American Fisheries Society Symposium 77:395–407, 2011

Impacts of Electrofishing Removals on the Introduced Flathead Catfish Population in the Satilla River, Georgia

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Abstract.—Recent modeling indicates that increased exploitation on nonnative flathead catfish *Pylodictis olivaris* may be an avenue for native species recovery. Flathead catfish were illegally introduced into the Satilla River, Georgia, and negative impacts have occurred on native fishes. In an effort to aid in the restoration of native fish on the Satilla River, the Georgia Department of Natural Resources initiated an intensive electrofishing removal effort. In this study, we evaluated the changes in flathead catfish total mortality, condition, and size structure from those efforts. From 2007 to 2009, 13,472 flathead catfish totaling 19,337 kg were removed along a 129-km stretch of the Satilla River. The population size structure changed substantially from containing many large individuals (59% ≥ 510 mm total length [TL]) in 2007 to mainly small fish (79% ≤ 356 mm TL) by 2009. Total biomass per effort declined from 57.05 kg/h in 2007 to 19.96 kg/h in 2009. Mean individual weight of fish removed decreased from 2.64 kg in 2007 to 1.32 kg in 2008 to 0.61 kg in 2009. Population age structure was also truncated, but there was evidence for higher recruitment and earlier maturation, which would require that intensive harvest be maintained to prevent the population from rebuilding within 2–5 years. Catch-curves revealed increasing total annual mortality rates of 37, 48 and 52%, for 2007–2009, respectively. Considering the life history of the flathead catfish, being a long-lived species that presumably cannot withstand excessive rates of exploitation (i.e., greater than 25% exploitation), our results indicated that an electrofishing removal program is a reasonable management option for areas where this apex predator has been introduced, but continual removal may be required to maintain low biomass.

Introduction

The flathead catfish *Pylodictis olivaris* is considered a riverine species that is native to the Mississippi and Mobile drainages of the central and eastern United States (Page and Burr 1991; Jackson 1999; Boschung and Mayden 2004). The recent introductions of flathead catfish into several Atlantic and Gulf of Mexico drainages (Thomas 1995; Cailteux et al. 2003; Cailteux and Dobbins 2005; Pine et al. 2005) have resource managers and the public concerned about the negative impacts on native riverine species such as the brown bullhead *Ameiurus nebulosus* (Thomas 1995), redbreast sunfish *Lepomis auritus* (Thomas 1995; Sakaris et al. 2006; Bonvechio et al. 2009), largemouth bass *Micropterus salmoides* (Bonvechio et al. 2009), and spotted bullhead *A. serracanthus* (Cailteux and Dobbins 2005). Furthermore, there is an increased concern for the potential adverse affects on anadromous fish restoration programs (Guier et al. 1981; Ashley and Buff 1987; Brown et al. 2005; Pine et al. 2005).

Historically, the Satilla River, Georgia has been one of the premier sunfish fisheries in the state of Georgia, with redbreast sunfish being one of the

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most sought after species (Georgia Department of Natural Resources, unpublished data). Reports of flathead catfish caught in the Satilla River were confirmed in the mid-1990s (Bonvechio et al. 2009) and are likely the result of an illegal stocking by anglers. Coincidently, the proof was fairly evident after Georgia Department of Natural Resources (GaDNR) biologists found unique adipose fin-clipped fish in the Satilla River in 1996, that had been marked in the Altamaha River, just a year before in 1995 (B. Deener, Georgia Department of Natural Resources, personal communication). While other density-dependent (e.g., cannibalism) and density-independent (e.g., water levels) factors can influence the abundance of native fishes (Everhart and Youngs 1981; Houde 1987; Sigler and Sigler 1990; Royce 1996), direct predation by the flathead catfish is believed to have caused dramatic declines in the abundances of native fishes in the Satilla River by the early 2000s (Bonvechio et al. 2009), similar to the scenario regarding the Altamaha River's introduced flathead population (Thomas 1995).

In an effort to restore native fish populations in the Satilla River, multiple removal efforts have been attempted on introduced flathead catfish despite research studies revealing negative aspects of flathead catfish removals, including the lack of public favor (Weller and Geihsler 1999) and their potential ineffectiveness (Moser and Roberts 1999). Agency biologists have used boat electrofishing in an attempt to remove flathead catfish since 1996 (Sakaris et al. 2006). Furthermore, there are no management regulations for this species, so angler harvest is encouraged in an effort to increase exploitation. Boat electrofishing removal efforts were simulated on the Satilla River by Sakaris et al. (2006) using Fisheries Analyses and Simulation Tools (FAST) software (Slipke and Maceina 2001). Sakaris et al. (2006) predicted the number of fish at stock, quality, and preferred sizes over a range of conditional fishing mortalities (cf = 0.0–0.9) and found that substantial declines in size structure were possible through fishing (Sakaris et al. 2006). Sakaris et al. (2006) predicted a 75% reduction in the number of fish at preferred size (i.e., 710 mm TL) at a 26% exploitation rate.

Pine et al. (2007) coined the term "maintenance control" as the suppression of flathead catfish biomass at some lower level where native fish communities should begin to benefit over time. We expand this definition as an attempted reduction of abundance of large fish (>50%) above 500 mm TL, where native fish species may have the potential for recovery. This length is where flathead catfish switch predominantly to piscivory (Guier et al. 1981; Jolley and Irwin 2003; Pine et al. 2005). As a result of the promising simulations (Sakaris et al. 2006), and a strong public sentiment to rid the Satilla River of flathead catfish, and adequate funding, a full-time three-man crew was assembled by the GaDNR in fall 2006 to increase the effort on electrofishing removals and determine the effects of the increased exploitation on the flathead catfish population. The objectives of this study were to evaluate the effect of increased boat electrofishing removals on annual survival, biomass, condition, relative abundance, size structure, and age structure of flathead catfish at the Satilla River, Georgia.

Methods

Study Area

The Satilla River originates near Fitzgerald, Georgia, flows 362 km in a southeasterly direction, and empties into the Atlantic Ocean at St. Andrew Sound, Georgia (Sandow et al. 1974). The Satilla River is contained within the physiographic province of the Coastal Plain in Georgia. The watershed is considered a low-lying area consisting of commercial slash pine and cypress swamp ecosystems that help produce a tannic stained color, typical of a blackwater river with a pH ranging between 4.5 and 6.0 (Sandow et al. 1974). The Satilla River has historical discharge ranging from 67 to 33,000 m^3/s, with a mean annual discharge of approximately 4,560 m^3/s (U.S. Geological Survey, Atkinson gauge). Currently, no major impoundment alters the flow of the river. Due to time constraints, limited accessibility, and the low abundance of flathead catfish observed above the Highway 301 bridge landing at river kilometer 132 (31°.18 N, 81°.58 W; Bonvechio et al. 2009), removal efforts were allocated solely downstream of this point ending at the Woodbine boat ramp at river kilometer 3 (30°.58 N, 81°.44 W). In general, the river gradient encountered upstream of the sample stretch is less than 60 cm/mi, and the gradient encountered within most of the sample site is less than 30 cm/mi (www.brownsguides.com/blog/satilla-river-paddling-guide).

Sampling

Low-amperage pulsed DC electrofishing (>1 A, 200–1,000 V, 18 pulses/s) was conducted during daylight hours in a downstream direction from either a 3.7- or 5.1-m aluminum johnboat equipped with either a Smith-Root model 12B backpack electrofisher or model LR-24 backpack electrofisher (Thomas 1995). Due to lower gear effectiveness in colder water temperatures (Quinn 1986) and high water levels, fish removals were generally conducted from April to October, 2007–2009, when water temperatures exceeded 20°C and when the river was within its banks. A chase boat was used to increase sampling efficiency (Quinn 1986; Cunningham 2004; Daugherty and Sutton 2005b), due to the large effective field produced in lotic systems (Thomas 1995). All flathead catfish were sacrificed, and 10 (2007 and 2008) or 5 (2009) fish per 2-cm group less than 1,020 mm total length (TL) and all fish ≥ 1,020 mm TL were retained for age analysis. Retained fish were placed on ice and returned to the laboratory for measurements of total length (nearest millimeter) and weight (nearest hundredth of a kilogram), determination of gender, and removal of lapilla otoliths. Two independent readers estimated the age of the fish using the otoliths, and any differences in age between readers were reconciled by concert reads (Nash and Irwin 1999; Buckmeier et al. 2002; Sakaris et al. 2006). Age composition was estimated by developing an age-length key from the aged fish and applying it to the entire sample (Ricker 1975).

Analysis

Total annual mortality (A) was estimated for each year using catch curves. Catch curves were constructed by regressing the loge number of fish against age, and the catch curve slope (Z) was used to estimate A ($A = 1 - e^{-Z}$; Ricker 1975). We removed age-0 fish and some older age-classes from the catch curves because capture efficiency was low (i.e., fish had not yet recruited to the gear) or there were fewer than three fish for an age. Genders were combined for all mortality estimates. An age-length key (Ricker 1975) was used to estimate the age frequency of subsampled flathead catfish (N = 5 or 10 fish per 2-cm group, depending on year of sample) through extrapolation to the entire length frequency (Ricker 1975). As a result, we assigned a percentage of each fish that was aged for each centimeter grouping and this number was expanded to the total number of fish obtained in the length frequency for each centimeter grouping.

We estimated fish condition and size structure. Fish condition was calculated using relative weight (W_r). Length-specific standard weights (W_s) for flathead catfish were derived from the standard weight equation, $\log_{10}(W_s) = -5.542 + 3.23 \log_{10}(\mathrm{TL})$ (Bister et al. 2000). Relative weight was not calculated for flathead catfish less than 140 mm TL due to variance-to-mean errors greater than 0.02 for smaller individuals (Bister et al. 2000). A one-way analysis of variance (ANOVA) was utilized to test differences in Wr among years. Proportional size distribution (PSD) and PSD for preferred-size fish (PSD-P) were calculated using 350 mm TL as stock size, 510 mm TL as quality size, and 710 mm TL as preferred size (Bister et al. 2000). To evaluate changes in size structure, we used a chi-square test to test for differences in the proportion of fish in each PSD size-group between 2007, 2008, and 2009 (Neumann and Allen 2007). All statistical analyses were conducted with SAS (SAS Institute 2000).

Results

Removal

Due to the allocation of a full-time crew and the incorporation of a volunteer program, total electrofishing effort (hours of pedal time) was highest in the last 3 years of the study and ranged from 178 h in 2009 to 201.6 h in 2007 (Table 1). From 1996 to 2006, only 1 year (2002; 128 h of pedal time, 72% of 2009) had even remotely similar amounts of effort allocated toward the removal effort. The amount of effort was nearly matched in the past 3 years (558 h from 2007 to 2009) to all of the effort allocated in the first 11 years (636 h from 1996 to 2006). In addition, a total of 42 volunteers donated 356 person hours from 2007 through 2009.

A total of 12,020 fish were removed the first 11 years (1996–2006), whereas 13,472 fish were removed during 2007–2009 (Table 1). The biomass of flathead removed also increased through time and ranged from 143 to 11,502 kg across all removal years (Table 1). The size and weight of individual flathead catfish collected during the electrofishing removal from 2007 to 2009 ranged from 60 to 1,192 mm TL and 0.001 to 25.8 kg, respectively. Due to removals, biomass of the flathead catfish population was substantially affected, with total biomass catch per effort declining from 57.05 kg/h in 2007 to 23.64 kg/h in 2008 to 19.91 kg/h in 2009. The average size of flathead harvested decreased from 2.6 kg in 2007 to 1.3 kg in 2008 to 0.61 kg in 2009 (Table 1). Despite a decline in biomass and average size, there was a notable increase in total catch per effort (fish/h) in 2009 (Table 1) when compared to 2007

TABLE 1. Summary statistics for the flathead catfish management activities on the Satilla River population by Georgia Department of Natural Resource personnel from 1996 to 2009. Electrofishing effort is expressed as hours of pedal time allocated toward removing fish per year. Total weight (kg), average size of flathead catfish removed (kg) and total number of flathead catfish removed per hour (fish/h) of electrofishing effort. Proportional size distribution (PSD) and PSD-*P* (PSD of preferred-size fish), are available for most years but were not calculated from 2004 to 2006 because a large proportion of the removed fish were not measured individually. *A* = total annual mortality.

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total electrofishing effort (h)	39	56	34	34	36	57	128	92	79	25.8	55	201.6	180.3	178.0
Number removed	42	289	227	359	284	915	2,442	1,933	3,182	1,028	1,319	4,399	3,285	5,788
Weight removed (kg)	143	268	373	574	319	664	2,402	1,351	3,284	2,000	3,468	11,502	4,263	3,544
A									0.45[a]			0.37	0.48	0.52
PSD	90	26	23	67	56	32	54	36	N/A	N/A	N/A	83	67	41
PSD-*P*	23	7	8	24	19	8	12	8	N/A	N/A	N/A	27	21	11
Average size removed (kg)	3.4	0.91	1.63	1.59	1.13	0.73	1	0.68	1.04	1.95	2.63	2.63	1.32	0.61
Catch per unit effort (fish/h) + 1 SE	1.1 + 0.3	5.2 + 1.4	6.6 + 6.7	10.6 + 2.6	7.9 + 2.9	16.1 + 4.8	19.1 + 5.6	21.0 + 2.8	40.3 + 4.2	39.9 + 12.5	24.0 + 5.5	21.8 + 3.5	18.2 + 2.0	32.5 + 2.0
Biomass per effort (kg/h)	3.66	4.79	10.97	16.09	8.86	11.65	18.76	14.69	41.56	77.51	63.05	57.05	23.64	19.91

[a] Taken from Sakaris et al. (2006).

and 2008 catch rates, due to an increased number of small fish in the samples.

Changes in Population Structure

Age was estimated for a total of 1,220 flathead catfish, and these ages ranged from 0 to 14 years across all sample years (2007–2009). Total annual mortality rates increased from 2007 to 2009 (Figure 1). Catch-curves revealed instantaneous total mortality estimates (Z) were 0.46 (r^2 = 0.59, P = 0.01), 0.66 (r^2 = 0.89, P = 0.01), and 0.74 (r^2 = 0.97, P = 0.01), from 2007 to 2009, respectively. As a result, total annual mortality (A) rates of 37, 48 and 52% were calculated for 2007–2009, respectively.

The age frequencies showed the loss of older fish in the population (Figure 2). During the beginning stages of the more intense removal (2007), the age-structure contained about 15% of age-1 and age-2 fish but was dominated by a strong age-4 year-class (2003), which made up 50% of the sample. The sample also consisted of many larger older adults up to age 13, with 5% of the sample being age 6 or older (Figure 2). In 2008, the strong 2003 year-class was still present and made up 13% of the sample, and the same amount of larger older fish, (>age 6) still comprised 5% of the sample, but the population began to show signs of elevated exploitation (Figure 2) because 50% of the catch was age-1 and age-2 fish. The 2009 age-frequency data revealed a population typical of one following a high level of harvest, characterized by a large numbers of small fish (≤356 mm TL) with more than 80% of the fish being age-1 or age-2 and very few older adults present (Figure 2). Only 3% of the sample was age-6 or older fish in 2009.

The size structure of flathead catfish increased, whereas the condition improved throughout the study. Flathead catfish mean length was 512 mm TL in 2007 but dropped to 352 mm in 2008 and 281 mm in 2009 (Figure 3). Both PSD and PSD-*P* declined substantially across years due to the reduction of large fish in the sample (Table 1). The number of preferred size fish (>710 mm TL) declined from 839 in 2007 to 259 fish in 2008 and to 139 in 2009. The chi-square test revealed significant differences in the length-frequency distributions for the three size-groups tested (<356 mm TL or young, 356–509 mm TL or stock, and quality ≥ 510 mm TL fish) (χ^2 = 3,227.6, P < 0.0001). Mean flathead catfish relative weight (W_r) across all 2-cm size-groups from 14 to 118 cm, increased from 93 in 2007 to 97 in 2008 to 103 in 2009 (Figure 3). There were no trends observed for W_r with increasing size, but W_r was significantly lower in 2007 than in 2008 and 2009 (ANOVA; F = 151.81; P < 0.001).

We found some evidence that size of maturity changed after harvest was intensified in 2007. We collected four visually gravid flathead catfish females ranging from 234 to 257 mm TL in 2007. Age was estimated for only one of these fish. The age of a 251-mm-TL fish weighing 0.137 kg, harvested on May 24, 2007, was estimated to be age 2. In 2008, we collected six visually gravid females ranging from 200 to 296 mm TL. Age was estimated for five of these fish; three were age 3 and two were age 2. The smallest gravid age-2 female measured 200 mm TL and weighed 0.084 kg.

Discussion

Our results suggested that the maintenance control of flathead catfish in the Satilla River is possible, similar to predictions from previous simulation studies (Sakaris et al. 2006; Pine et al. 2007). Our observed decline in the number of large fish in the population was similar to predictions by Sakaris et al.'s (2006) simulations. Condition likely increased over the course of this study owing to reduced competition for food resources, as a result of 13,472 flathead catfish being removed from the river. Undoubtedly, some level of increased mortality was being subjected to the flathead catfish population from 1996 to 2006 due to GaDNR removals, as evidenced by Sakaris et al.'s (2006) A estimate of 0.45 in 2004 and our 2007 estimate of 0.37. We found dramatic changes in the size structure, condition, and biomass per effort (kg/h) that were not observed until the removal effort was increased and then replicated for three consecutive years from 2007 to 2009. As result of this increased effort, total mortality increases were detected in the catch-curves in the subsequent years of 2008 and 2009.

Mortality in flathead catfish has just recently been studied in both its native and introduced range. Our rates of total annual mortality for introduced flathead catfish populations were high (0.37, 0.48, and 0.52) in comparison to the majority of introduced and native populations examined. Sakaris et al. (2006) reported a total annual mortality rate of 0.14 for the native population on the Coosa River, Alabama, in 2001–2002. Similarly, Marshall et al. (2009) reported a total annual mortality rate of 0.17 for Lake Wilson Alabama. Summerfelt et al. (1972) reported higher total annual mortality rates of native

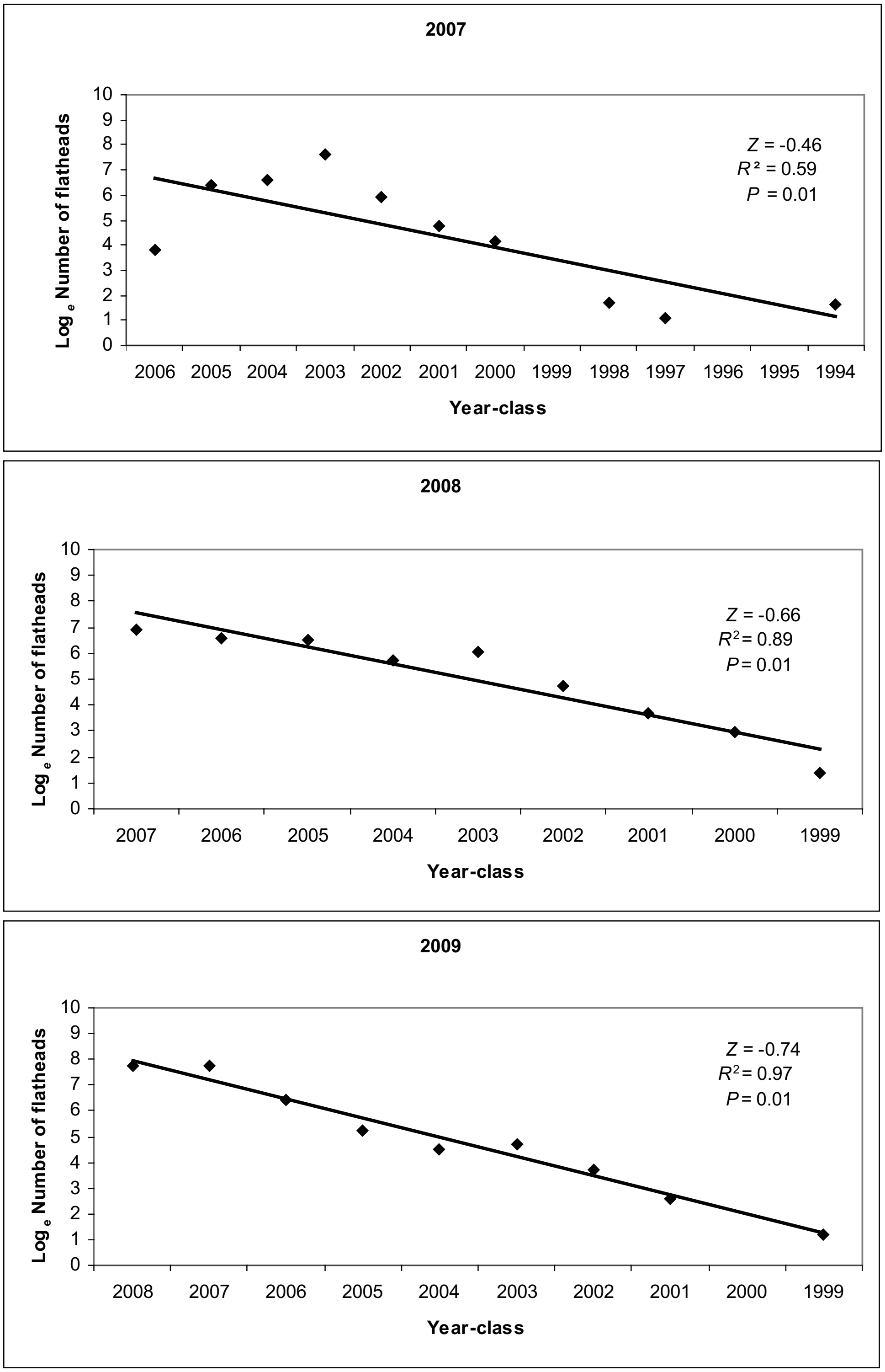

FIGURE 1. Catch-curve regressions based on the number-at-age data for flathead catfish collected during electrofishing on the Satilla River from 2007 (n = 3,946), 2008 (n = 3,252), and 2009 (n = 5,660).

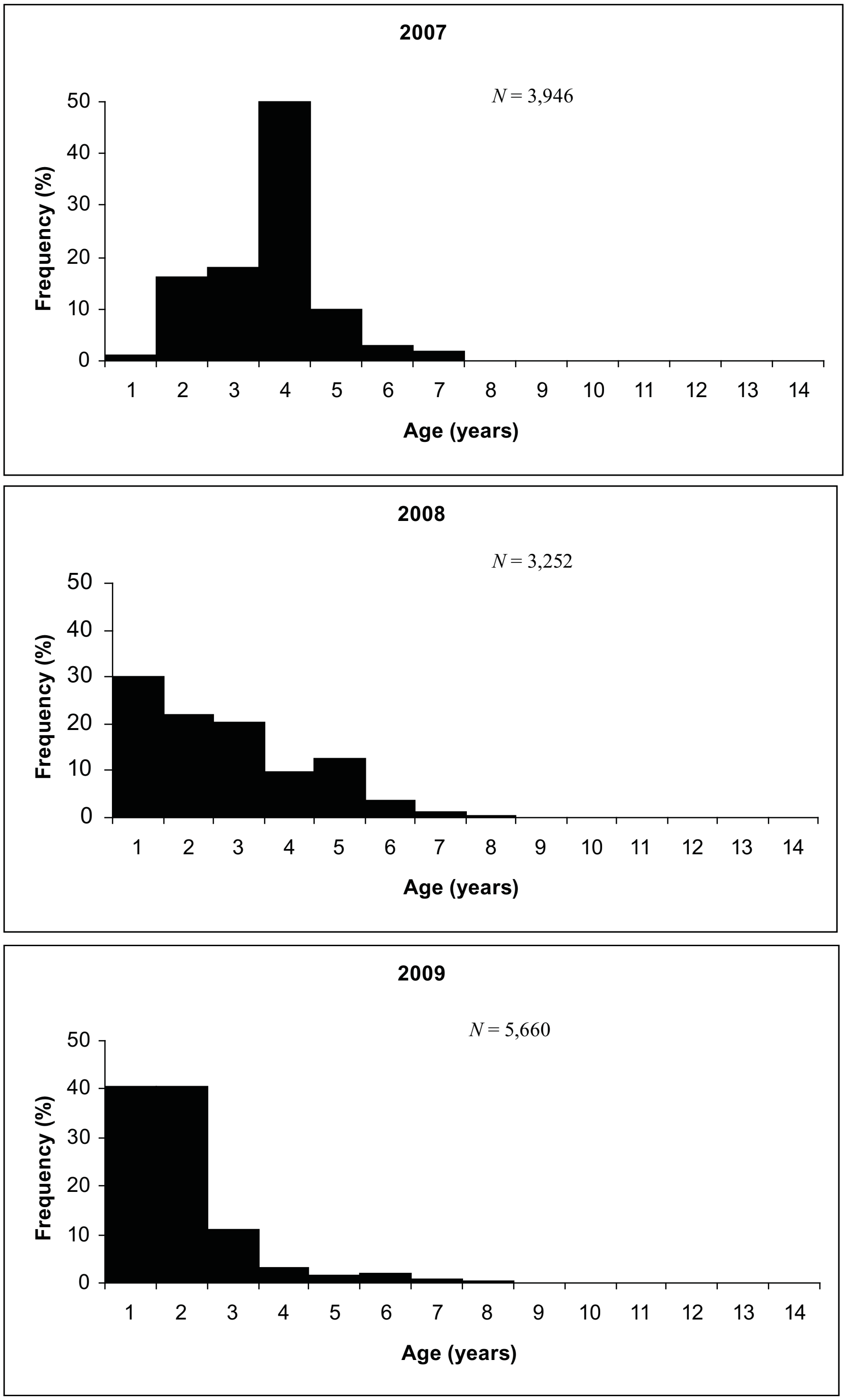

FIGURE 2. Age-frequency distributions of flathead catfish collected from the Satilla River, Georgia during 2007, 2008, and 2009.

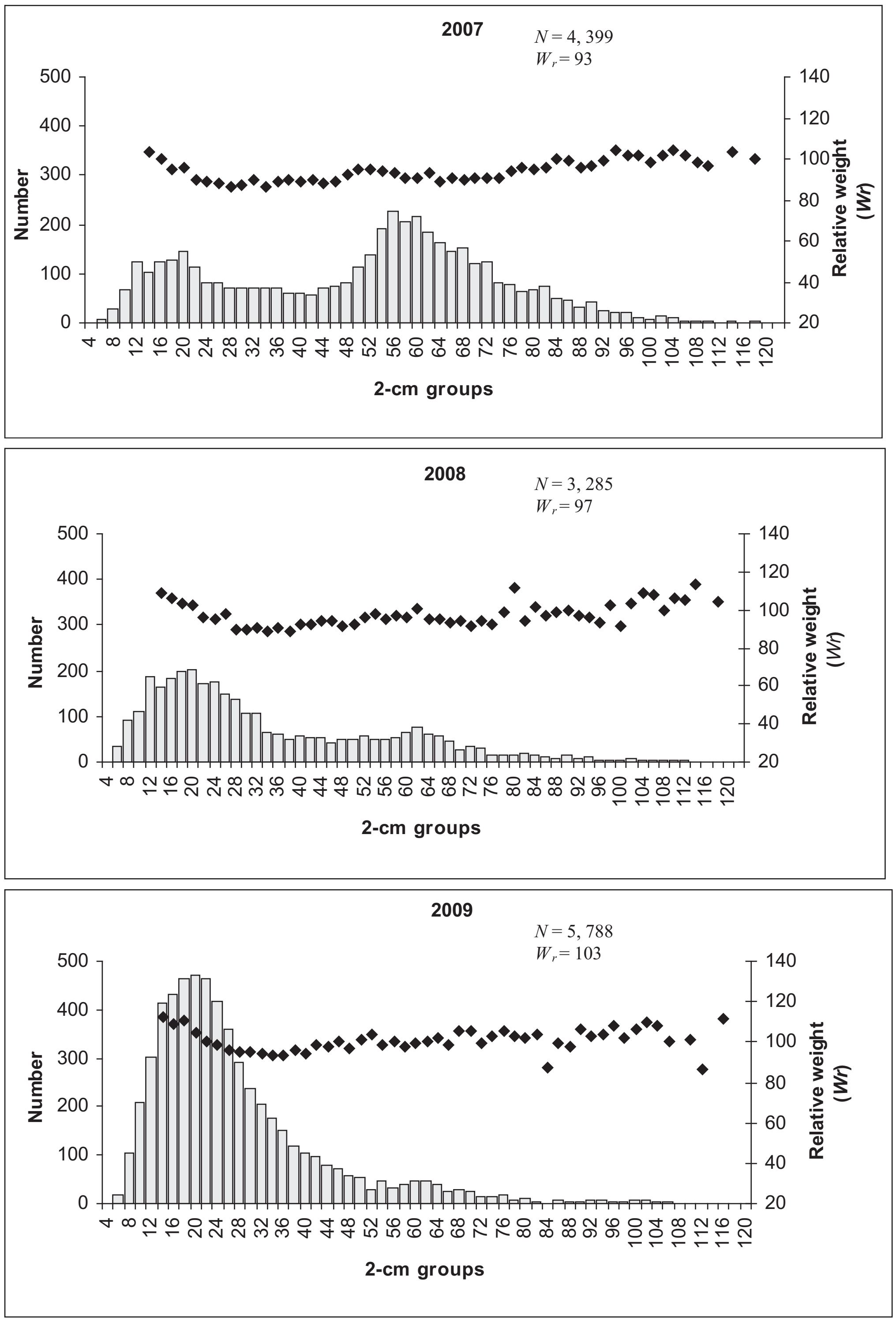

FIGURE 3. Length-frequency distributions (2-cm bins, shaded bars) and mean relative weights (w_r; solid diamonds) of flathead catfish collected from the Satilla River, Georgia in 2007–2009.

flathead catfish of 0.31–0.49 for Lake Carl Blackwell, Oklahoma.

Sakaris et al. (2006) found total annual mortality rates in the introduced Satilla River of 0.45. Kaeser et al. (2011, this volume) found a total annual mortality rate of 0.36 in Altamaha River in 2009, which is similar to our Satilla River estimate in 2007 but much lower than the 2008 or 2009 estimate. Lower rates of total annual mortality were documented on other introduced populations in Georgia, including the Ocmulgee River (0.20) in 1997 (Sakaris et al. 2006), the Flint River (0.29) in 2007 (Kaeser et al. 2011), and Ichawaynotchaway Creek (0.31) in 2009 (Kaeser et al. 2011). Furthermore, Kwak et al. (2006) documented lower total annual mortality rates ranging from 0.16 to 0.20 in three introduced flathead catfish populations along North Carolina's Atlantic slope rivers. Thus, after removal efforts, our estimates of total mortality were substantially higher than most published values for both introduced and native populations for this species.

Robinson's (1997) modeling suggested that a reduction of total mortality to 0.40 would increase the number of large fish and improve the size structure after he had estimated that *A* averaged 0.56 over several years in the native Missouri and Mississippi rivers. Pine et al.'s (2007) model simulations on a North Carolina river fish community revealed that with sustained exploitation (*U*) of flathead catfish (0.06–0.25), the potential for restoration of native fish communities is possible. Sakaris et al. (2006) reported that their samples probably did not encounter the theoretical maximum age (i.e., oldest fish obtained was age 10) because the population had not yet stabilized. When enough older fish are encountered in a sample, the slope of the mortality estimates will decrease, thus allowing for a lower mortality rate calculation (i.e., 2007 sample). Nonetheless, our estimates of mortality were high relative to most other published estimates and, as a result, may have improved native fish community. Future research should also be directed toward determining if native fish populations in the Satilla River have rebounded as a result of the removal.

We documented substantial changes in the size and age structure of an introduced flathead catfish population over a relatively short period of time, apparently due to an intense fish removal effort. Similar to the scenario described by Daugherty and Sutton (2005a) for exploited flathead catfish populations, we found fewer older and larger fish in the 2009 samples, presumably due to the high rate of exploitation over the past 3 years. Furthermore, smaller and younger fish dominated the 2009 size and age structure data in comparison to the 2007, which consisted of a more uniform length-frequency distribution spread out over a broader range of fish sizes and ages, indicative of a population experiencing lower exploitation. It appeared that there was higher recruitment in 2008 and 2009, based on length-frequency histograms, as well as an increase in catch per effort (fish/h) in 2009. Similarly, Kaeser et al. (2011) stated that removal efforts by the GaDNR in the Ocmulgee River from 1997 to 2000 may have influenced relative abundances of flathead catfish because a decline in catch-per-effort biomass was observed followed by a separate increase in the frequency of small individuals in 2001 and 2003. Futhermore, Zipkin et al. (2008) found similar increases in the abundance of young smallmouth bass *Micropterus dolomieu* in Moose Lake, New York and attributed this increase to recruitment overcompensation in response to 7 years of smallmouth bass removal. Like smallmouth bass, the flathead catfish population in the Satilla River appeared to respond to fish removals by increasing recruitment. In addition, we observed that some fish matured at a much smaller size and younger age than is typical for flathead catfish.

As a result of these findings, a dome-shaped stock recruit curve may exist on the Satilla River flathead catfish population, and describing the shape of this curve will influence how effective removal programs like this one can become. If recruitment continues to increase following removal efforts, this would require increased sampling effort to obtain a maintenance control level. Future work should characterize the stock recruit relationship for flathead catfish. Alternately, it is possible that, through time, when large fish became scarce in the later years of sampling in 2008 and 2009, electrofishing catch included more small fish because sampling crew had selectively targeted larger fish in the beginning of the intense removal (2007). Known electrofishing gear bias could be partially responsible for the results we observed (Hardin and Connor 1992; Hilborn and Walters 1992; Reynolds 1996; Cunningham 1998; Bayley and Austen 2002). Future studies should quantify electrofishing catchability for flathead catfish and the potential for a dome-shaped stock–recruitment curve.

The elevated levels of mortality presented in this study are encouraging when you consider the life history of the flathead catfish, being a long-lived species that theoretically cannot withstand excessive harvest (Jenkins and Burkhead 1994; Stauffer et al. 1996; Jackson 1999). Pine et al. (2007) predicted that at a 33% exploitation rate or higher, flathead catfish populations were not sustainable. Furthermore, a 95% reduction in flathead catfish biomass was predicted within a 5-year time span at an exploitation rate of 54%, nearly extirpating it from the system for at least 15 years (Pine et al. 2007). It appears that by using Pine et al.'s (2007) maintenance control techniques, the flathead population in the Satilla River can be kept at a lower biomass. However, maintaining low density would require higher sampling effort and/or sampling with a gear that is more effective at removing small fish than electrofishing. Pine et al. (2007) warned that despite the anticipated decline in catch rates of all sizes of fish, the predicted benefits to native fish communities (e.g., redbreast sunfish) is only achievable if flathead catfish exploitation is sustained at a high level. Reduced exploitation would allow flathead catfish populations to revert back to pre-exploitation levels, and as a result, native fish communities would be suppressed (Pine et al. 2007). Intuitively, complete eradication of flathead catfish from the Satilla River seems highly unlikely, but a maintenance control of this species could potentially hold the population in check where positive responses in the native fish community may occur over time as of the result of suppressed flathead catfish biomass and size structure, especially if the majority of the population is being growth overfished to below a size (mean total length in 2009 was 281 mm TL) where piscivory is not the predominant feeding behavior (Guier et al. 1981; Jolley and Irwin 2003; Pine et al. 2005).

Our findings indicated that some flathead catfish in the Satilla River responded to high exploitation by maturing at smaller sizes and younger ages. Many studies have reported total length at sexual maturity for flathead catfish (Barnickel and Starrett 1951; Minckley and Deacon 1959; Munger et al. 1994). Munger et al. (1994) found that flathead catfish in Texas reservoirs become sexually mature between ages 2 and 5 and were between 29 and 63.5 cm. Jackson (1999) reported that sexual maturity in flathead catfish is reached in 3–5 years and between total lengths of 40 and 75 cm (1.5–4.0 kg). In previous removals before 2007, GaDNR staff documented that Satilla River flathead catfish did not become sexually mature until 50 cm or larger (Deener, personal communication), but with the finding of age 2, 20-cm mature fish, there appeared to be a shift to sexual maturity at smaller sizes, which may have occurred due to the increased exploitation, similar to what has been observed for some marine species (e.g., Haug and Tjemsland 1986). To our knowledge, this phenomenon has not been reported for flathead catfish. We surmise that the reduction in the age at maturity is a compensatory response due to reduced stock size. Furthermore, higher exploitation on the later maturing individuals relative to the early maturing individuals may also have contributed to these changes. Life history theory does predict that a change in mortality schedules would cause selection for earlier maturation, increased reproductive investment, or a change in growth rate (Roff 1992; Stokes et al. 1993; Law 2000). Thus, it does appear that the small number of young, mature females found in 2007 and 2008 could be selecting for a higher reproductive investment; hence, the gravid eggs found. As high rates of exploitation via these targeted removal activities continue for this population, the gravidity and age estimation of smaller flathead catfish should continue to be monitored. It is important to note that high water conditions during the beginning of sampling in 2009 could have prevented the collection of any small gravid flatheads, as found in 2007 and 2008.

Our study documented significant changes in the age structure, condition, size structure, and biomass of the population over the study period, suggesting the removal efforts altered the population. Unlike the Altamaha River, Georgia (Weller and Geihsler 1999), where a flathead catfish fishery is desired, the public desires a more traditional native sunfish fishery on the Satilla River (Georgia Department of Natural Resources, unpublished data), making an electrofishing removal program acceptable to the public. This fish removal may be appropriate in rivers that display similar size and nature as the Satilla River. However, high exploitation may need to be continued indefinitely in order to keep the flathead catfish biomass and size structure suppressed.

Acknowledgments

This project was funded by the Georgia Department of Natural Resources. We graciously appreciate the support of many individuals: G. Rogers and the Satilla Riverkeeper; G. Dowling and S. Barmeyer with the Georgia Wildlife Federation; K. Altha, K. Emme, R. Oester, and M. Roberts with the Kentucky Department of Fish and Wildlife Resources; and Southeast regional fisheries units of the Georgia Department of Natural Resources. K. Bonvechio and A. Kaeser provided previous revisions of this manuscript.

References

Ashley, K. W., and B. Buff. 1987. Food habits of flathead catfish in the Cape Fear River, North Carolina. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 41:93–99.

Barnickel, P. G., and W. C. Starrett. 1951. Commercial and sport fishes of the Mississippi River between Caruthersville, Missouri and Dubuque, Iowa. Bulletin of the Illinois Natural History Survey 25:267–350.

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

Bister, T. J., D. W. Willis, M. L. Brown, S. M. Jordan, R. M. Neumann, M. C. Quist, and C. S. Guy. 2000. Proposed standard weight (W_s) equations and standard length categories for 18 warmwater nongame and riverine fish species. North American Journal 20:570–574.

Bonvechio, T. F., D. Harrison, and B. Deener. 2009. Population changes of sportfish following flathead catfish introduction in the Satilla River, Georgia. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 63:133–139.

Boschung, H. T., Jr., and R. L. Mayden. 2004. Fishes of Alabama. Smithsonian Books, Washington, D.C.

Brown, J. J., J. Perillo, T. J. Kwak, and R. J. Horowitz. 2005. Implications of *Pylodictis olivaris* (flathead catfish) introduction into the Delaware and Susquehanna drainages. Northeastern Naturalist 12:473–384.

Buckmeier, D. L., E. R. Irwin, R. K. Betsil, and J. A. Prentice. 2002. Validity of otoliths and pectoral spines for estimating ages of channel catfish. North American Journal of Fisheries Management 22:934–942.

Cailteux, R. L., and D. A. Dobbins. 2005. Population status and distribution of spotted bullhead Ameirus serracanthus in north Florida rivers. Florida Scientist 68:122–129.

Cailteux, R. L., D. A. Dobbins, and R. S. Land. 2003. Apalachicola/Ochlockonee River investigations. Florida Fish and Wildlife Conservation Commission, Annual Report, Tallahassee.

Cunningham, K. K. 2004. Efficacy of a chase boat for electrofishing flathead catfish in three Oklahoma reservoirs. North American Journal of Fisheries Management 24:1427–1430.

Cunningham, K. K. 1998. Influence of environmental variables on flathead catfish electrofishing catch. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 52:125–135.

Daugherty D. J., and T. M. Sutton. 2005a. Population abundance and stock characteristics of flathead catfish in the lower St. Joseph River, Michigan. North American Journal of Fisheries Management 25:1191–1201.

Daugherty D. J., and T. M. Sutton. 2005b. Use of a chase boat for increasing electrofishing efficiency for flathead catfish in lotic systems. North American Journal of Fisheries Management 25:1528–1532.

Everhart, W. H., and W. D. Youngs. 1981. Principles of fisheries science, 2nd edition. Cornell University Press, London.

Guier, C. R., L. E. Nichols, and R. T. Rachels. 1981. Biological investigation of flathead catfish in the Cape Fear River. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 35:607–621.

Hardin, S., and L. L. Connor. 1992. Variability of electrofishing crew efficiency and sampling requirements for estimating reliable catch rates. North American Journal of Fisheries Management 12:612–617.

Haug, T., and J. Tjemsland. 1986. Changes in size and age-distributions and age at sexual maturity in Atlantic halibut, *Hippoglossus hippoglossus*, caught in north Norwegian water. Fisheries Research 4:145–155.

Hilborn, R., and C. J. Walters. 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman and Hall, New York.

Houde, E. D. 1987. Fish early life dynamics and recruitment variability. Pages 17–29 *in* R. D. Hoyt, editor. 10th annual larval fish conference. American Fisheries Society, Symposium 2, Bethesda, Maryland.

Jackson, D. C. 1999. Flathead catfish: biology, fisheries, and management. Pages 23–35 *in* E. R. Irwin, W. A. Hubert, C. F. Rabeini, H. L. Schramm, Jr., and T. Coon, editors. Catfish 2000: proceedings of the international ictalurid symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

Jenkins, R. E., and N. M. Burkhead. 1994. Freshwater fishes of Virginia. American Fisheries Society, Bethesda, Maryland.

Jolley, J. C., and E. R. Irwin. 2003. Food habits of catfishes in tailwater and reservoir habitats in a section of the Coosa River, Alabama. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 57:124–150.

Kaeser, A. J., T. F. Bonvechio, D. Harrison, and R.

R. Weller. 2011. Population dynamics of introduced flathead catfish in rivers of southern Georgia. Pages 409–422 *in* P. H. Michaletz and V. H. Travnichek, editors. Conservation, ecology, and management of catfish: the second international symposium. American Fisheries Society, Symposium 77, Bethesda, Maryland.

Kwak, T. J., W. E. Pine, and D. S. Waters. 2006. Age, growth, and mortality of introduced flathead catfish in Atlantic rivers and a review of other populations. North American Journal of Fisheries Management 26:73–87.

Law, R. 2000. Fishing, selection, and phenotypic evolution. ICES Journal of Marine Science 57:659–668.

Marshall, M. D., M. P. Holley, and M. J. Maceina. 2009. Assessment of the flathead catfish population in a lightly exploited fishery in Lake Wilson, Alabama. North American Journal of Fisheries Management 29:869–875.

Minckley, W. L., and J. E. Deacon. 1959. Biology of the flathead catfish in Kansas. Transactions of the American Fisheries Society 88:344–355.

Munger, C.R., G. R. Wilde, and B. J. Follis. 1994. Flathead catfish age and size and maturation in Texas. North American Journal of Fisheries Management 14:403–408.

Moser, M., and S. B. Roberts. 1999. Effects of nonindigenous ictalurids and recreational electrofishing on the ictalurid community of the Cape Fear River drainage, North Carolina. Pages 479–485 *in* E. R. Irwin, W. A. Hubert, C. F. Rabeini, H. L. Schramm, Jr., and T. Coon, editors. Catfish 2000: proceedings of the international ictalurid symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

Nash, M. K., and E. R. Irwin. 1999. Use of otoliths versus pectoral spines for aging adult flathead catfish. Pages 309–316 *in* E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. Schramm, Jr., and T. Coon, editors. Catfish 2000: proceedings of the international ictalurid symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

Neumann, R. M., and M. S. Allen. 2007. Size structure. Pages 375–421 *in* C. S. Guy and M. L. Brown, editors. Analysis and interpretation of freshwater fisheries data. American Fisheries Society, Bethesda, Maryland.

Page, L.M., and B. M. Burr. 1991. A field guide to freshwater fishes of North America, North of Mexico. Houghton Mifflin Company, Boston.

Pine, W. E., T. J. Kwak, D. S. Waters, and J. A. Rice. 2005. Diet selectivity of introduced flathead catfish in coastal rivers. Transactions of the American Fisheries Society 134:901–909.

Pine, W. E., T.J. Kwak, and J.A. Rice. 2007. Modeling management scenarios and the effects of an introduced apex predator on a coastal riverine fish community. Transactions of the American Fisheries Society 136:105–120.

Reynolds, J. B. 1996. Electrofishing. Pages 221–253 *in* B. R. Murphy and D. W. Willis, editors. Fisheries techniques, 2nd edition. American Fisheries Society, Bethesda, Maryland.

Quinn, S. P. 1986. Effectiveness of an electrofishing system for collecting flathead catfish. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 40:85–91.

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

Robinson, J. W. 1997. The development of a qualitative system to evaluate populations of channel and flathead catfish in the Missouri and Mississippi rivers. Missouri Department of Conservation, Project F-1--R-46, Final Report, Jefferson City.

Roff, D. A. 1992. The evolution of life histories: theory and analysis. Chapman and Hall, New York.

Royce, W. F. 1996. Introduction to the practice of fishery science. Academic Press, San Diego, California.

Sandow, J. T., D. R. Holder, and L. E. McSwain. 1974. Life history of the redbreast sunfish in the Satilla River, Georgia. Proceedings of the Annual Conference Southeastern Association of Game and Fish Commissioners 28:279–295.

Sakaris, P. C., E. R. Irwin., J. C. Jolley, and D. Harrison. 2006. Comparison of native and introduced flathead catfish populations in Alabama and Georgia: growth, mortality, and management. North American Journal of Fisheries Management 26:867–874.

SAS Institute. 2000. User's guide, version 8. SAS Institute, Cary, North Carolina.

Sigler, W. F., and J. W. Sigler. 1990. Recreational fisheries: management, theory, and application. University of Nevada Press, Reno.

Slipke, J. W., and M. J. Maceina. 2001. Fishery analyses and simulation tools (FAST 2. 0). Auburn University, Department of Fisheries and Allied Aquacultures, Auburn, Alabama.

Stauffer, K. W., R. C. Binder, B. C. Chapman, and B. D. Koenen. 1996. Population characteristics and sampling methods of flathead catfish *Pylodictis olivaris* in the Minnesota River. Minnesota Department of Natural Resources, Division of Fish and Wildlife, Section of Fisheries, Study IV, Job 389, St. Paul.

Stokes, T. K., J. M. McGlade, and R. Law. 1993. The exploitation of evolving resources. Springer-Verlag, Lecture Notes in Biomathematics 99, Berlin.

Summerfelt, R. C., L. Hart, and P. R. Turner. 1972. Flathead catfish movements. Oklahoma Department of Wildlife Conservation Completion Report, Federal Aid in Sportfish Restoration, Project 4–60-R, Oklahoma City.

Thomas, M. E. 1995. Monitoring the effects of introduced flathead catfish on sport fish populations in the Altamaha River, Georgia. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 47:531–538.

Weller, R. R., and M. R. Geihsler. 1999. Angler attitudes concerning the management of the introduced flathead catfish in the Altamaha River system, Georgia. Pages 435–442 *in* E. R. Irwin, W. A. Hubert, C. F. Rabeini, H. L. Schramm, Jr., and T. Coon, editors. Catfish 2000: proceedings of the international ictalurid symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

Zipkin, E. F., P. J. Sullivan, E. G. Cooch, C. E. Kraft, B. J. Shuter, and B. C. Weidel. 2008. Over compensatory response of a smallmouth bass (*Micropterus dolomieu*) population to harvest. Release from competition? Canadian Journal of Fisheries and Aquatic Sciences 65:2279–2292.