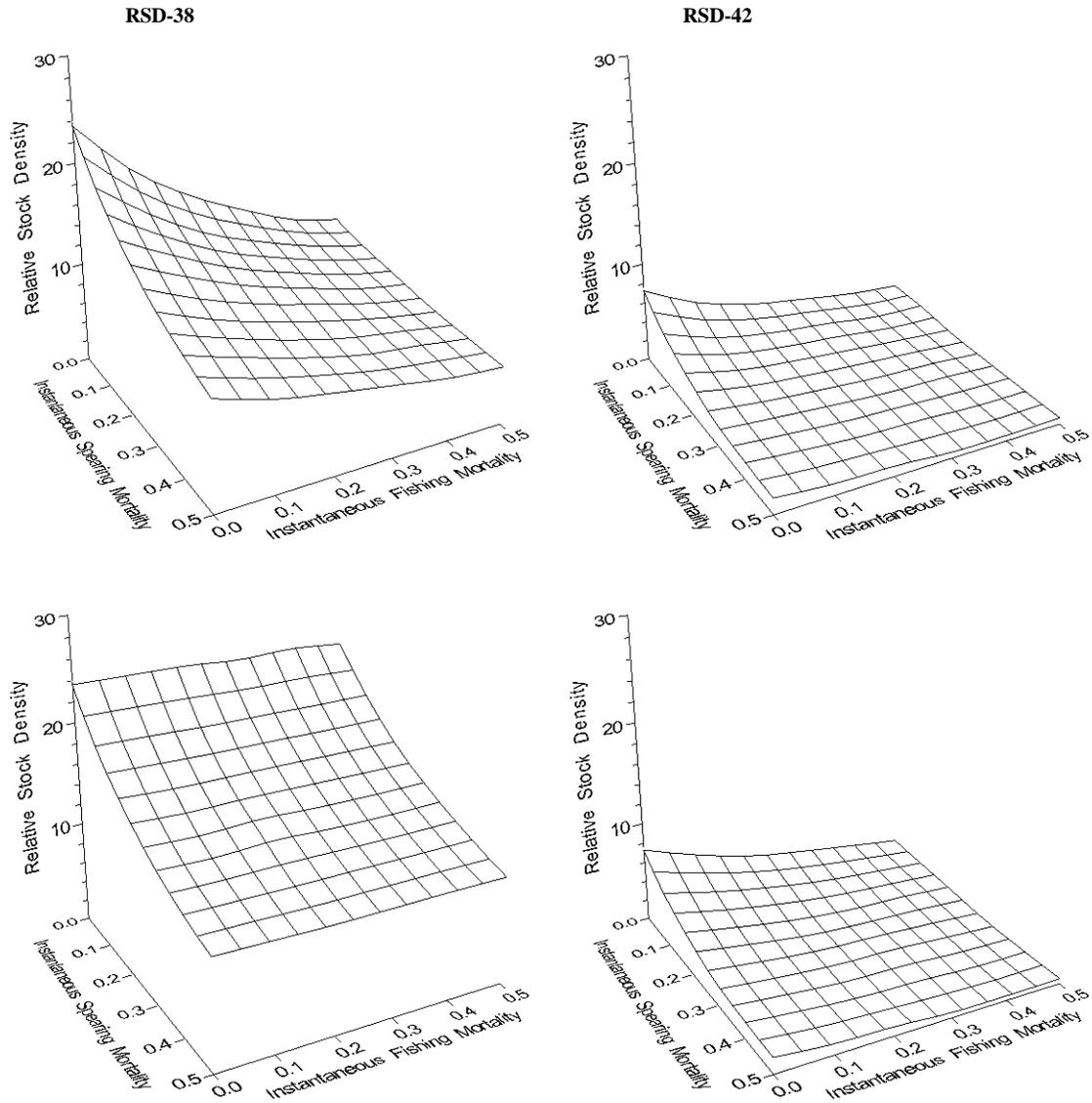


FIGURE 17.—Response surfaces illustrating relationship between relative stock density of muskellunge greater than 38 in (RSD-38) and 42 in (RSD-42) and instantaneous sparring mortality ( $F_{sparring}$ ) and instantaneous fishing mortality ( $F_{angling}$ ) for a small-bodied population simulated under a mixed fishery with a 28-in minimum length limit (top) and a 40-in minimum length limit (bottom).

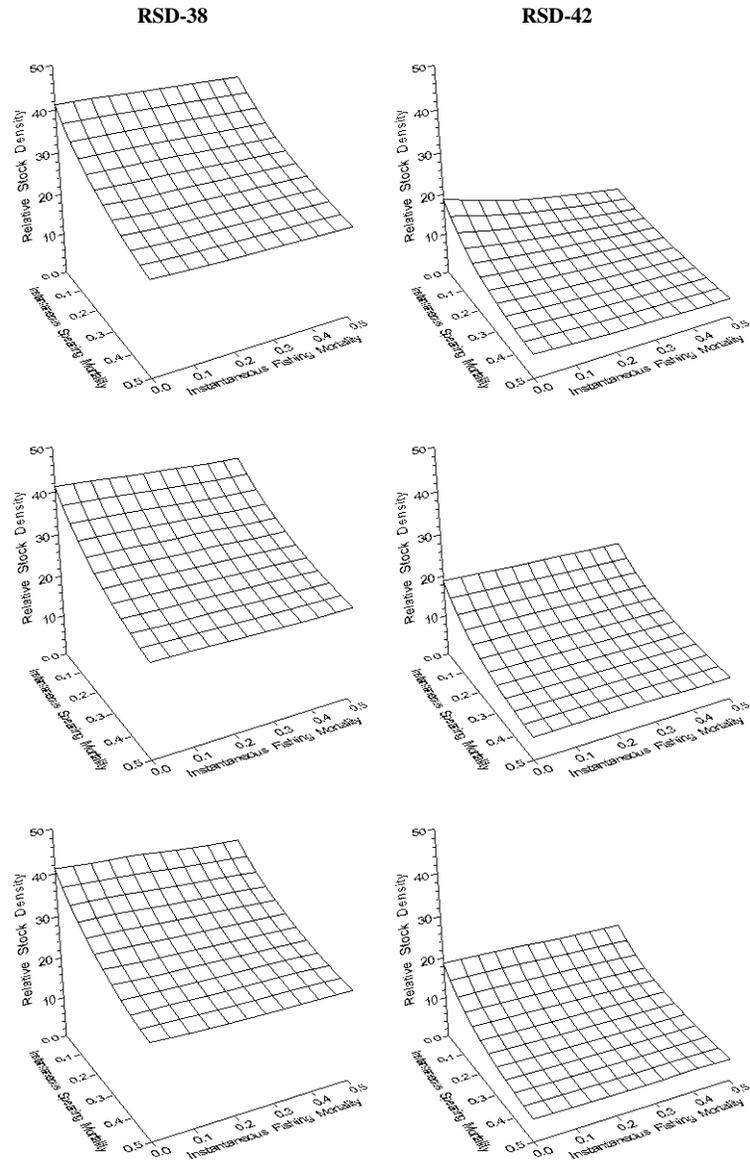


FIGURE 18.—Response surfaces illustrating relationship between relative stock density of muskellunge greater than 38 in (RSD-38) and 42 in (RSD-42) and instantaneous spearing mortality ( $F_{spearing}$ ) and instantaneous fishing mortality ( $F_{angling}$ ) for a medium-bodied population simulated under a mixed fishery with a 40-in(top), 45-in (middle), and 50-in (bottom) minimum length limit.

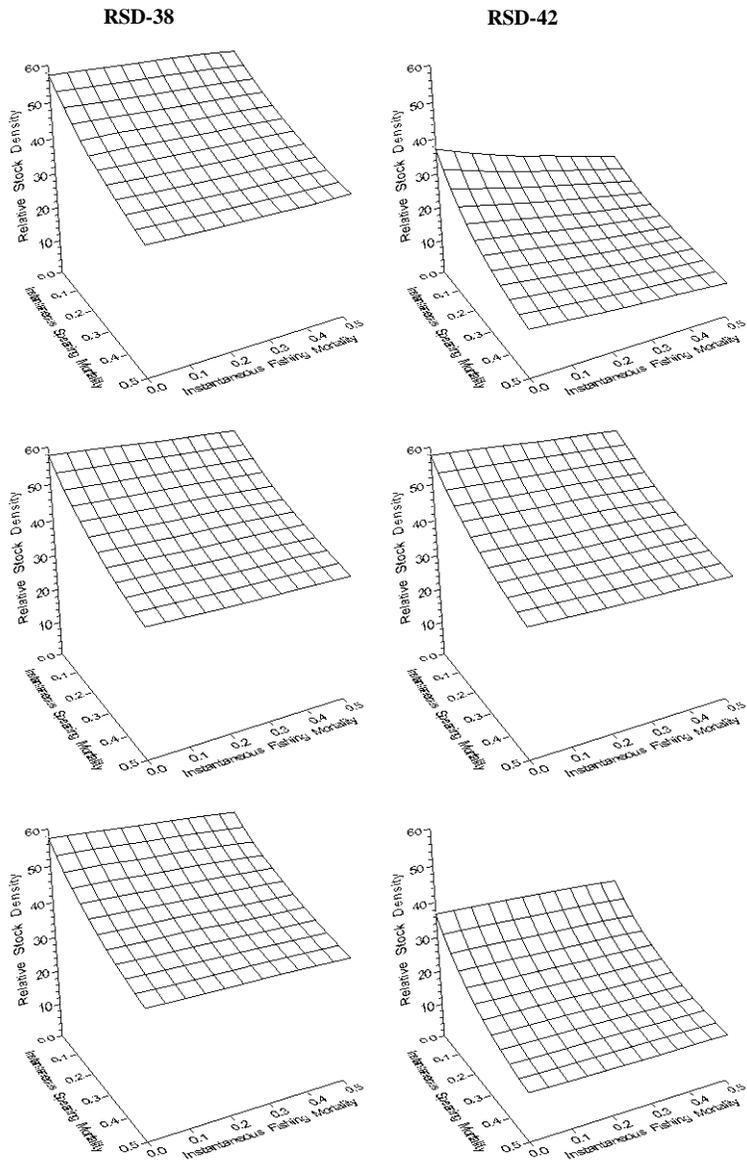


FIGURE 19.—Response surfaces illustrating relationship between relative stock density of muskellunge greater than 38 in (RSD-38) and 42 in (RSD-42) and instantaneous spearing mortality ( $F_{spearing}$ ) and instantaneous fishing mortality ( $F_{angling}$ ) for a large-bodied population simulated under a mixed fishery with a 40-in(top), 45-in (middle), and 50-in (bottom) minimum length limit.

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