Assessment of overfishing and bycatch for an exploited paddlefish population in the lower Tennessee River

A FINAL REPORT SUBMITTED TO

Marie Maltese
Division of Scientific Authority
U.S. Fish and Wildlife Service
Washington, D.C.

PREPARED BY

Phillip W. Bettoli, Ph.D.
U.S. Geological Survey

George D. Scholten, M.S.
Tennessee Cooperative Fishery Research Unit
Tennessee Technological University
Cookeville, TN

9 May 2005

EXECUTIVE SUMMARY

1. Paddlefish (n = 576) were collected from Kentucky Lake, KY-TN, with experimental gillnets in 2003-2004 to assess population characteristics and the likelihood of commercial overfishing. Additional data were collected from 1,039 paddlefish caught in gillnets set by commercial fishers in this impoundment.

2. Size and age structure have been reduced and annual mortality has tripled since the most recent study in 1991. Thirty-seven percent of the fish collected in 1991 were older than the maximum age we observed (age 11) and annual mortality (A) for age 7 and older paddlefish in 2003 was high (68%). Natural mortality (v) is presumably low (<10%) for paddlefish; therefore, exploitation in recent years was high.

3. Previous and current estimates of total annual mortality were negatively related to river discharge in the years preceding each estimate. The number of paddlefish harvested since 1999 was also negatively related to river discharge during the fishing season because gill nets cannot be easily deployed when discharge exceeds ~ 850 m^3/sec.

4, All female paddlefish longer than 1,034 mm eye-fork length (EFL) were gravid, which is evidence that large females spawn annually.

5. No mature (i.e., gravid) females were protected from harvest by the current 864 mm (34 inch) minimum EFL limit.

6. Before the 2003-2004 season began, the percentage of mature males did not vary ($P = 0.849$) between the riverine (uplake) and lacustrine (downlake) reaches of Kentucky Lake. Similarly, the percentage of mature females in both reaches was nearly identical (7% and 8%; $P = 0.895$) before the season began. However, after the season ended in April-May 2004, most of the mature fish were in the riverine reach and most of the immature fish were downlake.

7. Simulated flesh yields increased 10-20% with higher EFL limits when exploitation was high (40-70%), suggesting that growth overfishing was occurring.

8. At low levels of exploitation (*u* = 21%), Spawning Potential Ratios (SPR) under the current minimum size limit fell below 20%, which is indicative of a population prone to recruitment overfishing. If the minimum size limit was increased to 1,016 mm (40 inches) EFL, the population could withstand exploitation up to 62% before the SPR fell below 20%.

9. An analysis of mortality caps indicated that the best way to increase the average size of harvested fish is to increase the minimum size limit. However, increasing the minimum size limit will likewise increase bycatch rates, which are already very high for a commercial fishery. Mature females, the most commercially valuable component of the fishery, represented only 8% of the commercial paddlefish catch (i.e., the bycatch rate for fishers harvesting only gravid females was 92%). Legal-length males and females together represented only 40% of the catch; thus, the bycatch rate was 60% for fishers targeting all legal paddlefish for their flesh and eggs.

10. Initial mortality of paddlefish (i.e., fish were dead when nets were retrieved) was positively and significantly related to water temperature and net soak time. Fish were also more likely to be dead when captured by monofilament nets compared to multifilament nets. Mesh size was not a significant ($P = 0.15$) predictor of initial mortality.

11. Predicted initial mortality in multifilament nets set for 12 hours was high (= 26%) at water temperatures (~17 °C) characteristic of the end of the commercial season each April. Predicted mortality was low ($\leq$ 5%) in the same nets set during winter months (January –February) when water temperatures are usually below 9 ^{o}C.

12. Rates of delayed mortality of paddlefish released as bycatch are unknown and the subject of an ongoing investigation to be completed December 2006.

13. The hobbled (i.e., tied-down) gillnets deployed by commercial fishers were not size selective. The range of lengths and mean lengths of paddlefish captured in six different sizes of mesh were similar. Requiring fishers to use larger meshes will not increase the average size of the paddlefish they harvest, nor reduce the bycatch.

14. Recruitment overfishing probably occurred in previous decades during droughts, but interannual variation in river discharge (and fishing effort) prevented long-term exploitation at unsustainable rates. However, recent focus on paddlefish caviar as a substitute for sturgeon caviar from dwindling Caspian Sea stocks, and a growing market for paddlefish flesh, may increase harvest to levels that the stock cannot recover from when river discharges favor commercial fishing. Current commercial regulations do little, if anything, to protect the stock from overfishing and do not guarantee sustainable annual harvests of paddlefish flesh and caviar.

15. The findings contained in this report were presented in April 2005 to biologists with the Tennessee Wildlife Resources Agency (TWRA), the Tennessee Wildlife Resources Commission (the governing body of the TWRA), and the public, including several commercial fishers. A paddlefish management plan will be developed with stakeholder participation and regulation changes will be proposed before the 2005-2006 commercial harvest season opens. Management strategies and regulation changes should include (but are not limited to): banning monofilament gillnets; ending the commercial harvest season earlier each spring; creating a no-fishing refuge in the lacustrine reach of Kentucky Lake; and raising the minimum size limit to 965 mm (38 inches) EFL. Regulation changes should be accompanied by a commitment from all stakeholders and TWRA managers to engage in “Adaptive Management”, whereby minimum target levels of key population attributes are established, the population is monitored, and regulations are subsequently modified as needed to achieve the specific goals of the management plan.

16. Future research and sampling should focus on monitoring the average size and age of harvested paddlefish, assessing the catchability and size-selectivity of un-hobbled gillnets, and estimating dam passage rates and subsequent rates of immigration and emigration by paddlefish in the lower Tennessee River.

TABLE OF CONTENTS

FOREWORD

This report generally follows the formatting guidelines of the Transactions of the American Fisheries Society.

Two abbreviations that appear throughout the text are *i.e.* (from the Latin "*id est*"), meaning "that is", and *e.g.* (from the Latin *exempli gratia*) meaning "for example".

All units of measurement are metric, unless otherwise indicated.

- To convert Celsius (^{o} C) to Fahrenheit (^{o} F), multiply ^{o} C by 9/5 and add 32.
- One hectare equals 2.47 acres, and one km equals 0.621 miles.
- To convert length in millimeters (mm) to length in inches, divide by 25.4.
- One kilogram (kg) = 1,000 grams (g) = 2.2 pounds

The results and discussion pertaining to the assessment of overfishing will appear in a publication entitled *"Population characteristics and assessment of overfishing for an exploited paddlefish population in the lower Tennessee River"*, which was accepted for publication (April 2005) by the editors of the Transactions of the American Fisheries Society.

INTRODUCTION

Population Characteristics and Assessment of Overfishing

Paddlefish *Polyodon spathula* were once abundant in the Mississippi River drainage basin and several other tributaries of the Gulf of Mexico (Combs 1982). By the 1980s, many paddlefish populations had declined due to dam construction, industrial pollution, and overexploitation (both legal and illegal) by commercial and recreational fishers (Carlson and Bonislawsky 1981). What was once a largely ignored resource became the focus of interstate efforts in 1995, under the auspices of the Mississippi Interstate Cooperative Resource Association (MICRA), to study, conserve, and ultimately rebuild stocks of paddlefish throughout their historic range.

Tennessee is one of only six states that currently allow commercial paddlefish harvest and in the past two decades over half of commercially harvested paddlefish came from Tennessee waters (Hoffnagle and Timmons 1989; Timmons and Hughbanks 2000). On average, 80% of Tennessee's commercial paddlefish harvest is from Kentucky Lake on the lower Tennessee River, making it one of the largest, if not the largest, paddlefish fisheries in the world (R. Todd, Tennessee Wildlife Resource Agency [TWRA], personal communication). Paddlefish have been harvested from Kentucky Lake since its impoundment in 1944, but significant harvest did not occur until the early 1970s, when paddlefish roe became popular as an acceptable substitute for sturgeon (e.g., *Huso huso*; *Acipenser* spp.) caviar. Wholesale paddlefish roe prices in Tennessee steadily increased from US $78/kg in 1973 (in 2005 dollars) to ~ US$130/kg in 2005 (D. Blackwelder, commercial fisher, personal communication).

Until recently there were few regulations to manage the harvest of paddlefish in Tennessee. In 1998, TWRA required all commercial fishers who sold paddlefish to obtain a free permit (in addition to a US$125 commercial fishing license) and report their catches monthly to TWRA. Commercial fish markets were also required to record all commercial paddlefish transactions, including the number of paddlefish and weight of flesh and eggs purchased from commercial fishers. Despite these regulations, the current liberal minimum length limit (864 mm eye-to-fork length, EFL), lengthy commercial fishing season

(November 15 to April 23) that encompasses the entire paddlefish spawning migration, and an unlimited-entry fishery make overexploitation of paddlefish in Kentucky Lake a distinct possibility.

Under certain conditions, paddlefish can be easily overfished in a commercial gill net fishery. Paddlefish are especially vulnerable to entanglement gear when they congregate in spawning areas located below dams (Pasch and Alexander 1986). High flows induce paddlefish to migrate to spawning areas (Zigler et al. 1999; Paukert and Fisher 2001a), but it is difficult for fishers targeting mature females to deploy and retrieve gillnets in high flows. Regularly alternating periods of high and low discharge in a regulated system such as Kentucky Lake create conditions that are favorable to commercial fishing with gillnets.

Impounding large rivers such as the Tennessee River can hamper paddlefish recruitment (Purkett 1961; Russell 1986; Scarnecchia et al. 1996) and make it difficult for populations to recover after periods of heavy exploitation. The creation of reservoirs inundates gravel shoals required by paddlefish for egg incubation (Hoxmeier and DeVries 1996), although adults can thrive in these lentic environments (Russell 1986). Regulated river discharges often fail to mimic natural flow regimes that are important cues for paddlefish spawning (Unkenholz 1986). Even if flows are sufficient to induce spawning, dams can obstruct paddlefish migrations and alterations to the channels and banks may force fish to spawn in inferior habitats (Southall and Hubert 1984; Unkenholz 1986; Runstrom et al. 2001).

Late maturation hampers the recovery of a paddlefish population after a period of heavy exploitation. Female paddlefish generally do not reach sexual maturity until age 7 or later (Hoyt 1984; Reed et al. 1992). In Kentucky Lake, some age 6 males and age 8 females were sexually mature, but 100% maturity of a year class was not achieved until age 12 for males and age 16 for females (Timmons and Hughbanks 2000). Paddlefish grow relatively quickly, so they often recruit into a fishery before they are sexually mature. In 1991, the average age at recruitment in Kentucky Lake was 9.7 and 11.1 years for males and females, respectively, and many harvested fish were not sexually mature (Timmons and Hughbanks 2000). Early recruitment to the fishery and late maturation make paddlefish especially susceptible to recruitment overfishing (Pasch and Alexander 1986).

The reported commercial harvest of paddlefish in Kentucky Lake dropped 66% between 2000 and 2003 (R. Todd, TWRA, personal communication), despite the fact that wholesale roe prices received by fishers remained fairly stable over the same period (D. Blackwelder, commercial fisher, personal communication). The steep decline in reported catch suggested that the Kentucky Lake stock was being overfished, particularly when fishing effort and demand for flesh and roe were presumably high. Previous studies on Kentucky Lake reported classic signs of overexploitation such as high mortality, a comparatively young population, and few large, mature females (Bronte and Johnson 1985; Hoffnagle and Timmons 1989).

The Division of Scientific Authority (DSA) of the U.S. Fish and Wildlife Service reviews applications for international trade in species listed by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). Paddlefish were listed by CITES as an Appendix II species in 1992. The DSA determines whether a proposed activity (e.g., commercial harvest) will be detrimental to the survival of the species. After reviewing numerous applications for the export of paddlefish roe harvested from Kentucky Lake, the DSA voiced concerns in 2002 that paddlefish in Kentucky Lake were being overfished. Therefore, the objectives of this portion of the study were to:

(1) Describe the size structure and age structure of the paddlefish population in Kentucky Lake;
(2) Investigate reasons for recent harvest declines;
(3) Assess the likelihood that the paddlefish population in Kentucky Lake was suffering from growth overfishing or recruitment overfishing.

Bycatch

Bycatch refers to any non-target organism that encounters and is subsequently captured in commercial fishing gear. High-profile examples of bycatch posing threats to a species' survival include loggerhead sea turtles *Caretta caretta* captured in shrimp trawls and marine mammals (e.g., dolphins, F. Delphinidae) harvested in purse seines targeting yellowfin tuna *Thunnus albacares*. The Magnuson-Stevens Fishery Conservation and Management Act of 1994 (amended 1996) mandated reductions in bycatch where practicable; no such legislation protects freshwater fish stocks in the United States. Bycatch becomes problematic when the survival of released organisms is poor and the fisheries literature is replete with such examples. For instance, if sublegal Pacific halibut *Hippoglossus stenolepis* caught in a traditional longline halibut fishery are not released carefully, mortality can be extremely high (50-75%; Kaimmer and Trumble 1996). Clark and Hare (1998) reported that bycatch and subsequent mortality of migrating sublegal (< 81 cm) Pacific halibut reduced coastwide recruitment by about 10%. Size limits, creel limits, and quotas have been used to manage Gulf of Mexico red snapper *Lutjanus campechanus*; however, management objectives for that stock could not be reached unless their bycatch in shrimp trawls was reduced (Wallace 1996). Coho salmon *Oncorhynchus kisutch* in the Pacific Northwest are often caught incidentally in gill nets set for other salmon species. Shortly after entanglement in commercial gill nets, 35-70% of coho salmon died (Coho Response Team 1998). A decade ago, it was estimated that commercial marine fishers annually discarded about 25% of what they caught, or ~ 27 million metric tons of fish and wildlife (Alverson et al. 1994). In 2000, commercial fishers in US marine fisheries discarded about 2.3 billion pounds of wildlife (i.e., birds, marine mammals, turtles, fish) as bycatch (Pew Oceans Commission 2003). The total elimination of bycatch in any commercial fishery may be unrealistic (U.S. Commission on Ocean Policy 2004); however, a broad-based consensus has emerged in recent years that bycatch should be minimized to levels approaching insignificance (Crowder and Murawski 1998).

Unlike marine fisheries, a depauperate literature exists for bycatch in freshwater fisheries and most information pertains to commercial fisheries in coastal rivers targeting anadromous fishes. For instance, shortnose sturgeons *Acipenser brevirostrum* and Atlantic sturgeon *A. oxyrhynchus* were commonly observed in gill net fisheries targeting migrating American shad *Alosa sapidissima* (Collins et al. 1996). Paddlefish bycatch rates were described in a Missouri River hoop net fishery targeting buffalo *Ictiobus* spp, and exotic carps (Dieterman et al. 2000); they predicted one incidental paddlefish mortality for every 37 net-days of fishing effort. We are unaware of any published reports detailing bycatch rates for commercially exploited paddlefish, nor are we aware of any studies that describe rates of bycatch mortality for paddlefish captured in gill nets. The positive relationship between gill net soak time and initial mortality has been described for some stocks (e.g., coho salmon; Buchanan et al. 2002) and it is generally assumed that mortality increases with water temperature (e.g., Davis and Olla 2001).

Markets continue to develop for paddlefish flesh, yet most fishers target paddlefish exclusively for their eggs because of high demand and prices received for roe. Therefore, bycatch in Kentucky Lake refers to paddlefish that are either (1) illegal to possess because they are smaller than the minimum EFL limit (regulatory discards), or (2) non-egg fish (i.e., economic discards; males and immature females). Bycatch mortality has two components: the rate at which fish encounter the fishing gear, and the subsequent mortality rate for those fish. Rates of bycatch in paddlefish fisheries have not been described, nor have initial mortality rates been estimated. Therefore, our objectives in this portion of the study were to:

(1) Estimate the relative abundance of sublegal paddlefish (≤ 864 mm EFL), legal paddlefish, and mature females in the commercial catch in Kentucky Lake; and

(2) Model the influence of water temperature, fish size, net soak time, mesh size, and netting material on rates of initial mortality for paddlefish caught in gill nets.

Gill Net Selectivity

Minimum mesh-size restrictions in commercial gill net fisheries are routinely proposed to increase yield-per-recruit (Ehrhardt and Die 1988), re-structure predator-prey interactions (Schindler et al. 1998), or protect stocks from recruitment overfishing by delaying the size and age of recruitment to the fishery (Jude et al. 2002). Failure to protect some spawners in a heavily-exploited stock will increase the likelihood of recruitment overfishing which, if left unchecked, can lead to stock collapse. Using that rationale, in 2002 the Tennessee Wildlife Resources Commission established a minimum bar measure of 152-mm (6”) for any entanglement gear (i.e., gill nets and trammel nets) used by commercial fishers to capture paddlefish. The minimum size limit for legal paddlefish was also raised to 864 mm eye-fork length (EFL). Concerns about overfishing were justified because until recently, most of the paddlefish caviar that is exported from the United States originated from Tennessee waters (M. Maltese, Division of Scientific Authority, U.S. Fish and Wildlife Service, personal communication), particularly from Kentucky Lake on the lower Tennessee River. Several high-profile convictions for interstate trafficking in illegal paddlefish roe also heightened efforts to conserve the resource and the new mesh size restriction met with little opposition from commercial fishers. Commercial fishers usually target paddlefish for their roe, but the flesh can also be sold to wholesale fish markets. Since the collapse of Eurasian sturgeon stocks (e.g., *Huso huso*, *Acipenser* spp.), national and international demand for caviar has increased pressure on U.S. paddlefish stocks. The listing of paddlefish as a CITES Appendix II species in 1992 served to regulate export trade in the species through a system of permits issued by the USFWS. The Appendix II listing also increased the scope of law enforcement oversight of the species, thereby affording paddlefish additional protection from illegal harvest and trade. More recently, the U.S. Fish and Wildlife Service listed the beluga sturgeon as a federally threatened species under the Endangered Species Act of 1973, although some importation of its caviar may be permitted provided certain requirements are met by exporting countries. The U.S. represents one of the largest markets for sturgeon caviar and demand for Eurasian caviar substitutes will likely increase pressure on paddlefish stocks in the six states where they are commercially harvested.

Enacting minimum mesh-size requirements to conserve fish stocks may not meet with the same vehement opposition that can accompany other methods of reducing fishing mortality such as limiting entry to a fishery or closing seasons (e.g., Huhmarniemi and Salmi 1999). Perhaps a more important reason to enact minimum mesh size regulations is the fact that entanglement gears such as gill nets are usually highly size-selective (Hamley 1980) and it is theoretically possible to reduce the bycatch of smaller fish by increasing the minimum mesh size that fishers can deploy. The exact degree to which particular gill net meshes select for different sizes of target species has been the subject of many investigations (e.g., Hamley 1975; Hansen et al., 1997; Carlson and Cortés 2003) and the best approach to measure such selectivity has been debated (e.g., Hesler et al. 1998; Millar 2000).

Many marine and freshwater fish species have been the subject of gill net selectivity studies, but we are unaware of any such studies that examined selectivity, or lack thereof, in a paddlefish fishery. Preliminary observations made while retrieving more than 150 experimental gillnets in 2003-2004 suggested that unlike most species, little if any size-selectivity was evident for paddlefish. Apparent lack of selectivity for different sizes of paddlefish may have been due in part to their elongated rostrum, which can represent about 25% of the total length of the fish but is no wider than ~ 11 cm on a large (> 20 kg) fish. Thus, our objectives in this portion of the study were to test the following null hypotheses:

1. Mean lengths of paddlefish captured in experimental gillnets would not vary with mesh size;
2. The proportion of the catch in each mesh that was bycatch (i.e., sublegal fish less than 864 mm EFL) would not vary with mesh size;
3. Fish girth:mesh perimeter ratios (G:P) would be similar in each mesh.

Failure to reject the first two hypotheses would indicate that mesh size restrictions could not be used to alter the size-structure of the commercial catch and, subsequently, reduce fishing mortality for sublegal paddlefish. Rejection of the third hypotheses would likewise indicate that paddlefish of varying lengths (and girths) are susceptible to capture by a wide range of mesh sizes. By way of comparison, we performed the same analyses on a large database of lengths of saugers *Sander canadense* collected using experimental gillnets in the 1990s in Kentucky Lake (i.e., we expected experimental gill nets to display a high degree of size-selectivity for saugers).

STUDY AREA

Kentucky Lake is a mainstream impoundment of the Tennessee River located in western Tennessee and Kentucky (Figure 1). Impounded in 1944 by the construction of Kentucky Dam at Tennessee River km (TRkm) 35, this 296-km long reservoir is a eutrophic impoundment that covers 64,870 hectares at full pool and has a mean depth of 5.4 m. Water levels usually fluctuate about 1.5 m between winter and summer pools. Water discharged from Pickwick Dam, the upstream boundary of the reservoir at TRkm 331, flows north through Kentucky Lake. Kentucky and Pickwick dams have navigation locks, power generators, and flood gates that are controlled by the Tennessee Valley Authority (TVA). Kentucky Lake is riverine above (south half) and lacustrine below (north half) TRkm 186.

All riverine habitat and the upper portion of the lacustrine habitat lie within Tennessee; the remainder of the lacustrine habitat and Kentucky Dam lie within Kentucky.

METHODS

Population Characteristics and Assessment of Overfishing

Paddlefish were collected in the riverine and lacustrine regions of Kentucky Lake between TRkm 105 and TRkm 298 before (5 September to 2 November 2003) and after (20 April to 3 May 2004) Tennessee’s commercial fishing season. A cooperative interaction with experienced commercial fishers gave us access to "Traditional Ecological Knowledge" (Price and Rulifson 2004); that is, the collective experiences and knowledge of the people who rely on the resource for their livelihood. This interaction and the experiences we gained allowed us to collect paddlefish over a wide range of habitat types, flow regimes, and seasons. Horizontal experimental monofilament gill nets (3.6 × 128 m, tied down to 2.4 m; and 9.1 × 91 m, tied down to 7.6 m) with six panels of 89, 102, 127, 152, 178, and 203 mm bar-measure meshes were fished overnight. During the 2002-2003 and 2003-2004 commercial fishing seasons, we occasionally accompanied commercial fishers and observed their catch to collect additional data for certain analyses; specifically, creating an age-length key and estimating bycatch rates and mortality.

Eye-to-fork length (EFL, mm), weight (nearest 0.25 kg), sex, and maturity (immature or mature) were recorded for each captured paddlefish. Sex and maturity were determined by examining gonads. Immature males had long, wavy, tubular gonads that were slightly gray; females had pinkish, lamellar gonads that were highly convoluted (Russell 1986). Fish were classified as mature if testes were large and swollen or ovaries contained large (2-3 mm diameter) dark eggs (Bronte and Johnson 1985).

Ovaries were excised from all females and weighed (nearest 0.1 g). A subsample of eggs was collected from at least six locations that spanned the length and depth of each mature ovary. Each subsample was weighed and preserved with a 5% unbuffered formalin solution (Markle 1984). Twenty-five randomly selected eggs from the pooled subsample of each ovary were measured (maximum diameter, nearest 0.01 mm). The eggs in each subsample were weighed (nearest 0.001 g), counted, and fecundity was estimated through extrapolation (Reed et al. 1992). Relative fecundity was determined by calculating the number of eggs per kilogram of body weight (Hoxemeier and DeVries 1997).

Dentary bones of at least five male and five female paddlefish per each 25-mm EFL group were removed for age estimation. Dentary bones were submersed in a 10:90 solution of ALL® laundry detergent and water and heated to 43° C for 14 hours to loosen flesh adhering to the bones. After cleaning, the dentary bones were soaked in a 50:50 solution of ammonia and water for five hours and then a 50:50 solution of ethanol and water for 24 hours (R. Todd, TWRA, personal communication). After drying, five sections (~0.5 mm thick) were obtained from the left dentary bone 10 mm posterior to the mesial bend with a Buehler Isomet® low-speed saw (Scarnecchia et al. 1996; Lein and DeVries 1998). Age was estimated for each set of sections in two independent readings. Annuli were counted (Adams 1942) without knowledge of fish size or sex using a microprojector at 40X magnification. When discrepancies occurred between first and second readings, those sections were read a third time. Two of the three readings always agreed; therefore, the modal age was assigned (Hoxmeier and DeVries 1997). Ages were then assigned to unaged fish using an age-length key.

Length-frequency (25-mm groups) and age-frequency histograms were constructed to visually assess size and age structure of the population. Size and age structure were estimated from the paddlefish catch in experimental gill nets before spawning migrations began. Spatial and temporal differences between ratios of males to females, and immature fish to mature fish, were tested with the chi-square statistic. Mean ages between sexes were compared using t-tests.

The annual paddlefish harvest from Kentucky Lake between 1999 and 2003 (data from TWRA harvest reports) was regressed against the number of fishable days each season using linear regression. Typically, commercial fishers will not deploy their nets in Kentucky Lake when discharge from Pickwick Dam exceeds ~ 850 m^3/s because nets will encounter too much debris and become entangled (and not fish properly) (D. Blackwelder, commercial fisher, personal communication); therefore, a fishable day was assumed to be any day during the commercial paddlefish season with a mean discharge from Pickwick Dam of 850 m^3/s or less.

The natural logarithm of catch from each age class in the preseason sample was plotted against age to construct a catch curve. The age at full recruitment was considered the age at which the catch curve began descending. Instantaneous total annual mortality (Z) was derived from the slope of the descending limb of the catch curve and transformed into an interval annual mortality rate ($A = 1 - e^{-Z}$). Bronte and Johnson (1985), Hoffnagle and Timmons (1989), and Timmons and Hughbanks (2000) estimated annual mortality of paddlefish from ages that were fully recruited (> age 6) to the Kentucky Lake fishery in their 1980, 1985, and 1991 studies. Their estimates and the annual mortality estimate from the present study were regressed against total discharge from Pickwick Dam each fishing season in the years preceding each of the four studies. We assumed that natural mortality would remain constant; thus, variation in total mortality would reflect different levels of exploitation.

The yield-per-recruit option in Fisheries Analyses and Simulation Tools (FAST) software was used to determine if growth overfishing was occurring. This option uses the Jones (1957) modification of the Beverton-Holt equilibrium yield equation to calculate yield (Ricker 1975). Yields (kg of flesh per 1,000 recruits) were simulated for the current size limit (864 mm, 34") and two size limits (965 and 1,016 mm EFL) that would protect approximately 33% and 50% of the mature females sampled in this study. This simulation utilized the y-intercept and slope from the $\log_{10}$EFL-$\log_{10}$weight regression model, the von Bertalanffy growth parameters (L_{inf}, k, and t_0), and hypothetical exploitation rates (Table 1). Data on the largest (1,220 mm) and oldest (age 21) paddlefish collected by Timmons and Hughbanks (2000) in their 1991 study on Kentucky Lake were included in the von Bertalanffy growth model. Timmons and Hughbanks (2000) suggested that natural mortality was low (v = 8%) for paddlefish in Kentucky Lake; therefore, the conditional natural mortality rate (CM) was assumed to be 8%. Conditional fishing mortality rates (CF) from 10% to 70% were used to simulate yield over a wide range of exploitation levels.

A maturation schedule for females was formulated by determining the percent of mature fish in each size (25-mm EFL groups) and age class. Female paddlefish maturity was indexed using a gonadosomatic index (GSI; Irwin and Bettoli 1995):

$$\mathrm{OW}*100 / (\mathrm{WT} - \mathrm{OW}),$$

where OW is ovary weight and WT is body weight. Relations between GSI, ovary weight, mean egg diameter, and fecundity and paddlefish lengths and weights were described using linear models. With age- and length-specific fecundity data and a maturation schedule, the Spawning Potential Ratio (SPR; Goodyear 1993) was calculated using FAST software:

$$SPR = P_{EXPLOITED} / P_{UNEXPLOITED},$$

where P (potential recruit fecundity) represents the lifetime production of eggs by the average recruit in an exploited and unexploited population.

Miranda (2002) defined mortality caps as thresholds of mortality above which management objectives can no longer be met. Mortality caps can be used to identify which length objectives are practical and to forewarn managers when mortality is too high. Annual mortality caps were estimated for the current minimum EFL limit (864 mm) and the two potential minimum EFL limits discussed above (965 mm and 1,016 mm) using parameters (K and L_{inf}) from the von Bertalanffy growth model and Miranda's (2002) equation:

$$Z = K \times [(L_{inf} - L_{mean}) \times (L_{mean} - L_x)^{-1}],$$

where L_{mean} represents the desired mean EFL of harvested fish (i.e., management objective), and L_x is the minimum EFL at which fish are vulnerable to harvest (minimum EFL limit). Length objectives (L_{mean}) have not been set for Kentucky Lake paddlefish; therefore, Z was estimated over a range of L_{mean} (L_x to L_{inf}) for each EFL limit and subsequently transformed into A.

Programs written for the Statistical Analysis System® (SAS Institute 2001) were used for all statistical analyses. All tests were considered significant at P = 0.05.

Bycatch Rates and Initial Mortality

Paddlefish removed from commercial (0.52 mm diameter multifilament) and experimental (0.40-0.57 mm diameter monofilament) gill nets before, during and after the

2002-2003 and 2003-2004 commercial harvest seasons were coded as dead (i.e., no opercular flap movements; unresponsive to touch) or alive. Water temperature and soak time were recorded for each net. Capturing mesh size, twine type (monofilament or multifilament), and EFL (mm) were recorded for each paddlefish. This binomial data was then subjected to multiple logistic regression (SAS Institute 2001) to test whether fish length, mesh size, twine type, soak time, or water temperature were significant ($P \leq 0.05$) predictors of initial mortality. The relative abundance of sublegal fish shorter than 864 mm EFL, legal males and immature females, and mature (egg-laden) females was subsequently calculated for the commercial catch during the 2002-2003 and 2003-2004 fishing seasons.

Gill Net Selectivity

The data needed to assess size selectivity were collected in the course of describing the population characteristics and assessing the effects commercial fishing had on the Kentucky Lake paddlefish population. Only data on paddlefish collected using our experimental monofilament gill nets were used in the size-selectivity analyses. All mesh sizes had equal fishing power, which is a key assumption in gill net selectivity studies. The eye-to-fork length (EFL, mm) was recorded for each paddlefish, as well as the mesh size in which they were captured.

Saugers were collected in the headwaters of Kentucky Lake during their spawning migrations in the winters of 1993-1996 using experimental monofilament gill nets (46 x 1.8 m) with 19, 25, 38, 51, and 63-mm meshes. Total lengths (TL) were recorded for all saugers (n = 1,961) as well as the mesh size in which they were captured. Few (n = 18) saugers were collected in the 63-mm mesh; therefore, those data were not considered. No distinction was made between fish captured via wedging or entanglement.

Mean lengths of fish captured in different meshes were compared separately for each species using one-way analysis of variance (ANOVA). If the global null hypothesis was rejected, mean lengths were compared using Tukey's test. The chi-square statistic was used in a 2 x 6 contingency table to test whether mesh size and the proportion of legal-sized paddlefish (> 864 mm EFL) caught in each mesh were associated. Although there is no commercial fishery for saugers in Kentucky Lake, the species was managed with a 356-mm

TL minimum size limit. Thus, for the purposes of this report we assumed that any sauger longer than 356-mm TL was a legal fish in a hypothetical gill net fishery. The percentage of the total catch for each species that was bycatch (i.e., shorter than the minimum size limit) was regressed against mesh size to determine whether the bycatch of each species decreased with increasing mesh sizes.

Maximum girth was measured for 403 paddlefish but girth measurements were not available for 173 paddlefish collected before the fishing season began. Simple linear models were used to assign girth measurements to fish for which girth was not measured based on their EFL, sex, and date of capture. The relation between EFL and girth for 56 preseason females ($r^2 = 0.90$; $P < 0.001$) was used to predict girth measurements for 108 additional preseason females. Similarly, the EFL-girth relation for 58 preseason males ($r^2 = 0.74$; $P < 0.001$) was used to predict girth measurements for 65 additional preseason males. The maximum girths of a subsample of saugers (n = 87) were measured and girth measurements were then assigned to the remaining saugers based on the linear relation between girth and TL ($r^2 = 0.93$; $P < 0.001$). For most species, maximum gill net selectivity corresponds to girth:perimeter (G:P) ratios centered around 1.1 – 1.4 (e.g., Spangler and Collins, 1992; Van Den Avyle et al., 1995) and the optimum girth for capture is about 1.25× the mesh perimeter (Hamley 1980). Frequency-distributions of G:P ratios were created for each species in each mesh size to determine whether the ratios for each species fell within the expected range. Mean G:P ratios were also compared among meshes for each species using one-way ANOVA models and Tukey's multiple comparison test.

RESULTS

Population Characteristics and Assessment of Overfishing

Although 576 paddlefish were collected with experimental gill nets, length-frequency (Figure 2) and age-frequency (Figure 3) histograms represent only paddlefish collected in the preseason sample (n = 287) because we observed distinct spatial and temporal differences in the distribution of paddlefish throughout Kentucky Lake. Specifically, the ratios of mature-to-immature and males-to-females varied spatially in the post-season sample. Before the season began (2 October - 2 November 2003), the percentage of males that were mature (76% and 78%) did not vary ($X^2 = 0.04$; df = 1; $P = 0.849$) between the two reaches of Kentucky Lake (Figure 4). Similarly, the percentage of females that were mature was almost identical (7% and 8%; $X^2 = 0.02$; df = 1; $P = 0.895$) in both reaches of the reservoir before the season began. In contrast, the same percentages differed ($X^2 \geq 21.7$; df = 1; $P < 0.001$) after the season ended in April-May 2004. Sex ratios in the riverine (1.05 males: 1 female) and lacustrine (0.57 males: 1 female) reaches differed ($X^2 = 6.3$; df = 1; $P = 0.012$) before the season began; it was assumed that the pooled sex ratio (i.e., both reservoir regions; 0.76 males: 1 female) accurately reflected the sex ratio of this population. After the season closed, the difference in sex ratios in the riverine (9.05 males: 1 female) and lacustrine (0.49 males: 1 female) reaches was more pronounced ($X^2 = 100.5$; df = 1; $P < 0.001$). Few mature males and almost no mature females remained downstream in the lacustrine reach of Kentucky Lake at the end of the spring spawning season. Thus, postseason estimates of size and age structure would probably have been biased because the relative abundances of paddlefish of each sex and stage of maturity were dissimilar in each reservoir reach.

During the past 30 years the amount of water discharged through Pickwick Dam each commercial fishing season has varied more than four-fold (Figure 5). The 66% drop in commercial paddlefish harvest between 2000 and 2003 was more likely a function of increased volume of water discharged through Pickwick Dam than stock collapse. There was a strong positive relationship between the number of fishable days each commercial fishing season and the number of paddlefish harvested from Kentucky Lake (n = 5; $P < 0.023$; $r^2 = 0.86$; Figure 6). Those five years (1999-2003) encompassed drought years as well as years of average and slightly above-average discharge from Pickwick Dam.

The age structure of Kentucky Lake's paddlefish stock reflected a young population. The 661 paddlefish that were aged ranged from 398-1,238 mm EFL and represented ages 2-11. Repeatability (i.e., assigning the same age for each of the two readings) was 66%. Most (96%) discrepancies between readings did not exceed 1 year and discrepancies never exceeded 3 years. Females (mean age = 7.2 years; range = 3-11) were significantly older on average ($t = 6.03$, d.f. = 283, $P < 0.001$) than males (mean age = 6.3 years; range = 2-9). Age 7 was considered the age at full recruitment based on the catch curve.

Paddlefish in Kentucky Lake experienced high mortality. Instantaneous annual mortality (Z) was 1.126, which equates to an interval annual mortality rate (A) of 68%. There was essentially no deviation ($r^2 = 0.95$) of points about the catch curve. Annual mortality estimates (from this study and studies in 1980, 1985, and 1991) and mean discharge from Pickwick Dam during the previous 1, 2, 3, 4, and 5 seasons were negatively related ($r^2 = 0.58\text{-}0.96$) and mean discharges during the previous two and three seasons were significant ($P < 0.05$) predictors of annual mortality.

The relationship between EFLs (398-1,238 mm) and weights (0.75-29.25 kg) were best described by:

$$\text{Log}_{10}\ (\text{weight}) = -8.71 + 3.31\ \text{Log}_{10}\ (\text{EFL})$$

(n = 978; $P < 0.001$; $r^2 = 0.87$). The von Bertalanffy model (Table 1, Figure 7) closely fit observed mean lengths-at-age and was best described by:

$$\text{EFL}_t = 1{,}279\ (1 - e^{-0.131\ (t - 1.527)})$$

where t is age. The model predicted that paddlefish took 7.1, 8.0, 9.2 and 10.6 years to reach legal size (i.e., 864 mm EFL, 34”), 914 mm (36”), 965 mm (38”), and 1,016 mm (40”), respectively.

Mature females represented a small fraction of the population. Four percent of the paddlefish collected before the 2003-2004 season began and 8% of the paddlefish caught by commercial fishers during the 2002-2003 and 2003-2004 seasons were mature females. Males began to mature earlier (age 4; 452 mm; 6.0 kg) than females (age 8; 885 mm; 10.0 kg). There was no age class of either sex in which all of the individuals were mature, but at least 50% of the age 5 males and age 10 females were mature (Table 2). One age 11 female was not mature; however, all females (n = 21) equal to or longer than 1,034 mm EFL were mature. As EFL increased from 885 mm to 1,034 mm the proportion of mature females in each 25-mm group increased; 29% of females between 926 mm and 950 mm were mature and 61% of females between 1,001 mm and 1,025 mm were mature.

No mature females collected during this study were protected by the current minimum size limit (Figure 8). Female GSI values were positively correlated to EFL (r^2 = 0.54, $P < 0.0001$). Minimum EFL limits of 914 mm (36”), 965 mm (38”) and 1,016 mm (40”) would have protected 7%, 29% and 58% of mature females from commercial harvest, respectively. The GSI values for mature females ranged from 6.1% to 36.7% and there was little adipose tissue associated with mature ovaries. GSI values for immature females ranged from 0.1% to 4.4%, but gonads were usually attached to large fat bodies that represented as much as 12% of somatic body weight.

Fecundity was estimated for 75 mature females (885-1,161 mm EFL; 10.5-29.0 kg) and the fecundity of similar-sized paddlefish was highly variable. The number of eggs per female ranged from 109,048 to 504,112 (mean = 279,256; SE = 9,590) and relative fecundities ranged from 9,281 to 26,374 eggs per kg of body weight (mean = 16,381; SE = 417). The relationship between fecundity and body size was best described by:

$$\text{Log}_{10}\,(\text{fecundity}) = 4.282 + 0.937\,\text{Log}_{10}\,(\text{weight}) \quad (P < 0.0001;\ r^2 = 0.48)\text{, and}$$

$$\text{Log}_{10}\,(\text{fecundity}) = -4.284 + 3.236\,\text{Log}_{10}\,(\text{EFL}) \quad (P < 0.0001;\ r^2 = 0.38).$$

Mature ovary weights ranged from 0.957 to 4.884 kg (mean = 2.310; SE = 0.093). Log_{10}-EFL and weight were significant ($P \leq 0.005$) predictors of ovary weight but each variable explained little of the variation (r^2 = 0. 21 and 0.10, respectively). Egg diameters ranged from 1.3 to 3.2 mm (mean = 2.33; SE = 0.01) and mean egg diameter for individual fish ranged from 1.6 to 2.7 mm (mean = 2.33; SE = 0.03). There was a weak positive relationship between mean egg diameter and body weight ($P < 0.01$; $r^2 = 0.15$), but not EFL ($P = 0.34$; $r^2 = 0.01$).

Simulation modeling suggested modest growth overfishing under the current 864 mm minimum EFL limit. When exploitation was high (40-70%), increasing the minimum EFL limit from 864 mm to 965 mm or 1,016 mm increased simulated flesh yields by 10–15% and 12–20% (Figure 9); however, these size limits did not increase flesh yields at low (< 20%) levels of exploitation.

Simulated SPRs were very low for Kentucky Lake's paddlefish stock. SPR values ranged between 1% and 46% under the current 864 mm minimum EFL limit when exploitation rates ranged from 10% to 70% (Figure 10). Increasing the minimum size limit to 965 mm or 1,016 mm increased the SPR to 7-57% and 18-65%, respectively. Under the 864 mm minimum EFL limit, SPR values fell below 20% when exploitation rates exceeded 21%. If the size limit was raised to 965 mm, this population could theoretically withstand exploitation rates as high as 35% before the SPR value fell below 20%. A 1,016 mm size limit allowed the simulated population to withstand exploitation rates as high as 62% before the SPR fell below 20%.

Total annual mortality would have to be extremely low ($A \leq 17\%$) under the current size limit if the objective was to increase the mean length of harvested fish (919 mm in 2003) to the length at which all females are mature (i.e. 1,034 mm EFL and longer; Figure 11). If the minimum size limit was increased from 864 mm to 965 mm or 1,016 mm, annual mortality caps could be much higher (37% and 83%, respectively), and still allow that same target size to be achieved. If the target size was more conservative (e.g., the length at which ~ 50% of females are mature; 965 mm EFL), exploitation and total mortality would still need to be low ($A \leq 33\%$) to achieve that target if the population was managed with the current size limit.

Bycatch Rates and Initial Mortality

We examined 1,445 paddlefish (618 captured in monofilament nets; 827 captured in multifilament nets) to estimate rates of bycatch (i.e., fish shorter than the minimum size limit, or all males and immature females) and initial mortality. During the 2002-2003 and 2003-2004 fishing seasons 60% of the paddlefish captured by commercial fishers were sublegal ($\leq$ 864 mm EFL; 34 inches) and mature females represented only 8% of the catch (i.e., the bycatch rate for fishers targeting mature, egg-laden females was 92%). Initial bycatch mortality was high at certain times of the year. Most (86%) of the paddlefish were dead when water temperatures exceeded 20 ^{o}C. Conversely, the observed initial mortality rate was low (< 7 %) at water temperatures less than 10 ^{o}C.

A chi-square test of association between the percentage of dead and live fish captured in each mesh size was not significant ($?^2 = 6.0$; df = 5; $P = 0.305$) and mesh size was a non-significant (P = 0.1446) predictor variable in the logistic regression model. Fish length (P = 0.0984) was the only other non-significant predictor variable specified in the logistic regression model. Initial mortality increased significantly with soak time (P = 0.0042) and water temperature (P < 0.0001) and fish were more likely to be dead in a monofilament net than a multifilament net (P < 0.0001). The logistic equation model that included only the soak time, temperature, and net material variables predicted the probability of death (P_i) as:

$$P_i = \frac{e^{-4.7790 + (0.2410 \times Temperature) - (0.8545 \times Twine) + (0.0396 \times Time)}}{1 + e^{-4.7790 + (0.2410 \times Temperature) - (0.8545 \times Twine) + (0.0396 \times Time)}}$$

where *Temperature* = surface water temperature (^{o}C), *Twine* = monofilament (0) or multifilament (1) netting, and *Time* = soak time (in hours). The Hosmer and Lemeshow goodness-of-fit test indicated that the logistic model provided a good fit to the data (P = 0.3010).

If soak time is held constant at 12 hours, the relationship between water temperature and twine type is clearly evident (Figure 12). Predicted mortality rates exceeded 26-45% when water temperatures exceeded 17 ^{o}C; those temperatures are often observed in mid-April, at the end of the current commercial season. Water temperatures at the beginning of the commercial harvest season are usually less than 15^{o}C (Figure 13) and predicted mortality rates are lower (18-33%) at 15^{o}C. Low initial mortality rates (<10%) for both twine types would not be expected until the water temperature fell below 8.7 ^{o}C. According to the model, netting should be restricted to waters cooler than 14.2 ^{o}C (58 ^{o}F) to keep initial mortality below 15% in a typical commercial gill net (i.e., multifilament net set for 12 hours).

Rates of delayed bycatch mortality are unknown and are the subject of an ongoing investigation. Efforts to protect Kentucky Lake paddlefish from overfishing using minimum EFL limits will be confounded if delayed mortality is high during winter months, when initial mortality is low.

Gill Net Size Selectivity

Mean lengths (EFL) of paddlefish captured in each mesh size of the experimental gill nets were marginally different (F = 2.20; df = 5, 570; P = 0.053; Figure 14). The mesh size effect was attributed to the fact that the mean length of paddlefish captured in the 89-mm mesh (mean = 824 mm) differed slightly from the mean length in the 127-mm mesh (mean = 860 mm). However, the length distributions of fish captured in these two meshes overlapped broadly. Mean lengths of paddlefish were statistically similar among all other meshes. Modal lengths were 800 or 825 mm EFL for all meshes, and the means varied over a narrow range (824 – 860 mm EFL). With the exception of the smallest mesh size, the EFL-frequency distributions were not strongly positively or negatively skewed for any mesh.

Although we did not detect size selectivity for large juveniles and adult fish that recruited to our gear, it should be noted that we failed to capture any fish shorter than 452 mm EFL. If we assume that some offspring were present from recent year classes, our experimental gear was, in fact, selective for paddlefish longer than 452 mm EFL.

The sizes of saugers captured in each mesh varied in a more typical manner. The mean lengths (TL) of saugers collected in the four-panel experimental gillnets increased with mesh size and all means were different (F = 1451.6; df = 3, 1939; $P < 0.001$; Figure 15). Also, modal lengths increased with mesh size and varied over a wide range (250 – 450 mm TL). Finally, the length-frequency distributions for the three smallest meshes were all negatively skewed, which is common for advanced fish species with spines, well-developed mandibles, and strong dentition (i.e., large fish are susceptible to capture in small meshes via entanglement rather than wedging).

The bycatch of sublegal paddlefish did not decrease with increasing mesh size. The proportion of the total catch in each mesh size that was sublegal was not related to the mesh size (linear regression; F = 1.11; df = 1,4; P = 0.35; $r^2 = 0.22$) and the chi-square test of association between the percentage of legal and sublegal fish captured in each mesh size was not significant ($X^2 = 9.2$; df = 5; P = 0.103). In contrast, the proportion of sublegal saugers in the catch was inversely related to mesh size (linear regression, F = 31.7; df = 1,2; P = 0.03; $r^2 = 0.94$) and there was a significant association between the percentage of legal and sublegal sauger and mesh size ($X^2 = 1067$, df = 3; $P < 0.001$).

The similarity in lengths of paddlefish collected in each mesh, coupled with the linear relation between lengths and girth, resulted in declining G:P ratios with increasing mesh size (Figure 16). The mean G:P ratios for most meshes differed (ANOVA, $F = 310.8$; df =5, 570; $P < 0.0001$) and declined from 1.42 in the smallest mesh to 0.67 in the largest mesh. G:P ratios above ~1.5 in the smallest mesh represented large fish that were entangled (as opposed to wedged) in that mesh. The very low (≤ 0.7) G:P ratios in the three largest meshes also represented fish that were entangled because they were too small in girth to be caught by wedging in those large meshes. As expected, the G:P ratios for saugers captured in experimental gill nets varied less dramatically among the four meshes (Figure 17). Although mean G:P ratios differed among some meshes (ANOVA, $F = 67.2$; df = 3, 1939; $P < 0.0001$), the sample sizes were large (i.e., statistical power was high) and G:P ratios varied over a much narrower range (means: 1.17 – 1.47) than paddlefish G:P ratios.

DISCUSSION

Population Characteristics and Assessment of Overfishing

Our results suggest that growth and recruitment overfishing likely occur during seasons when discharge is low, but the population is afforded temporary relief from overfishing during high water years. Though not directly comparable, a similar negative relationship between catch and discharge was observed in the recreational tailwater trout fishery below Bull Shoals reservoir, Arkansas (Aggus et al. 1977) because high discharges reduced angling effort. Although weather and subsequent discharge could be affecting paddlefish movements in Kentucky Lake, we believe the relationship between harvest and discharge is the result of reduced effort when fishing conditions were unfavorable (i.e., river discharges were high). Similarly, river stage influenced the commercial catch of several species in the Amazon River in Peru by altering the accessibility of certain waters (De Jesús and Kohler 2004).

The relationship between paddlefish harvest and discharge from Pickwick Dam also resolves, in part, a question that has been posed by TWRA biologists for many years: why was the estimated exploitation rate for paddlefish in Kentucky Lake so low in 1991 (u =

14%; Timmons and Hughbanks 2000), yet most investigators (Bronte and Johnson 1985; Hoffnagle and Timmons 1989) had concluded that the same population was being overfished. Pickwick Dam discharges were higher during the 1991fishing season than they were when other studies were conducted (1980, 1985, and 2003). We would predict that fishing effort and harvest were low in 1991 compared to what the fishery experiences during drier seasons.

The maximum weight (24 kg) and age (11 years) of paddlefish we observed in the present study were lower than those observed in 1991 and we observed only 10 age-classes (compared to 16 age-classes in 1991). These observations all suggest that heavy exploitation in recent years has resulted in juvenescence of Kentucky Lake's paddlefish stock. The shift to smaller, younger fish that we observed in our study has also been observed in commercially harvested paddlefish stocks elsewhere and is a clear indicator of overfishing (Hoyt 1984; Alexander et al. 1985). Previous studies on Kentucky Lake suggest that the paddlefish stock was also heavily exploited in the early 1980s. Maximum size and age in 1980 (age 14; 1,020 mm EFL, 22.7 kg; Bronte and Johnson 1985) and 1985 (age 16; 1,060 mm EFL, 18.2 kg; Hoffnagle and Timmons 1989) were roughly comparable to what we observed in the present study, but Timmons and Hughbanks (2000) collected fish as large as 1,220 mm (34.0 kg) and as old as age 21 in 1991. Similarly, 37% of the fish collected in 1991, but less than 5% in 1980 and 1985, were older than the maximum age in our study. The reduced size and age structure of the population in the early 1980's was probably due to the low flows and subsequent high harvest prior to those studies. In contrast, flows prior to Timmons and Hughbanks' (2000) study in 1991 were relatively high, which probably made it difficult for fishers to deploy and retrieve nets. High flows in the late 1980s likely allowed the stock to recover from a period of high exploitation; conversely, favorable netting conditions in recent years probably resulted in another period of heavy exploitation preceding our study.

Maximum ages of other southern paddlefish stocks were comparable ($\leq$ age 14) to the maximum age that we observed in Kentucky Lake (Reed et al. 1992; Lein and DeVries 1998; Paukert and Fisher 2001b). However, maximum ages of 25-30 years are common in lightly exploited paddlefish fisheries at northern latitudes (Purkett 1963; Robinson 1966;

Rosen et al. 1982; Elser 1986) and the oldest paddlefish on record, collected from the Yellowstone River, Montana in 1985, was estimated to be age 55 (Scarnecchia et al. 1996).

Male paddlefish matured as early as age 6 and females as early as age 8 in this study, which was similar to previous studies on Kentucky Lake (Bronte and Johnson 1985; Hoffnagle and Timmons 1989; Timmons and Hughbanks 2000). Age at first maturity is similar in most systems (Adams 1942; Hoyt 1984; Reed et al. 1992); however, Gengerke (1978) observed mature male and female paddlefish in the upper Mississippi River as young as ages 4 and 6, respectively.

Previous studies (Meyer 1960; Hoyt 1984; Russell 1986) concluded that mature female paddlefish required more than one year to become gravid (i.e., they did not spawn every year). However, our data indicate that large (> 1,034 mm EFL) paddlefish become gravid each year. Although no age class was represented solely by mature fish, all females longer than 1,034 mm EFL were mature. If large mature females did not spawn annually, some non-gravid females longer than 1,034 mm EFL should have been collected; their absence suggests that females became gravid more as a function of size than age. Length at first maturity (885-1,034 mm EFL) varied for female paddlefish but once they were mature, they likely became gravid each year. Gravid paddlefish have also been observed in consecutive years in aquaculture ponds (S. Mims, Kentucky State University, personal communication).

The relative abundance of mature females in the Kentucky Lake population in 1980, 1985, and 1991 was likely lower than what was reported. Previous researchers reported that mature females made up 4% of the catch in 1980 (Bronte and Johnson 1985), 7% in 1985 (Hoffnagle and Timmons 1989), and 13% in 1991 (Timmons and Hughbanks 2000). These studies were based on paddlefish collected from the riverine reach of Kentucky Lake during the spawning run. In our study the relative abundance of mature females in the gill net samples was higher in the riverine reach during the spawning period (8%) than it was before the season began (4%).

The relative fecundity of the 75 mature paddlefish that we observed was within the broad range reported in previous studies. On a per-kg basis, Kentucky Lake paddlefish were 73% more fecund than paddlefish in Louisiana (n = 9; Reed et al. 1992), ~ 18% less fecund than paddlefish in the Alabama River drainage (n = 5 and 7 fish; Hoxmeier and DeVries

1997; Lein and DeVries 1998), and had fecundities nearly identical to those of fish in the upper Mississippi River (n = 11; Gengerke 1978).

Examination of age and size structure data indicated that mortality rates were high after paddlefish were fully recruited to the fishery. Total annual mortality in this study (68%) was nearly identical to that reported in 1985 (69%, Hoffnagle and Timmons 1989), but higher than 1980 and 1991 estimates (44% in 1980, Bronte and Johnson 1985; 22% in 1991, Timmons and Hughbanks 2000). Annual mortality estimates reflect the additive effects of exploitation because natural mortality is usually less than 10% for paddlefish (Timmons and Hughbanks 2000). The inverse relation between annual mortality estimates and mean discharge during the three seasons preceding each study suggests that exploitation (and total mortality) is highly variable and influenced by the amount of water discharged from Pickwick Dam.

Simulated flesh yields for Kentucky Lake's paddlefish stock suggested that modest growth overfishing was occurring because increasing the minimum size limit increased flesh yields over a wide range of exploitation rates above 20%. We believe that exploitation in recent years was much higher than 20%, despite the fact that Timmons and Hughbanks (2000) estimated exploitation in 1991 (not corrected for tag loss, non-reporting, or mortality associated with tagging) at only 14%. In that study, discharges were average or above average during the three commercial seasons preceding their sampling and commercial fishing pressure was presumed to be low. If natural mortality is less than 10%, recent exploitation rates likely exceeded 50% given the high annual mortality rate we observed.

None of the mature females we collected were protected by the current minimum size limit. Recruitment overfishing is a distinct possibility in Kentucky Lake because females reached legal size (864 mm EFL) at an average age (7.1 years) that is younger than the age at first maturity (age 8). Increasing the minimum length limit would delay the average age at recruitment by 2.1 years under a 965 mm EFL limit and by 3.5 years under a 1,016 mm EFL limit. Delaying the age at recruitment would allow some mature females to spawn at least once before becoming vulnerable to harvest, which is desirable because the number of spawning females might limit subsequent paddlefish abundance (i.e., there may be a stock-recruit relationship; Scarnecchia et al. 1989).

Paddlefish may reach legal size in Kentucky Lake before they mature, but immature fish are not likely to be caught if they do not leave the lacustrine reaches of the reservoir, where we observed little commercial fishing activity. Immature females represented less than 5% of all paddlefish we observed in the riverine section of the reservoir during the 2002-2003 and 2003-2004 commercial harvest seasons. Purkett (1961), Hageman et al. (1988), and Lein and DeVries (1998) also reported low relative abundance of immature fish in spawning areas in other systems. In the lower Alabama River, immature fish from channel and backwater habitats accompanied spawning fish during spring migrations, but immature fish in oxbow habitats did not migrate (Hoxmeier and DeVries 1997). This study and previous studies on Kentucky Lake were not designed to compare the relative abundances of mature and immature fish by reservoir reach; therefore, further monitoring of the commercial catch is necessary to confirm that most immature females do not migrate upriver. If the management objective was to reduce fishing mortality of immature females, gill netting could be banned in the lacustrine portions of the reservoir if immature females normally do not migrate upriver. If immature females occasionally migrate upriver with spawning fish, increasing the minimum EFL limit would be necessary to protect them and reduce the likelihood of recruitment overfishing.

Goodyear (1993) suggested that SPRs should be maintained above 20-30% to prevent recruitment overfishing in most fish populations. Although minimum SPRs necessary to prevent overfishing for nest-building species are likely lower, 20-30% is probably a reasonable minimum SPR for a species that leaves its eggs unattended (Slipke et al. 2002). According to the SPR model, recruitment overfishing in Kentucky Lake’s paddlefish population is occurring when exploitation exceeds 21%. Coincidentally, previous studies have suggested exploitation rates higher than 15%-20% should be considered excessive for paddlefish stocks (Combs 1982; Pasch and Alexander 1986). The exploitation rate in Kentucky Lake probably exceeds 15% during most commercial harvest seasons, and may have been as high as 50-60% in the years immediately preceding our study. Although minimum SPRs for paddlefish and other freshwater species are not well defined and are still being investigated (Slipke and Maceina 2001), an exploitation rate of 50% corresponds with a SPR value of only 3% under the current minimum EFL limit.

Low Spawning Potential Ratios have been associated with stock declines in heavily fished populations. The collapse of the striped bass *Morone saxatilis* fishery in the Chesapeake Bay during the late 1980s was associated with predicted SPR values of less than 10% (Slipke and Maceina 2001). Slipke et al. (2002) reported that declining yields of channel catfish *Ictalurus punctatus* in the upper Mississippi River were associated with predicted SPR values of 3% to 12%. In both situations, populations recovered after minimum length limits were increased. Manooch et al. (1998) suggested SPRs would increase in a red snapper *Lutjanus campechanus* fishery if fishers would comply with minimum size regulations enacted to delay the age-at-entry into the fishery. Increasing the minimum EFL limits for paddlefish in Kentucky Lake to 965 mm EFL or higher would allow the population to experience higher exploitation with less risk to the fishery.

We considered several important assumptions in the estimation of mortality caps for the Kentucky Lake population. Two assumptions (mortality is constant over time; recruitment is constant or varies randomly) were met because there was very little discrepancy between observed and predicted catches-at age in the catch curve, suggesting consistent mortality and recruitment (Maceina 1997). The growth curve fit the data on observed lengths-at-age reasonably well; therefore, we have no reason to believe that another assumption (growth is constant and adequately described by the von Bertalanffy model) was violated. A fourth assumption (recruitment into the smallest length considered for analysis [i.e., L_x] is constant through the year) can be met by taking multiple samples during the year and then pooling them before analysis (Ralston 1989), or by limiting the analysis to longer and older fish so that recruitment to L_x is constant throughout the year (Miranda 2002). We believe any bias associated with the fourth assumption was minimized by collecting paddlefish over a nine-month period and by modeling a relatively high L_x value for a species whose growth slows after age 4 (Hoffnagle and Timmons 1989; Scarnecchia et al. 1996; Hoxmeier and DeVries 1997). The final two assumptions (only lengths fully recruited into the gear are monitored; the sampling gear adequately represents age and size structure of the population) require that the fishing gear adequately samples the population. Pasch et al. (1980) and Paukert and Fisher (1999) concluded that experimental gill nets with mesh sizes ranging from 102-mm to 152-mm would adequately sample all paddlefish larger than 400-mm EFL and we used those and other mesh sizes to capture paddlefish in our study.

Simply reducing mortality rates of fish vulnerable to the gear cannot increase the mean size of harvested paddlefish. For example, the 17% mortality cap necessary to meet a 1,034 mm mean EFL objective would allow very little exploitation if this commercial fishery operated under the current minimum EFL limit. A more feasible approach to increase the length of harvested fish would be to increase the minimum EFL limits. Similarly, Quist et al. (2004) noted that a 500-mm mean length objective was unrealistic for walleye *Sander vitreum* in Kansas reservoirs unless the minimum length limit was increased from 381 mm to 457 mm total length. The mortality caps analysis provided additional support for more restrictive regulations, as suggested by our yield and SPR simulations; however, the benefits of increasing the minimum size limit will not be realized if bycatch mortality of sublegal fish is high.

Commercial fishing has reduced paddlefish stocks throughout history. Stocks in Mississippi, Louisiana, and Wisconsin were depleted after a few years of intensive seine net fishing in the early 1900s (Stockard 1907; Alexander 1914; Coker 1930). Paddlefish catches declined so severely in Norris Reservoir, Tennessee (e.g., the 1960 catch was only 8% of the 1958 catch), that commercial fishing was permanently terminated in 1960 (Carroll et al. 1963), although poor recruitment may have contributed to the stock collapse. Alexander and McDonough (1983) noted a severe decline in the number of age 0 paddlefish impinged at the Gallatin Steam-Electric Plant on Old Hickory Lake, Tennessee, after heavy commercial fishing during the late 1970s. Again, poor recruitment resulting from impounding the Cumberland River may have also contributed to stock collapse in Old Hickory Lake. The Alabama Department of Conservation and Natural Resources suspected that paddlefish in the Alabama waters of the Tennessee River were being overfished and a moratorium on commercial paddlefish harvesting was implemented in 1988. Five years later, Hoxmeier and DeVries (1996) were unable to collect a single paddlefish in those waters and hypothesized that the population had not recovered from previous overexploitation. Considering the high amount of harvest that regularly occurs in Kentucky Lake, it is remarkable that this paddlefish stock has not met a similar fate as the stocks immediately upriver in Alabama.

Commercial fishing is not exclusively responsible for paddlefish population declines throughout the species' range; however, the negative impacts of other, uncontrollable factors (e.g., dams; pollution) on reproduction and age 0 survival can be offset by reducing fishing mortality (Boreman 1997). Our study suggests that Kentucky Lake's paddlefish population is overfished during dry seasons and current regulations do little to restrict harvest and nothing to protect mature females. Fortunately, during years of high rainfall and high flows in the Tennessee river below Pickwick Dam this population is afforded temporary relief from bouts of high exploitation by commercial gill netters. However, the ability of this stock to sustain high exploitation rates may be compromised if national or international demand for paddlefish caviar increases, an extended drought occurs, or both situations develop simultaneously. A developing market for smoked paddlefish flesh may also increase the likelihood that the stock will experience growth and recruitiment overfishing, particularly if fishers target immature fish that remain downlake in areas amenable to netting during all river flows.

Bycatch Rates and Initial Mortality

The Tennessee Wildlife Resources Commission (TWRC) prohibited the use of smaller gill net meshes (< 152 mm bar measure) in 2002 to reduce the bycatch of small paddlefish and because it was thought that smaller meshes killed paddlefish at a higher rate than larger meshes. This study revealed that the current mesh size restriction does not achieve its objectives. Our experimental gill nets exhibited little or no size selectivity and we did not detect a difference in initial mortality rates among meshes. However, the mesh size restriction should be retained in the absence of compelling data to the contrary because the bycatch of other valuable commercial species such as catfish might increase if smaller meshes were allowed. We are unaware of any published information relating to differential mortality caused by monofilament and multifilament nets. Some hatchery managers always use multifilament nets to collect their wild broodfish because they feel they are less harmful to the fish than monofilament nets (M. Smith, manager, Eagle Bend State Fish Hatchery, Clinton, Tennessee; personal communication), but hard data are lacking as to why monofilament nets may be more harmful.

Lack of size selectivity by hobbled (tied-down) gill nets contributed to high bycatch rates. Gill nets are among the most lethal fishing gears employed in commercial fisheries, which is why their use is banned or severely restricted in many locales (e.g., Texas, 1988; Florida, 1994). In 1991, the United Nations adopted several resolutions establishing a worldwide moratorium on all high seas drift gill net fishing because of high bycatch rates and mortality. The ban is still in force in all the world's oceans and enclosed and semi-enclosed seas.

The fact that initial bycatch mortality rates are very low in mid-winter suggests that limiting fishing to those months may be a viable management strategy. The benefits that might accrue from limiting fishing to midwinter would rely on low rates of delayed mortality, which is the subject of an ongoing investigation. Cooler water temperatures increase the likelihood of survival of fish released as bycatch (Bettoli and Osborne 1998). The TWRC used this management strategy in the 1990s when they imposed higher minimum size limits in winter months for striped bass in a popular Tennessee reservoir sport fishery.

Lack of Gill Net Size Selectivity

The nearly complete lack of gill net size selectivity was unexpected. Paukert and Fisher (1999) reported a positive relationship between three mesh sizes and the mean size of paddlefish collected in gill nets in an Oklahoma Reservoir. However, those experimental nets were not tied-down or hobbled (perhaps because they were fished in slack water). The lack of size selectivity by hobbled gillnets fished in Kentucky Lake indicates that managers cannot influence the size of paddlefish captured by commercial gill net gear by changing minimum mesh size regulations. The inability to delay the size at recruitment to the gear would not be problematic if bycatch mortality of sublegal fish was low. However, observed initial mortality was 39% for all paddlefish captured when water temperatures were between 15 and 17.5 ^{o}C and those temperatures are common late in the commercial fishing season on Kentucky Lake.

The hobbled nature of the gillnets we used (and also used by commercial fishers) in Kentucky Lake may contribute to their lack of size selectivity for paddlefish. Hamley

(1980) noted that nets hung more loosely tend to capture more fish through entanglement, rather than wedging. The extreme G:P ratios we observed for paddlefish may have resulted from the loose netting that characterizes a hobbled gill net. The commercial fishers we accompanied and others who assisted our gill netting operations maintained that tying down the nets and creating a loose bag of netting was a critical aspect of successfully fishing gill nets that are anchored in moving water. The comparative capture efficiencies and size selectivity of hobbled and standard gillnets is unknown and should be investigated. If results similar to those reported herein were to be obtained for un-hobbled nets, management approaches other than mesh restrictions would have to be investigated, if the management objective was to increase spawning escapements by paddlefish.

MANAGEMENT ALTERNATIVES

CITES regulations prohibit international trade of animal products for Appendix II species such as paddlefish if regulatory authorities (e.g., Division of Scientific Authority) are not satisfied that (1) such products are legally acquired, and (2) trade will not be detrimental to the survival of the species in the wild. The research findings reported herein provide a preponderance of evidence that under certain conditions, the commercial paddlefish fishery in Kentucky Lake is exploited at unsustainable rates and that current regulations do not protect the stock from overfishing. If demand for paddlefish caviar and flesh increase in the future, threats to the stock will also increase. Therefore, a new management approach is needed to conserve the stock if fishers wish to maintain the option of exporting their product overseas.

The ultimate goal of any new management program for the Kentucky Lake paddlefish stock should be to reduce fishing mortality to sustainable levels and protect the stock from recruitment overfishing. Specific objectives of any management actions should include:

1. Provide for sufficient spawning escapement from commercial harvest each year;
2. Increase the Spawning Potential Ratio;

3. Reduce encounters between immature paddlefish (particularly females) and commercial gill nets;
4. Reduce mortality of all released paddlefish.

Alternative strategies exist to meet some or all of these management objectives. We now discuss common strategies that are employed in commercial fisheries worldwide to protect stocks against overfishing:

Moratorium (Closure) - In extreme circumstances, commercial fisheries have been closed to allow collapsed stocks to recover. Perhaps the most famous (and successful) example of this approach to rebuilding a stock was the moratorium on harvest of Chesapeake Bay striped bass in the 1980s. The stock rebounded and the commercial fishery was reopened (under tight regulations) in 1990. At the present time most Mississippi River basin states have closed their commercial paddlefish fisheries because of concern that their stocks are too depleted and cannot sustain commercial harvests.

Limited Entry – This form of management limits the number of fishers or units of gear utilizing a resource in order to protect a resource from overfishing. In some instances, limited entry programs also establish a Total Allowable Catch (TAC) for the fishery. Fisheries are "limited" when other means of protecting the resource, such as shortening the season or reducing possession limits or harvest quotas, are deemed ineffectual (Alaska Commercial Fisheries Entry Commission; http://www.cfec.state.ak.us/faq/whatle.htm). The regulatory authority grants permits, which are typically "permanent permits" and anyone wishing to enter a limited fishery must receive a permit via transfer or sale from another fisherman. Normally, anyone already participating in the fishery when a fishery is designated as "limited" can apply for a permanent permit during a one-time only application period. Limited entry fisheries are common in situations when the fishery resource is particularly valuable and overfishing is reducing stock abundance to historic low levels. Examples of limited entry fisheries abound in the marine environment; for instance, many salmon, sablefish, and crab fisheries in Alaska are managed through limited entry, as are lobster stocks off the coast of Maine and striped bass in Virginia and Maryland waters of the

Chesapeake Bay. Limited entry is less common, but not unheard of, in freshwater systems. For instance, all commercial fishing in Iowa is regulated through a limited entry contract procedure that involves competitive bidding and public bid letting. Commercial fisheries for percids (walleyes, yellow perch) in Lake Erie are also managed with a form of limited entry. The recent decision by the TWRC to raise permit and license fees for residents to fish for paddlefish from $125 to $1300, in order to support TWRA's commercial fishing program, might have the added benefit of reducing the number of commercial fishers harvesting paddlefish in Kentucky Lake.

Shorten season - It is common for fishery managers to reduce harvest of sport and commercial fish stocks by shortening the fishing season. During periods of drought and low flows, the commercial season for paddlefish in Kentucky Lake is too long. In 1999 and 2000, daily discharges averaged less than 850 m^3/sec (30,000 cfs) for more than 75 days each season and harvest rates were correspondingly high. If demand increases, the number of paddlefish harvested during droughts could go even higher. Conversely, during recent wet winters when river discharges were high, fishers were limited in the number of days they could deploy nets. For instance, commercial fishers in 2002 experienced only 18 days when flows averaged less than 850 m^3/sec and relatively few paddlefish were harvested. One potential management strategy could be to suspend all commercial fishing once a predetermined number of "fishable days" was reached. Achieving consensus among all stakeholders on the number of fishable days allowed each season could be accomplished within the context of "Adaptive Management". That is, subsequent population and harvest monitoring would indicate whether an arbitrarily chosen number less than 75 days was too liberal, or too conservative. Although it is common to manage fisheries with TAC regulations, which suspend fishing when a predetermined number (or weight) of fish is harvested, regulating the Kentucky Lake commercial paddlefish fishery using a predetermined number of fishable days to limit effort (and harvest) could be a unique approach.

Truncate the Season – This management action could be initiated independently of limiting the number of days fishers could fish. Specifically, this management action would end the season earlier in the year each, regardless of the number of days that were fishable. Water temperatures are usually high enough to cause high bycatch mortality in mid and late April. Most paddlefish that encounter gill nets are immature females or males, which exacerbates the problem of high bycatch mortality late in the season.

Ban monofilament nets - Monofilament nets were more lethal to paddlefish than multifilament nets, for reasons that are unclear. However, the statistical effect of twine type on initial mortality was strong. Banning gillnets constructed of monofilament is commonplace along the Gulf of Mexico and Atlantic coasts, but such bans are usually not accompanied with data as conclusive as those presented herein regarding their lethality relative to multifilament nets.

Mesh Size Restrictions This study determined that hobbled gill nets exhibited little if any selectivity and initial mortality rates were similar in all mesh sizes. It was beyond the scope of this study to collect data on size selectivity (or lack thereof) when using unhobbled gill nets. Simultaneously fishing hobbled and unhobbled experimental gill nets would determine whether unhobbled nets exhibited size selectivity, and refute or confirm the assertion that unhobbled nets are less effective at catching paddlefish in Kentucky Lake.

Create no-fishing refuge Spatial segregation of mature and immature paddlefish during the spawning run was clearly evident in samples we collected before, during and after the 2003-2004 fishing season. Recent field samples during the 2004-2005 season confirm that virtually no mature paddlefish remain downlake in the lacustrine waters of the Tennessee River once water temperatures fall and the spawning run commences. The concept of fishing refuges (often referred to as reserves or sanctuaries) is popular in marine fisheries, where the objective is to prevent overfishing of the entire stock, particularly the spawning stock. Setting aside the lacustrine waters of Kentucky Lake as a refuge would provide many immature paddlefish with protection from harvest and bycatch mortality.

Set harvest quota The establishment of harvest quotas or TACs (Total Allowable Catches) is common, particularly in marine fisheries. Sturgeon harvests in the Caspian Sea are, in theory, regulated with TACs. Quotas are also used to manage some paddlefish sport fisheries. The annual TAC for a snag fishery for paddlefish in the Missouri River below Gavin's Point Dam, SD/NE, is 1,600 fish; an additional TAC of 200 fish exists for a short archery season. The snag fishery for paddlefish in North Dakota at the confluence of the Yellowstone River and Missouri River is tightly regulated with a 1,000 fish TAC during a 30-day season.

Raise the Minimum Size Limit The current 864 mm (34 inch) minimum size limit does not increase spawning escapements (i.e., no mature females are protected from harvest), nor does it protect the stock from growth overfishing. A minimum size limit of 965 mm (38 inches) or even 1,016 mm (40 inches) would improve yields and help protect the Kentucky Lake paddlefish stock from recruitment overfishing.

Establish an Adaptive Management Program In recent decades, resource managers have embraced a form of management that relies on systematic feedback learning and the gradual accumulation of knowledge to drive management decisions (Pomeroy 2003). Adaptive Management (AM) attempts to include the views and knowledge of all interested parties and it is recognized by stakeholders that management must proceed with imperfect knowledge of the system of interest (Johnson 1999). Monitoring the resource is an integral part of any AM plan. Adaptive Management is not a panacea, in that it requires a strong commitment by major stakeholders and it is undoubtedly easier to propose an AM plan than conduct one. However, such a management approach would be ideally suited to the high-profile paddlefish caviar fishery in Kentucky Lake. At the very least, it would be hard to argue against assembling stakeholders on a regular basis in a structured forum in order to (1) disseminate new technical information, (2) seek input from commercial fishers and buyers, (3) jointly agree on whether target goals for maintaining the health of the fishery are being met, and (4) decide on future courses of action.

RECOMENDATIONS

1. The Kentucky Lake stock has not collapsed and a fishing moratorium is not justified at this time.

2. The stock is not in danger of imminent collapse and taking the drastic step of limiting entry is unwarranted at this time, particularly when other management options exist to protect the fishery from overfishing.

3. End the commercial harvest season on April 7. Water temperatures would usually not exceed 15^o C, bycatch mortality would be reduced, and commercial fishers would lose, on average, no more than 7 fishable days each season (based on historical flow regimes).

4. Ban monofilament gill nets. Multifilament nets are readily available, the costs are comparable between the two netting materials, and many commercial fishers already use multifilament nets exclusively.

5. We do not recommend changing the current mesh size restriction ($\geq$ 152 mm bar measure).

6. To protect immature fish and reduce the likelihood of growth and recruitment overfishing, we recommend prohibiting all commercial fishing for paddlefish in the reach of Kentucky Lake below river km 113 (river mile 70). Creating this “No Fishing Refuge” would reduce exploitation of large (but immature) paddlefish for their flesh, particularly after January 1 when nearly all the paddlefish in the lower reaches are juveniles.

7. Too little information exists on the Kentucky Lake stock (specifically, stock size) to allow us to establish a TAC for the fishery at this time. Instead, managers should focus on accurately estimating the total harvest each year and subsequent bycatch rates after a new management plan is enacted. Routine monitoring of stock characteristics (e.g., average age and size; maximum age; percentage of mature females in the population) will provide clear,

unambiguous data by which the health and status of the population can be assessed. These particular characteristics can also be related to harvest numbers and bycatch rates to better understand what level of fishing and harvest the stock can sustain.

8. High bycatch rates, high bycatch mortality at certain times, and the inability to regulate the size of the paddlefish catch with mesh size restrictions confound what would otherwise be a simple decision to raise the minimum size limit. Nevertheless, we recommend that the minimum size limit be raised immediately to 965 mm (38 inches) EFL to increase spawning escapements and protect the stock from recruitment overfishing. The fishery will have to be monitored closely to determine whether high bycatch mortality persists and negates the benefits that would usually accrue with a higher minimum size limit.

9. Establish an Adaptive Management Plan that would include input from all stakeholders and provide for regularly scheduled meetings to share information and discuss research needs and management actions.

10. Throughout this investigation it has been assumed that the Kentucky Lake paddlefish stock was a closed population; however, we recaptured three fish that were tagged in the Ohio River (representing immigration). Those fish swam through the navigation lock at Kentucky Dam, or through the lock at Barkley Dam and into Kentucky Lake via the barge canal connecting the two rivers. We also have indirect evidence of paddlefish passing upstream through the navigation lock at Pickwick Dam (representing emigration). A thorough investigation of dam passage rates and the influence (or lack thereof) of immigration and emigration of paddlefish on stock characteristics in Kentucky Lake would provide additional, valuable management information.

ACKNOWLEDGMENTS

Principal funding for this project was provided by the U.S. Geological Survey, acting on the recommendation of the Division of Scientific Authority, U.S. Fish and Wildlife Service. Additional funds and logistical support were provided by the Center for the Management, Utilization, and Protection of Water Resources at Tennessee Technological University, and the Tennessee Cooperative Fishery Research Unit. Melissa Sandrene, Project Leader, coordinated all field collections and laboratory analyses. We are grateful to the commercial fishers who introduced us to the Kentucky Lake paddlefish fishery and allowed us to monitor their catches, particularly Debbie Blackwelder and Patsy Cornelius. We would also like to thank the Tennessee Tech University students who volunteered to help collect fish and process samples. Special thanks also go to Tim Broadbent, Rob Todd, and Reggie Wiggins from the Tennessee Wildlife Resources Agency for all of their assistance. The sections on overfishing benefited from comments offered by Mr. Jeff Quinn (Arkansas Game and Fish Commission), Dr. Dan Isermann (Minnesota Department of Natural Resources), Dr. Craig Paukert (U.S. Geological Survey), and editors and two anonymous reviewers with the Transactions of the American Fisheries Society.

LITERATURE CITED

Adams, L. A. 1942. Age determination and rate of growth in *Polyodon spathula*, by means of the growth rings of the otoliths and dentary bone. American Midland Naturalist 28:617-630.

Aggus, L. R., D. I. Morais, and R. F. Baker. 1977. Evaluation of the trout fishery in the tailwater of Bull Shoals reservoir, Arkansas, 1971-73. Proceedings of the Annual Conference of the Southeast Association of Fish and Wildlife Agencies 31:565-573.

Alexander, C. M., A. I. Myhr III, and J. L. Wilson. 1985. Harvest Potential of paddlefish stocks in Watts Bar Reservoir, Tennessee. Proceedings of the Annual Conference of the Southeast Association of Fish and Wildlife Agencies 39:45-55.

Alexander, C. M. and T. A. McDonough. 1983. Effect of water conditions during spawning on paddlefish year class strength in Old Hickory Reservoir, Tennessee. Tennessee Valley Authority, Office of Natural Resources, Division of Air and Water Resources, Knoxville, Tennessee, USA. Progress Report. 26 p.

Alexander, M. L. 1914. The paddlefish (*Polyodon spathula*). Transactions of the American Fisheries Society 44:34-39.

Alverson, D.L. M.H. Freeberg, M.H. Murawski, and J.G. Pope. 1994. A global assessment of fisheries bycatch and discards. FAO Fisheries Technical Paper 339, Rome FAO.

Boone, E. A., Jr., and T. J. Timmons. 1995. Density and natural mortality of paddlefish, Polyodon spathula, in an unfished Cumberland River subimpoundment, South Cross Creek Reservoir, Tennessee. Journal of Freshwater Ecology 10:421-431.

Bettoli, P.W., and R.S. Osborne. 1998. Hooking mortality and behavior of striped bass Following catch and release angling. North American Journal of Fisheries Management 18:609-615.

Boreman, J. 1997. Sensitivity of North American sturgeons and paddlefish to fishing mortality. Environmental Biology of Fishes 48:399-406.

Bronte, C. R., and D. W. Johnson. 1985. Growth of paddlefish in two mainstream reservoirs with reference to commercial harvest. Transactions of the Kentucky Academy of Science 46:28-31.

Buchanan, S., A. P. Farrell, J. Fraser, P. Gallaugher, R. Joy, and R. Routledge. 2002. Reducing gill-net mortality of incidentally caught coho salmon. North American Journal of Fisheries Management 22:1270-1275.

Carlson, D. M., and P. S. Bonislawsky. 1981. The paddlefish (*Polyodon spathula*) fisheries of the Midwestern United States. Fisheries 6:17-22.

Carlson, J.K., and E. Cortés. 2003. Gillnet selectivity of small coastal sharks off the southeastern United States. Fisheries Research 60: 405-414.

Carroll, B. B., G. E. Hall, and R. D. Bishop. 1963. Three seasons of rough fish removal at Norris Reservoir, Tennessee. Transactions of the American Fisheries Society 92:356-364.

Clark, W. G. and S. R. Hare. 1998. Accounting for bycatch in management of the Pacific halibut fishery. North American Journal of Fisheries Management 18:809-821.

Coho Response Team. 1998. Coho salmon final report. Fisheries and Oceans Canada, Pacific Region, Vancouver.

Coker, R. E. 1930. Studies of common fishes of the Mississippi River at Keokuk. United States Bureau of Fisheries Bulletin 45:141-225.

Collins, M.R., S.G. Rogers, and T.I.J. Smith. 1996. Bycatch of sturgeons along the southern Atlantic coast of the USA. North American Journal of Fisheries Management 16:24-29.

Combs, D. L. 1982. Angler exploitation of paddlefish in the Neosho River, Oklahoma. North American Journal of Fisheries Management 4:334-342.

Crowder, L.B., and S.A. Murawski. 1998. Fisheries bycatch: Implications for management. Fisheries 23(6):8-17.

Davis, M.W., and B.L. Olla. 2001. Stress and delayed mortality induced in Pacific halibut by exposure to hooking, net towing, elevated seawater temperature and air: implications for management of bycatch. North American Journal of Fisheries Management 21:725-732.

Dieterman, D.J., M.S. Baird, and D.L. Galat. 2000. Mortality of paddlefish in hoop nets in the lower Missouri River, Missouri. North American Journal of Fisheries Management 20:226-230.

De Jesús, M. J., and C. C. Kohler. 2004. The commercial fishery of the Peruvian Amazon. Fisheries 29:10-16.

Ehrhardt, N.M., and D.J. Die. 1988. Size-structured yield-per-recruit simulation for the Florida gill-net fishery for Spanish mackerel. Transactions of the American Fisheries Society 117: 581-590.

Elser, A. A. 1986. An overview of current management practices for paddlefish fisheries. Pages 62-67 *in* J. G. Dillard, L. K. Graham, and T. R. Russell, editors. The paddlefish: status, management, and propagation. North Central Division, American Fisheries Society Special Publication Number 7, Columbia, Missouri.

Gengerke, T. W. 1978. Paddlefish investigations. Iowa Conservation Commission, Fisheries Section, Commercial Fisheries Investigation Project 2-255-R, Completion Report, Des Moines, Iowa.

Goodyear, C. P. 1993. Spawning stock biomass per recruit in fisheries management: foundation and current use. Pages 67-71 *in* S.J. Smith, J.J. Hunt, and D. Rivard, editors. Risk evaluation and biological reference points for fisheries management. Canadian Journal of Fisheries and Aquatic Sciences, Special Publication 120.

Hageman, J. R., D. C. Timpe, and R. D. Hoyt. 1988. The Biology of paddlefish in Lake Cumberland, Kentucky. Proceedings of the Annual Conference of the Southeast Association of Fish and Wildlife Agencies 40(1986):237-248.

Hansen, M.J., Madenjian, C.P., Selgeby, J.H., and T.E. Helser. 1997. Gillnet selectivity for lake trout (Salvelinus namaycush) in Lake Superior. Canadian Journal of Fisheries and Aquatic Sciences 54: 2483-2490.

Hamley, J.M. 1975. Review of gillnet selectivity. Journal of the Fisheries Board of Canada 32: 1943-1969.

Hamley, J.M. 1980. Sampling with gill nets. Pages 37-53 *in* Backiel, T., and R.L. Welcomme, editors. Guidelines for sampling fish in inland waters. FAO European Inland Fisheries Advisory Commission Technical Paper 33, Rome Italy, pages 37-53.

Helser, T.E., Geaghan, J.P., and R.E. Condrey. 1998. Estimating gillnet selectivity using nonlinear response surface regression. Canadian Journal of Fisheries and Aquatic Sciences 55: 1328-1337.

Hoffnagle, T. L., and T. J. Timmons. 1989. Age, growth, and catch analysis of the commercially exploited paddlefish population in Kentucky Lake, Kentucky-Tennessee. North American Journal of Fisheries Management 9:316-326.

Hoxmeier, R. J. H., and D. R. DeVries. 1996. Status of paddlefish in the Alabama waters of the Tennessee River. North American Journal of Fisheries Management 16:935-938.

Hoxmeier, R. J. H., and D. R. DeVries. 1997. Habitat use, diet, and population structure of adult and juvenile paddlefish in the lower Alabama River. Transactions of the American Fisheries Society 126:288-301.

Hoyt, R. D. 1984. Population dynamics and biology of the paddlefish, Polyodon spathula, in Lake Cumberland. Project Completion Report 2-388-R. Department of Biology, Western Kentucky University, Bowling Green, Kentucky.

Huhmarniemi, A., Salmi, J. 1999. Attitudes and opinions of commercial fishermen on whitefish management in the Gulf of Bothnia, Finland. Fisheries Management and Ecology 6: 221-232.

Irwin, E. R., and P. W. Bettoli. 1995. Introduced clupeids in a southern reservoir: more evidence for system-specific reproductive styles. Environmental Biology of Fishes 42:151-159.

Jude, D., Neethiselvan, N., Gopalakrishnan, G.,and G.Sugumar. 2002. Gill net selectivity studies for fishing frigate tuna, Auxis thazard Lacepede (Perciformes/Scombridae) in Thoothukkudi (Tuticorin) waters, southeast coast of India. Indian Journal of Marine Science 31: 329-333.

Johnson, B.L. 1999. The role of adaptive management as an operational approach for resource management agencies. Conservation Ecology 3(2): 8 [online] URL:// www. consecol.org/vol3/iss2/art8/.

Jones, R. 1957. A much simplified version of the full yield equation. International Commission for Northwest Atlantic Fisheries, International Council for the Exploration of the Sea, Food and Agriculture Organization of the United Nations, Document P.21, Lisbon.

Kaimmer, S. M. and R. J. Trumble. 1996. Survival of halibut released from longlines: hooking location and release methods. Pages 101-105 *in* Fisheries Bycatch: Consequences and Management. Alaska Sea Grant College Program Report No. 97-02, University of Alaska Fairbanks, 1997.

Lein, G. M., and D. R. DeVries. 1998. Paddlefish in the Alabama River drainage: population characteristics and the adult spawning migration. Transactions of the American Fisheries Society 127:441-454.

Maceina, M.J. 1997. Simple application of using residuals from catch-curve regressions to assess year-class strength in fish. Fisheries Research 32:115-121.

Manooch, C. S., III, J. C. Potts, D. S. Vaughn, and M. L. Burton. 1998. Population assessment of the red snapper from the southeastern United States. Fisheries Research 38:19-32.

Markle, D. F. 1984. Phosphate buffered formalin for long term preservation of formalin fixed ichthyoplankton. Copeia 1984:525-528.

Meyer, F. P. 1960. Life history of *Marsipomtera hastata* and the biology of its host, *Polyodon spathula*. Science and Technology. Iowa State University, Ames.

Millar, R.B. 2000. Untangling the confusion surrounding estimation of gillnet selectivity. Canadian Journal of Fisheries and Aquatic Sciences 57: 507-511.

Miranda, L. E. 2002. Establishing size-based mortality caps. North American Journal of Fisheries Management 22:433-440.

Pasch, R. W., and C. M. Alexander. 1986. Effects of commercial fishing on paddlefish populations. J. G. Dillard, L. K. Graham, and T. R. Russell, editors. The paddlefish: status, management, and propagation. American Fisheries Society, North Central Division, Special Publication Number 7, Bethesda, Maryland.

Pasch, R. W., P. A. Hackney, and J. A. Holbrook II. 1980. Ecology of paddlefish in Old Hickory Reservoir, Tennessee, with emphasis on first year life history. Transactions of the American Fisheries Society 109:157-167.

Paukert, C. P., and W. L. Fisher. 1999. Evaluation of paddlefish length distributions and catch rates in three mesh sizes of gill nets. North American Journal of Fisheries Management 19:599-603.

Paukert, C. P., and W. L. Fisher. 2001a. Spring movements of paddlefish in a prairie reservoir system. Journal of Freshwater Ecology 16:113-124.

Paukert, C. P., and W. L. Fisher. 2001b. Characteristics of paddlefish in a southwestern U.S. reservoir, with comparisons of lentic and lotic populations. Transactions of the American Fisheries Society 130:634-643.

Pew Oceans Commission. 2003. America's Living Oceans: Charting a course for sea change. A report to the Nation and Recommendations for a new Ocean Policy.

Pomeroy, R. 2003. Adaptive management: a fact sheet for Connecticut fishermen. Sea Grant Publication CTSG-03-10. University of Connecticut, Groton.

Price, A. B., and R. A. Rulifson. 2004. Use of traditional ecological knowledge to reduce striped bass bycatch in the Currituck Sound white perch gill-net fishery. North American Journal of Fisheries Management 24:785-792.

Purkett, C. A., Jr. 1961. Reproduction and early development of the paddlefish. Transactions of the American Fisheries Society 90:125-129.

Purkett, C. A., Jr. 1963. The paddlefish fishery of the Osage river and the Lake of the Ozarks, Missouri. Transactions of the American Fisheries Society 92:239-244.

Quist, M. C., J. L. Stephen, C. S. Guy, and R. D. Schultz. 2004. Age structure and mortality of walleyes in Kansas reservoirs: use of mortality caps to establish realistic management objectives. North American Journal of Fisheries Management 24:990-1002.

Ralston, S. 1989. Effect of seasonal recruitment on bias of the Beverton-Holt length-based mortality estimator. Pages 190-197 *in* E. F. Edwards and B. A. Megrey, editors. Mathematical analysis of fish stock dynamics. American Fisheries Society, Symposium 6, Bethesda, Maryland.

Reed, B. C., W. E. Kelso, and D. A. Rutherford. 1992. Growth, fecundity, and mortality of paddlefish in Louisiana. Transactions of the American Fisheries Society 121:378-384.

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

Robinson, J. W. 1966. Observations on the life history, movement, and harvest of the paddlefish, Polyodon spathula, in Montana. Proceedings of the Montana Academy of Science 26:33-44.

Rosen, R. A., D. C. Hales, and D. G. Unkenholz. 1982. Biology and exploitation of paddlefish in the Missouri River below Gavin's Point Dam. Transactions of the American Fisheries Society 111:216-222.

Runstrom, A. L., B. Vondracek, and C. A. Jennings. 2001. Population statistics for paddlefish in the Wisconsin River. Transactions of the American Fisheries Society 130:546-556.

Russell, T. R. 1986. The biology and life history of the paddlefish – a review. Pages 2-21 *in* J. G. Dillard, L. K. Graham, and T. R. Russell, editors. The paddlefish: status, management, and propagation. North Central Division, American Fisheries Society Special Publication Number 7, Columbia, Missouri.

SAS Institute. 2001. SAS/STAT® User's guide, Version 8.2. SAS Institute, Cary, NC.

Scarnecchia, D. L., T. W. Gengerke, and C. T. Moen. 1989. Rationale for a harvest slot limit for paddlefish in the upper Mississippi river. North American Journal of Fisheries Management 9:477-487.

Scarnecchia, D. L., P. A. Stewart, and G. J. Power. 1996. Age structure of the Yellowstone-Sakakawea paddlefish stock, 1963-1993, in relation to reservoir history. Transactions of the American Fisheries Society 125:291-299.

Schindler, D.E., Kitchell, J.F., and R. Ogutu-Ohwayo. 1998. Ecological consequences of Alternative gill net fisheries for Nile perch in Lake Victoria. Conservation Biology 12: 56-64.

Slipke, J. W., and M. J. Maceina. 2001. Fishery Analysis and Simulation Tools (FAST). Version 1.1, Department of Fisheries and Allied Aquaculture, Auburn University.

Slipke, J. W., A. D. Martin, J. Pitlo, Jr., and M. J. Maceina. 2002. Use of the Spawning Potential Ratio for the upper Mississippi river channel catfish fishery. North American Journal of Fisheries Management 22:1295-1300.

Southall, P. D., and W. A. Hubert. 1984. Habitat use by adult paddlefish in the upper Mississippi river. Transactions of the American Fisheries Society 113:125-131.

Spangler, G.R . and J.J. Collins. 1992. Lake Huron fish community structure based on gillnet catches corrected for selectivity and encounter probabilities. North American Journal of Fisheries Management 12: 585 – 597.

Stockard, C. R. 1907. Observations on the natural history of *Polyodon spathula*. American Naturalist 41:753-766.

Timmons, T. J., and T. A. Hughbanks. 2000. Exploitation and mortality of paddlefish in the lower Tennessee and Cumberland rivers. Transactions of the American Fisheries Society 129:1171-1180.

Unkenholz, D. G. 1986. Effects of dams and other habitat alterations on paddlefish sport fisheries. Pages 54-61 *in* J. G. Dillard, L. K. Graham, and T. R. Russell, editors. The paddlefish: status, management, and propagation. North Central Division, American Fisheries Society Special Publication Number 7, Columbia, Missouri.

U.S. Commission on Ocean Policy. 2004. An Ocean Blueprint for the 21st Century. Final Report. Washington, D.C. ISBN #0-9759462-0-X.

Van Den Avyle, M.J., Ploskey, G.R., and P.W. Bettoli, P.W., 1995. Evaluation of gill-net sampling for estimating abundance and size structure of reservoir shad populations. North American Journal of Fisheries Management 15: 898-917.

Wallace, R. K. 1996. Catch and Bycatch: Is there really a difference? Pages 77-80 *in* Fisheries Bycatch: Consequences and Management. Alaska Sea Grant College Program Report No. 97-02, University of Alaska Fairbanks, 1997.

Zigler, S. J., M. R. Dewey, and B. C. Knights. 1999. Diel movement and habitat use by paddlefish in navigation pool 8 of the upper Mississippi river. North American Journal of Fisheries Management 19:180-187.

Table 1. Population parameters used to simulate paddlefish population dynamics in Kentucky Lake, Tennessee-Kentucky.

Parameter	Value
Von Bertalanffy growth coefficients	L_{inf} = 1279; K = 0.131; t_0 = -1.527
$\log_{10}$(weight) : $\log_{10}$ EFL coefficients	Intercept = -5.711; slope = 3.307
Log_{10} (fecundity) : $\log_{10}$ EFL coefficients	Intercept = -4.284; slope = 3.236
Maximum age	21 years (Timmons and Hughbanks 2000)
Conditional natural mortality	8%
Conditional fishing mortality	10% to 70%
Minimum length limits	864, 965, and 1016 mm
Age at sexual maturation	8 years
Percent of fish that are females	60% for all age groups
Percent of females spawning annually	5% for age 8, 26% for age 9, 76% for ages 10-21

Table 2. Maturity (%), mean length (EFL, mm), and mean weight (kg) by age class and sex for paddlefish collected with experimental gill nets from Kentucky Lake, Tennessee-Kentucky, 2003-2004.

	Males				Females				All fish	
Age	#	% Mature	Mean EFL	Mean Weight	#	% Mature	Mean EFL	Mean Weight	Mean EFL	Mean Weight
3	1	0	632	4.5	3	0	542	2.3	565	2.9
4	7	43	701	6.4	7	0	646	4.4	667	5.3
5	48	77	804	8.1	11	0	705	5.5	786	7.6
6	79	84	813	8.0	50	0	812	9.2	813	8.4
7	119	92	837	8.6	54	0	864	11.4	846	9.5
8	33	97	889	10.4	77	5	926	14.5	915	13.3
9	39	82	866	9.7	27	26	977	17.0	912	12.7
10	4	50	883	10.8	11	82	980	16.5	954	14.9
11	0	.	.	.	2	50	1065	23.4	1065	23.4

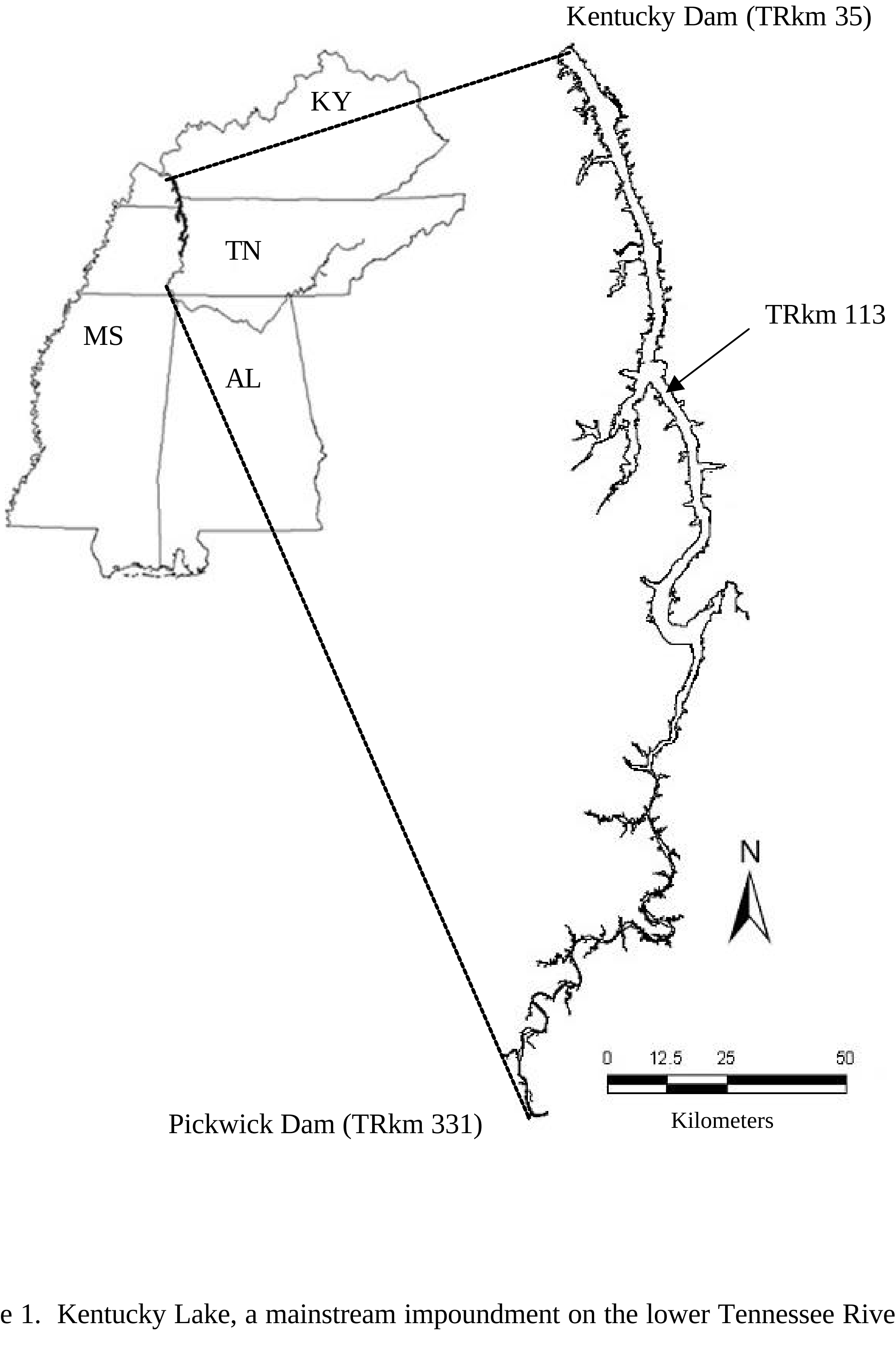

Figure 1. Kentucky Lake, a mainstream impoundment on the lower Tennessee River.

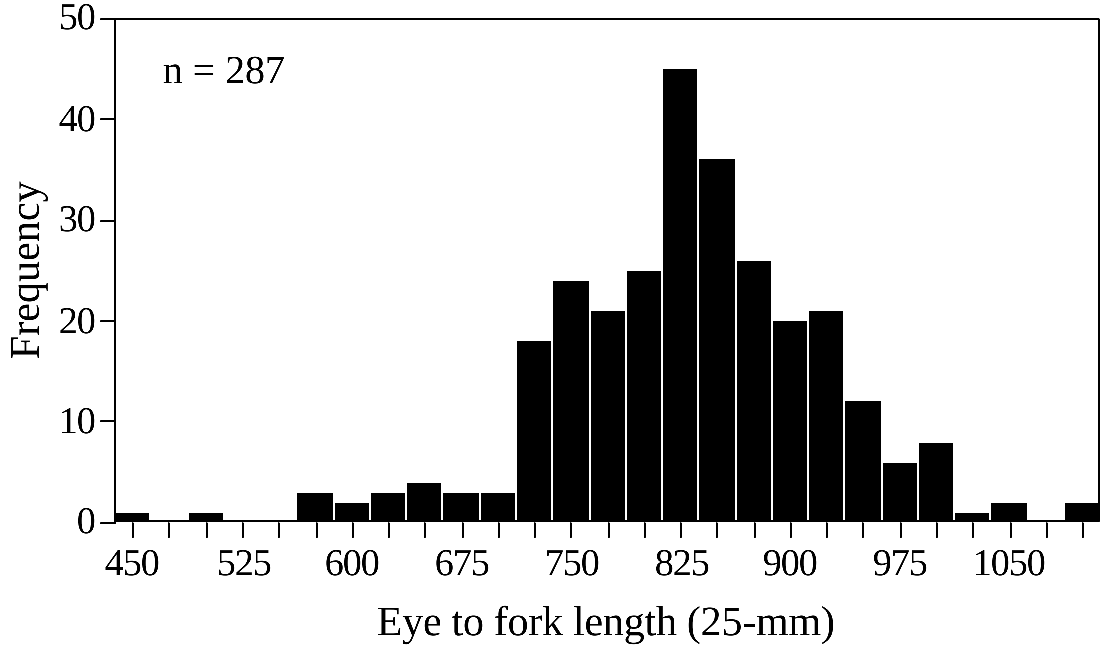

Figure 2. Length-frequency distribution of paddlefish collected with experimental gill nets from Kentucky Lake, Tennessee-Kentucky, during the fall of 2003.

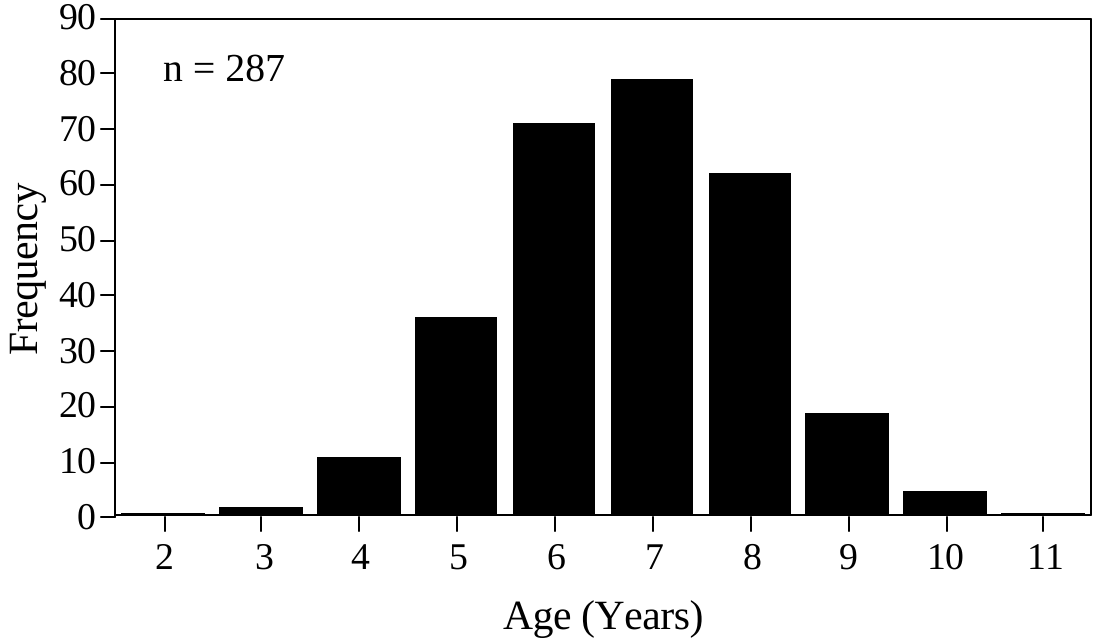

Figure 3. Age-frequency distribution of paddlefish collected with experimental gill nets from Kentucky Lake, Tennessee-Kentucky, during the fall of 2003.

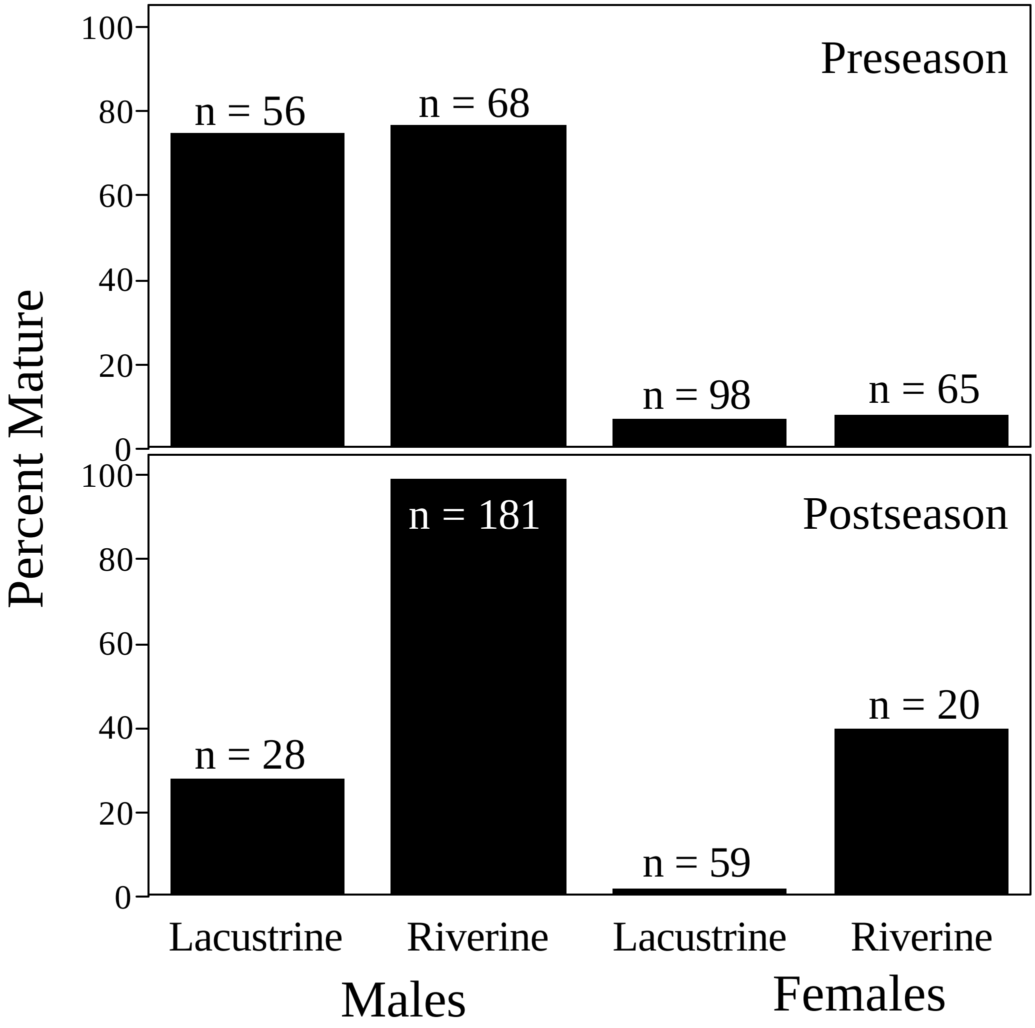

Figure 4. Percent of mature paddlefish of each sex in two regions of Kentucky Lake, Tennessee-Kentucky, before and after the 2003 commercial harvest season.

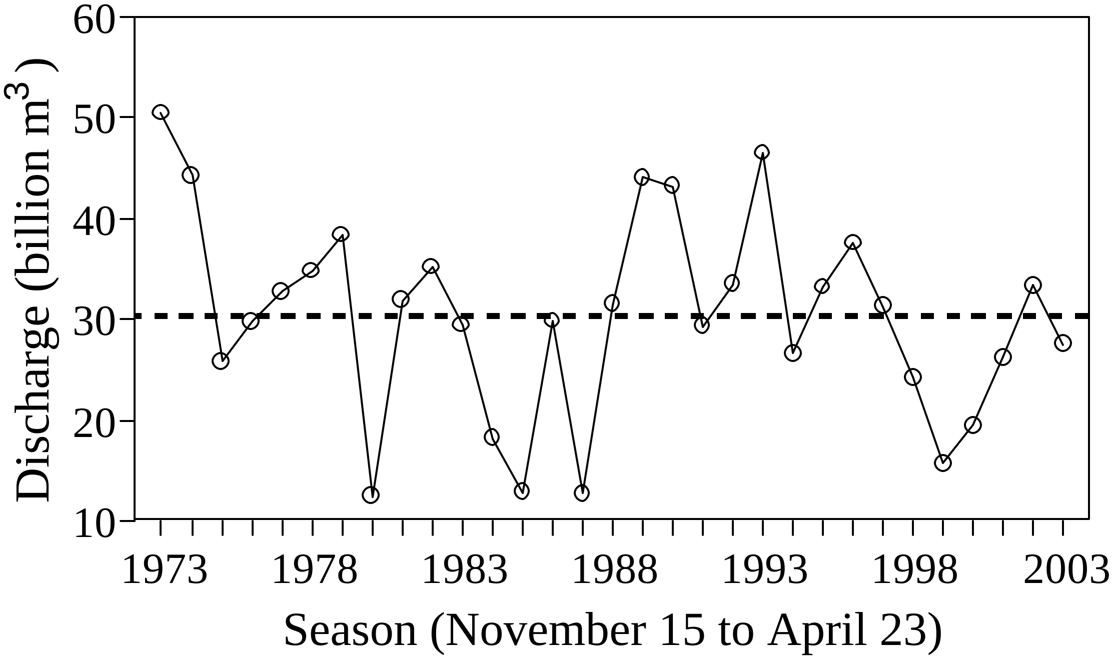

Figure 5. Total volume of water discharged from Pickwick Dam, Tennessee, between November 15 and April 23 (i.e., the current commercial paddlefish harvest season), 1973-2003. Dashed line represents mean volume discharged each season during that 20-year period

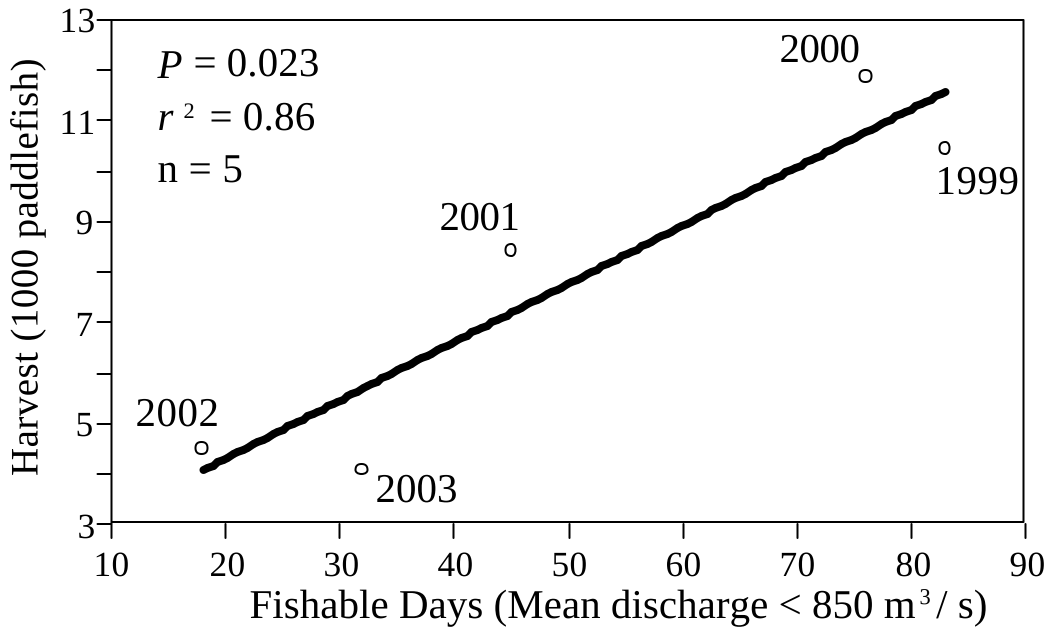

Figure 6. Number of days when mean discharge from Pickwick Dam was less than 850 m^3/s versus total paddlefish harvest from Kentucky Lake, Tennessee, during five commercial paddlefish harvest seasons.

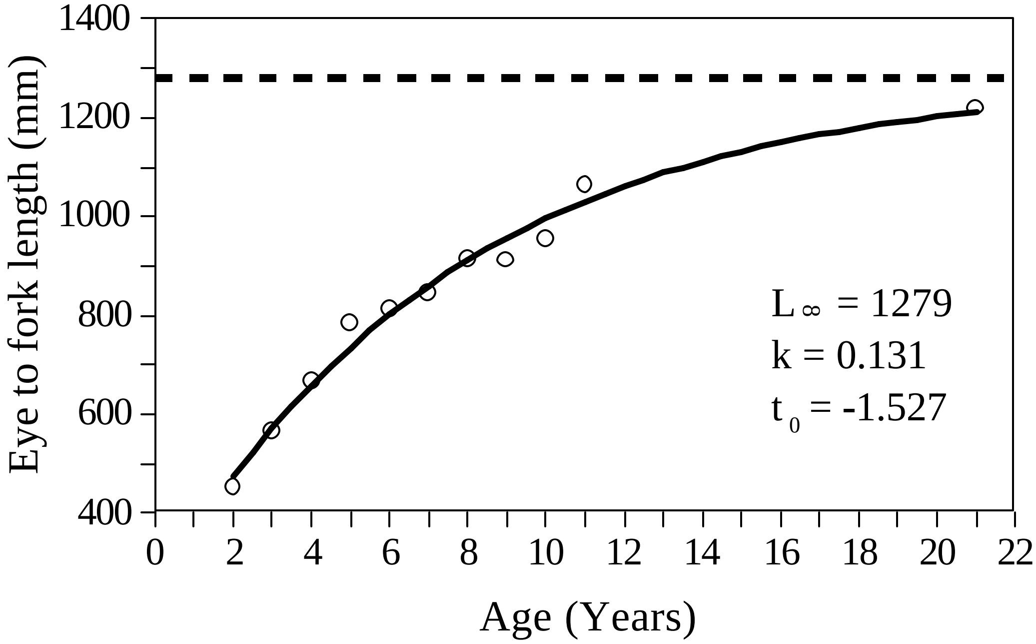

Figure 7. Predicted (solid line) and observed (first 10 open circles) lengths-at-age for paddlefish collected from Kentucky Lake, 2003-2004. The last open circle represents the largest fish (1,220 mm, age 21) collected from Kentucky Lake in 1991 by Timmons and Hughbanks (2000). Dashed line represents maximum asymptotic length (L8).

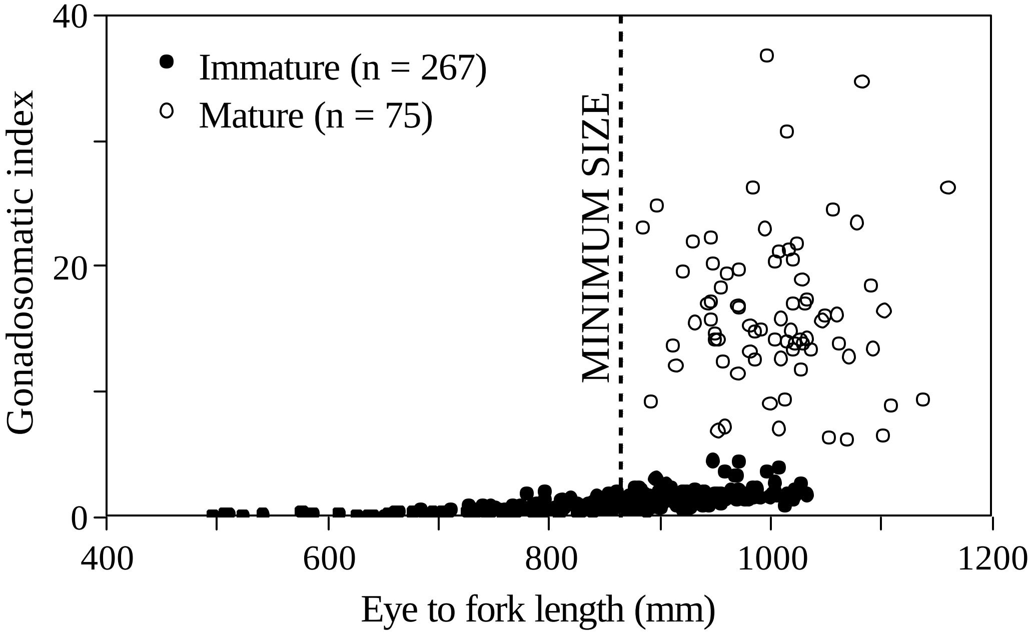

Figure 8. Gonadosomatic index values versus eye to fork lengths (EFL) for immature (solid circles) and mature (open circles) female paddlefish collected prior to and during the 2002-2003 and 2003-2004 commercial fishing seasons in Kentucky Lake, Tennessee-Kentucky (November 15 to April 23). Dashed line represents current 864 mm (34”) minimum EFL.

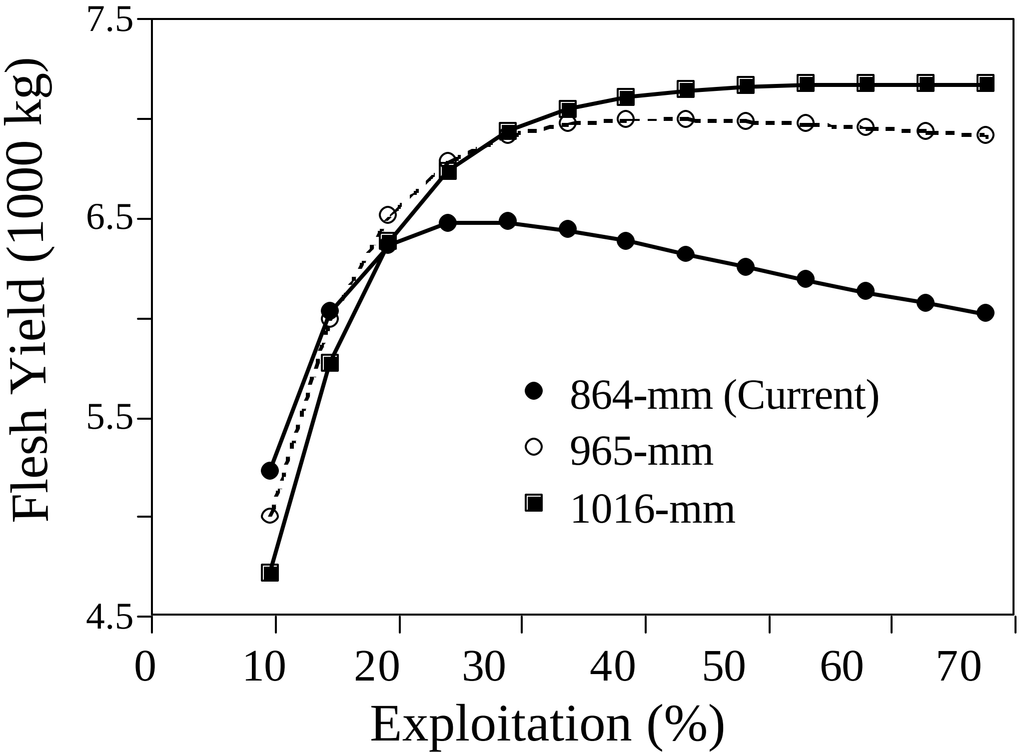

Figure 9. Predicted paddlefish flesh yield (per 1000 recruits) versus exploitation for three different minimum length limits in Kentucky Lake, Tennessee-Kentucky. Conditional natural mortality was 8%.

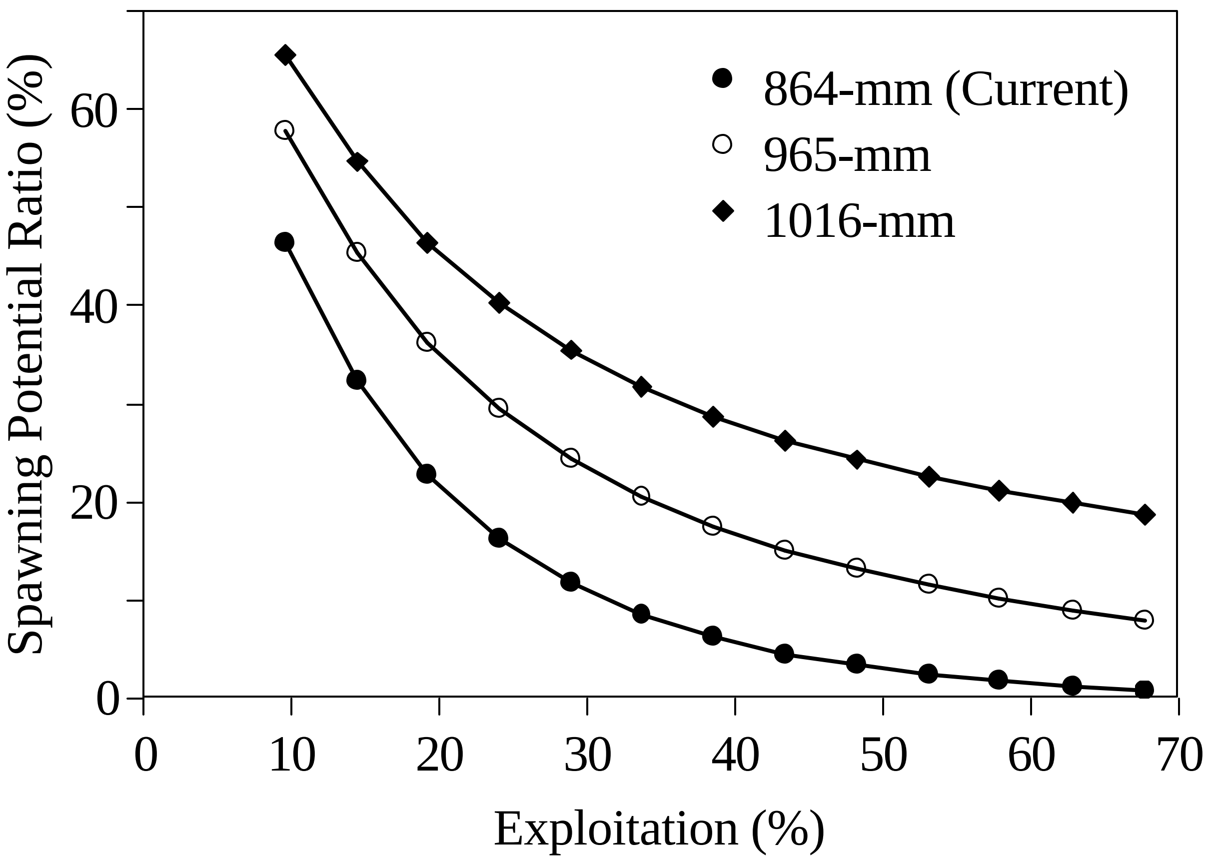

Figure 10. Predicted paddlefish Spawning Potential Ratios versus exploitation for three different minimum length limits in Kentucky Lake, Tennessee-Kentucky.

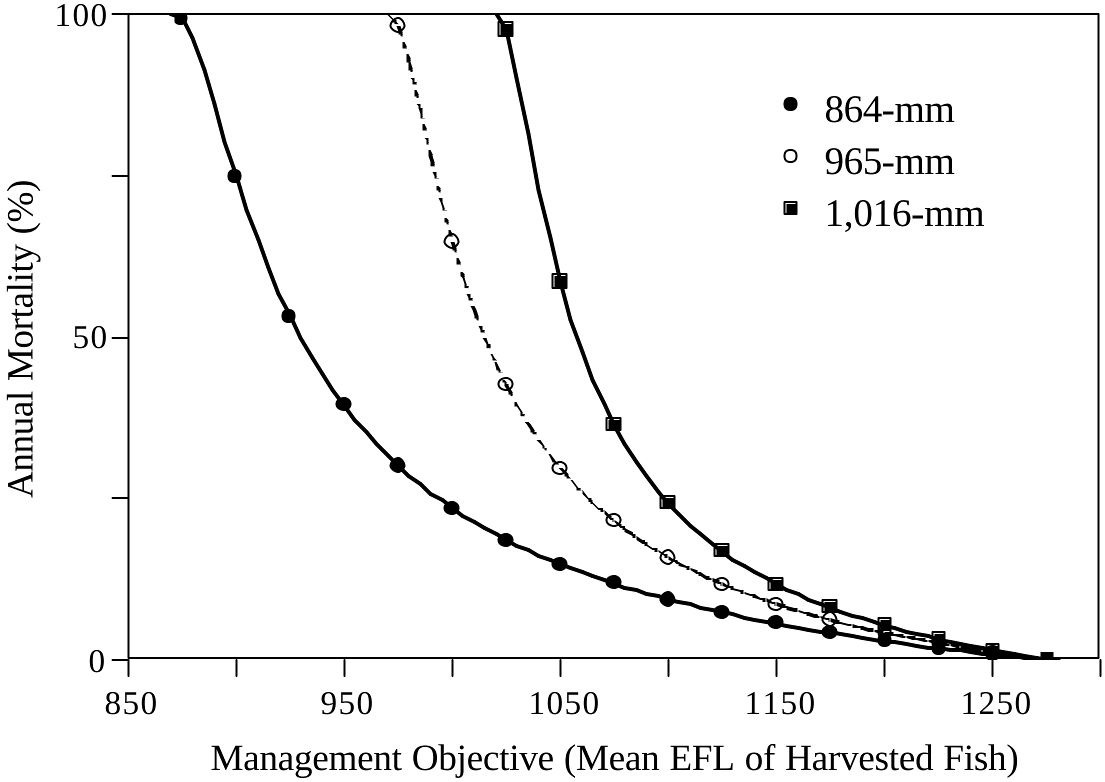

Figure 11. Annual mortality caps versus target mean EFL of harvested paddlefish for three minimum EFL limits in Kentucky Lake, Tennessee-Kentucky.

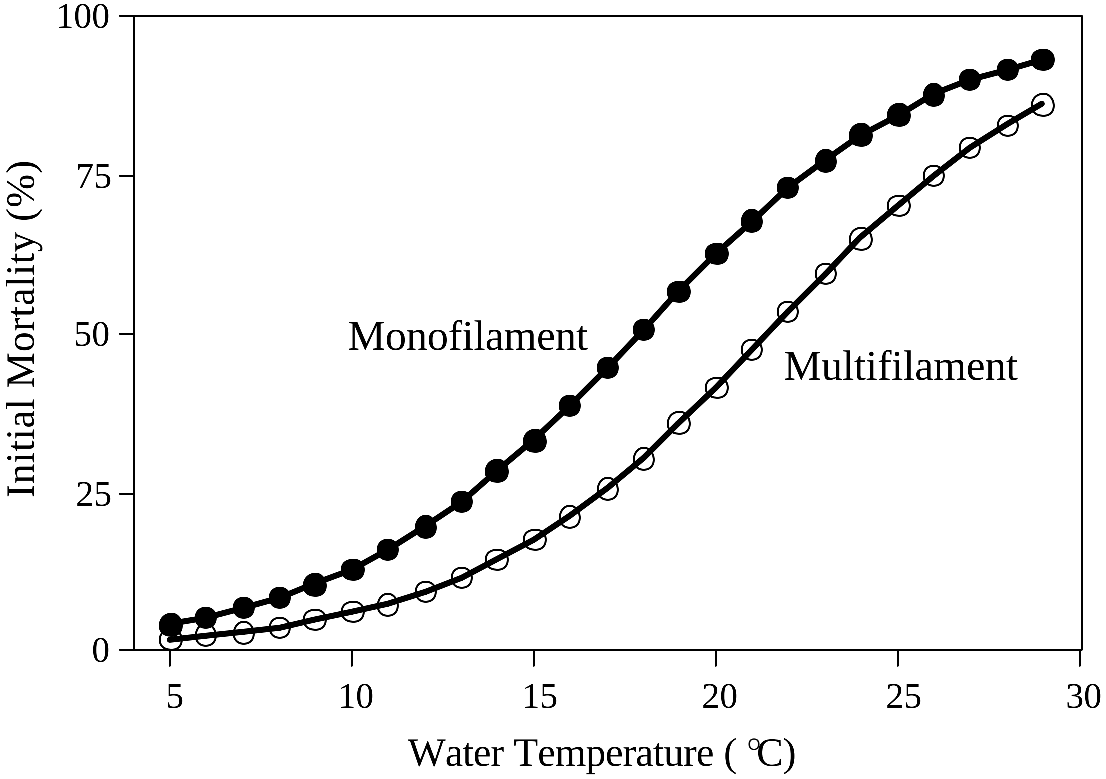

Figure 12. Predicted initial mortality of paddlefish removed from gill nets in Kentucky Lake, Tennessee-Kentucky, before, during, and after the 2002-2003 and 2003-2004 commercial paddlefish harvest seasons. Soak time was held constant at 12 hours.

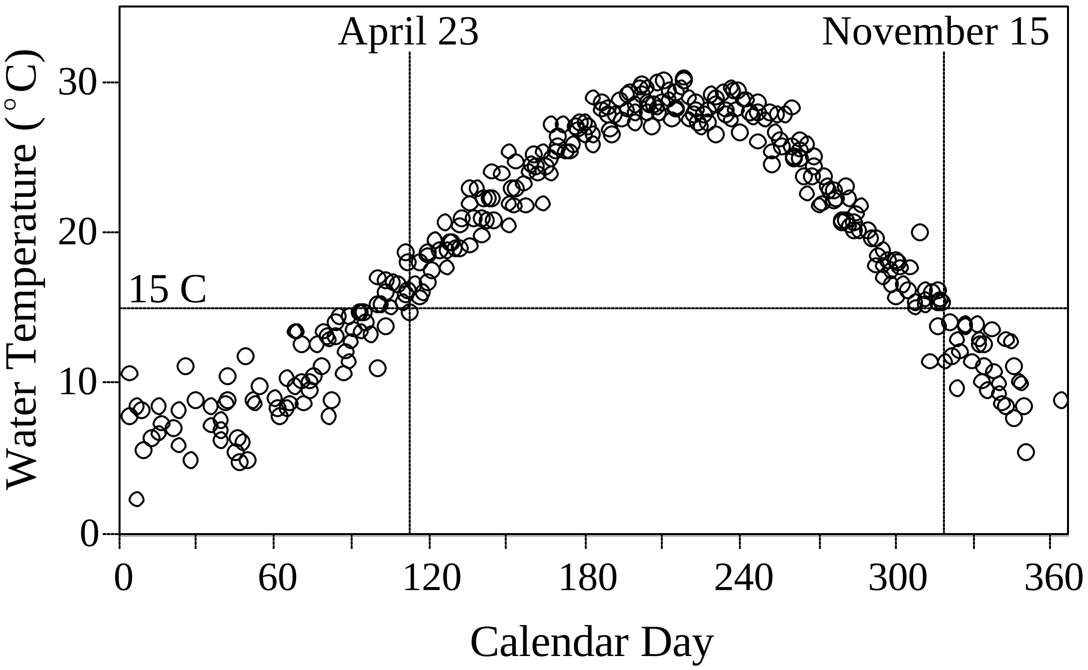

Figure 13. Water temperature measured in Kentucky Lake, Tennessee-Kentucky, at one-m depth intervals every 16 days at three stations between July 1988 and September 2004. Each data point represents the mean water column temperature pooled over all stations each date. Data courtesy of the Hancock Biological Station, Murray State University, Kentucky.

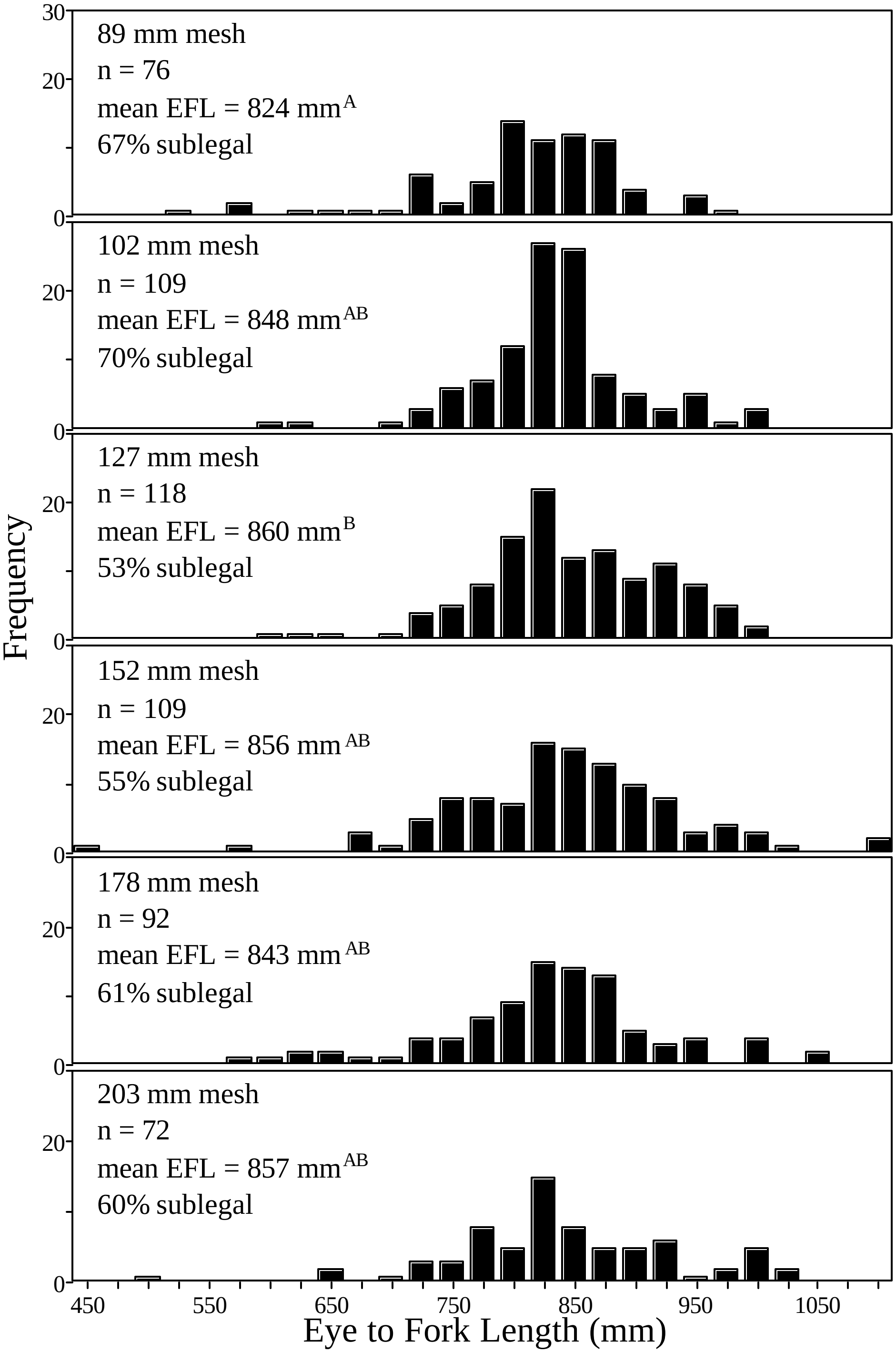

Figure 14. Length-frequency distributions for paddlefish captured in experimental gill nets in Kentucky Lake, Tennessee-Kentucky. Means sharing the same letter were not significantly different (Tukey's test; P = 0.05). Percentage of sublegal fish (< 864 mm eye-fork length) is indicated for each mesh panel.

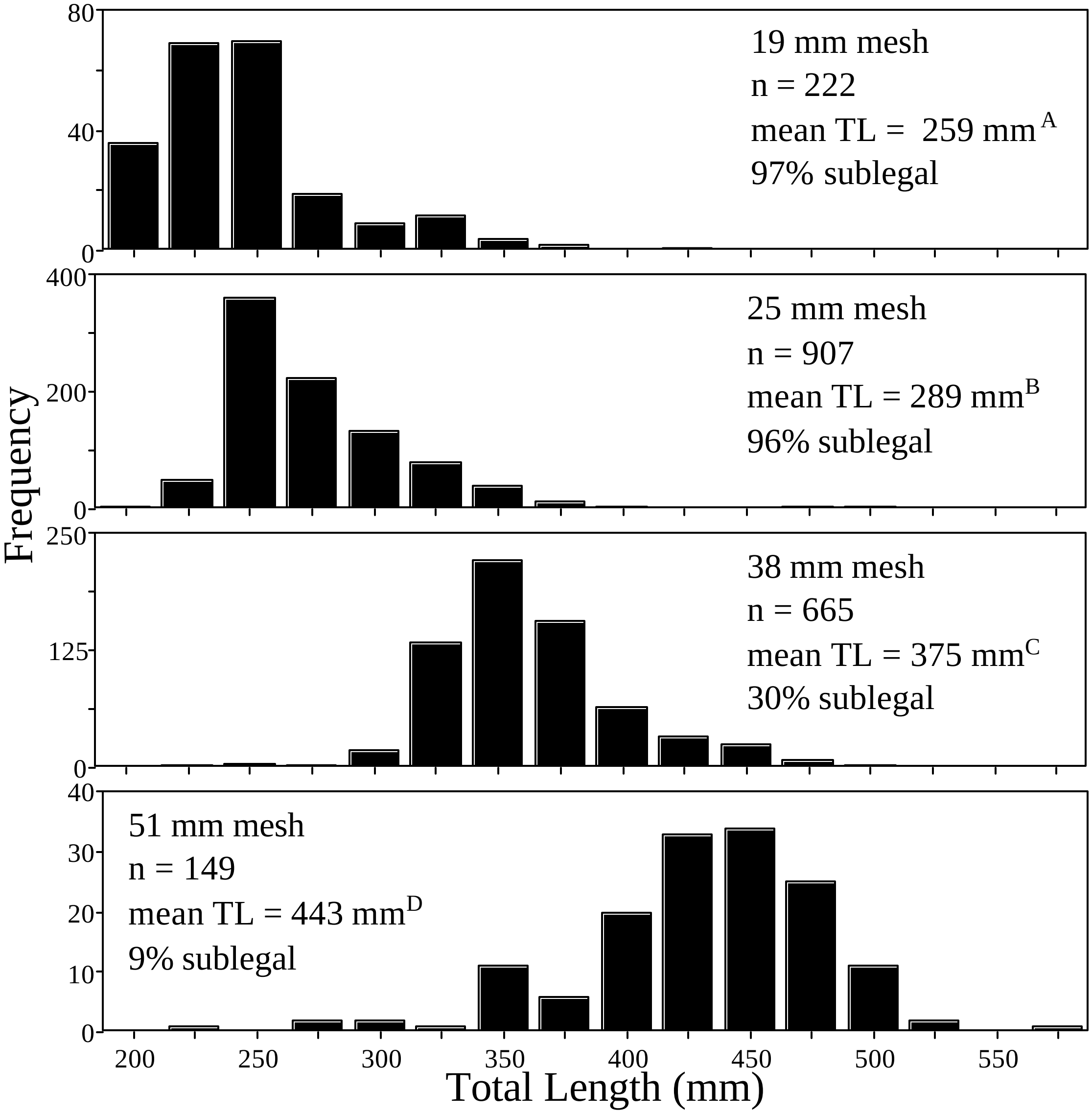

Figure 15. Length-frequency distributions for saugers captured in experimental gill nets in Kentucky Lake, Tennessee-Kentucky. Means sharing the same letter were not significantly different (Tukey's test; P = 0.05). Percentage of sublegal fish (< 356 mm total length) is indicated for each mesh panel.

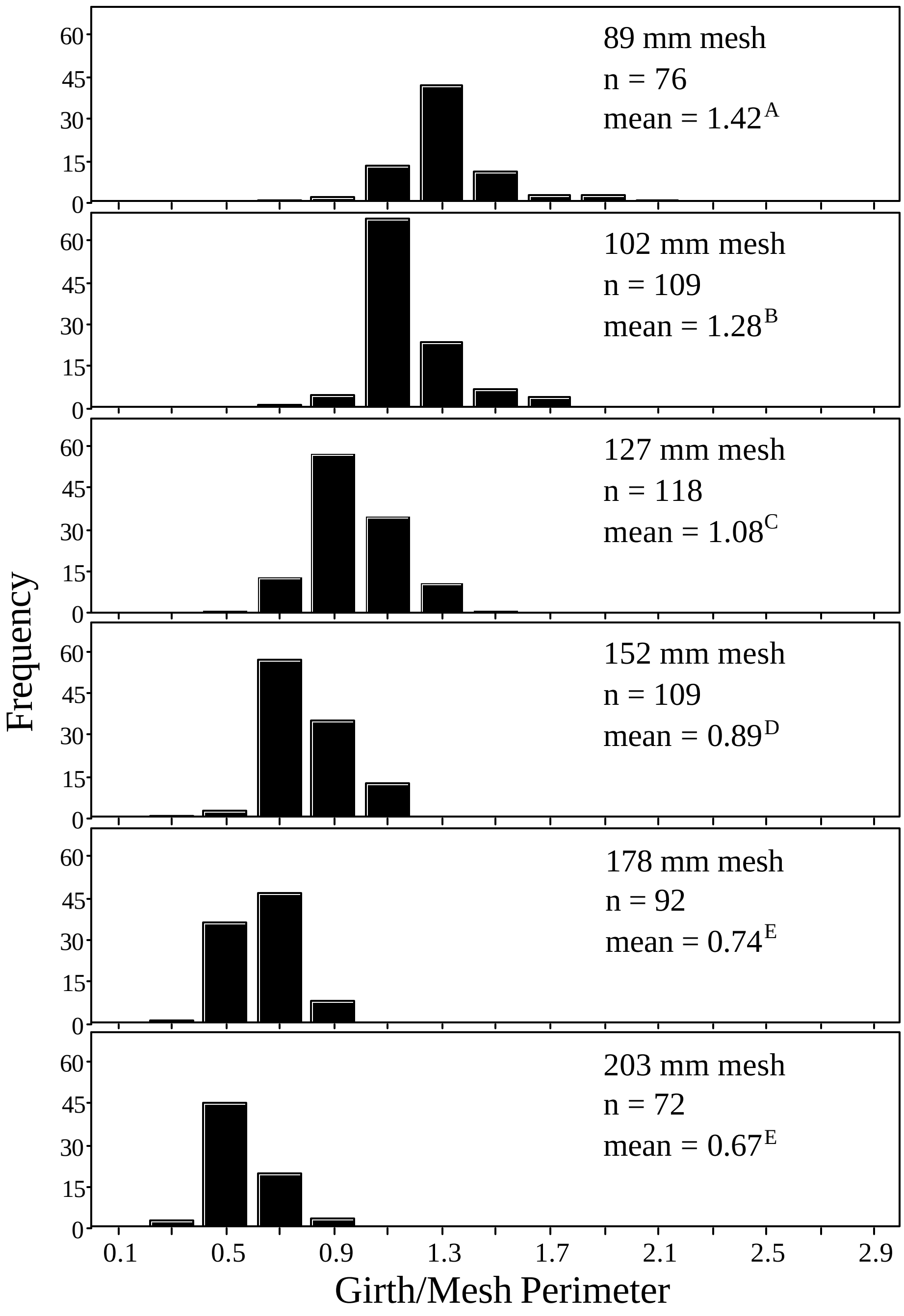

Figure 16. Fish girth:mesh perimeter ratios by mesh size for paddlefish collected in Kentucky Lake, Tennessee-Kentucky, 2003-2004. Means sharing the same letter were not significantly different (Tukey's test; P = 0.05).

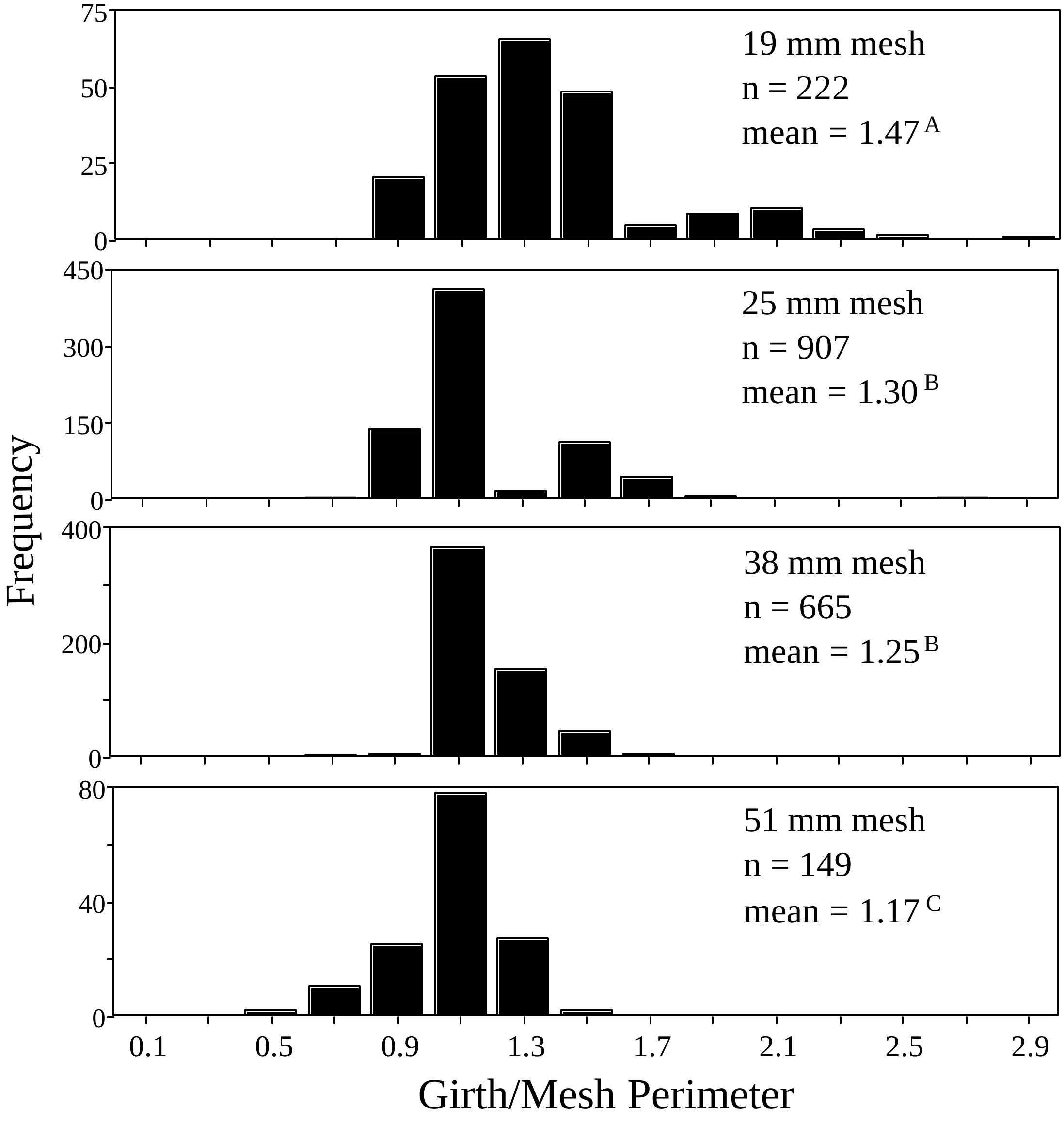

Figure 17. Fish girth:mesh perimeter ratios by mesh size for saugers collected in Kentucky Lake, Tennessee-Kentucky, 1993-1996. Means sharing the same letter were not significantly different (Tukey's test; P = 0.05).