FACTORS RELATED TO STOCKING SUCCESS OF

178-MM CHANNEL CATFISH IN MEDIUM SIZE

OKLAHOMA RESERVOIRS

By

DAVID RANDALL STEWART, JR.

Bachelor of Science in Biology
Martin Methodist College
Pulaski, TN
2006

Master of Science in Zoology
Middle Tennessee State University
Murfreesboro, TN
2009

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
December, 2013

FACTORS RELATED TO STOCKING SUCCESS OF

178-MM CHANNEL CATFISH IN MEDIUM SIZE

OKLAHOMA RESERVOIRS

Dissertation Approved:

Dr. James M. Long
<hr>
Dissertation Advisor

Dr. Daniel E. Shoup
<hr>

Dr. Shannon K. Brewer
<hr>

Dr. Carla L. Goad
<hr>

ACKNOWLEDGEMENTS

Acknowledgements reflect the views of the author and are not endorsed by committee
members or Oklahoma State University.

Name: DAVID RANDALL STEWART, JR.

Date of Degree: DECEMBER, 2013

Title of Study: FACTORS RELATED TO STOCKING SUCCESS OF 178-MM
CHANNEL CATFISH IN MEDIUM SIZE OKLAHOMA RESERVOIRS

Major Field: NATURAL RESOURCE ECOLOGY AND MANAGEMENT

Abstract:

The channel catfish *Ictalurus punctatus* is a commonly stocked freshwater fish species. Prior studies indicate that stocking advanced size (> 150 mm total length (TL)) fingerlings increases post-release survival but few studies have identified factors that influence stocking success. The present study was conducted to determine stocking contribution and growth of advanced size channel catfish (~178 mm TL), evaluate the impact of stocking and cessation of stocking, quantify habitat relationships, and evaluate trophic relationships of wild and stocked fish in medium size Oklahoma reservoirs: lakes McMurty and Ponca (control lakes), Okemah and Okmulgee (cease-stock lakes), and Greenleaf and Lone Chimney (stocked lakes). Channel catfish were immersed in a buffered solution of oxytetracycline (OTC) and stocked in October 2010 at lakes Greenleaf and Lone Chimney. The higher relative abundance of resident channel catfish in Lake Lone Chimney may have affected survival and growth of stocked fish. Stocking contribution at Lake Lone Chimney was low (~30%) compared to Lake Greenleaf (~98%). Fish stocked in Greenleaf reached an average length of 348 mm two years post-stock, whereas fish stocked in Lone Chimney grew to 240 mm, an increase by only 62 mm since stocking. To evaluate the full impact of stocking, two reservoirs were no longer stocked as part of an experimental manipulation. Relative abundance, growth, and size structure responded as expected. Cessation of stocking resulted in lower relative abundance, increased growth rates, and larger size structure. Whereas relative abundance increased for one stocked lake (Greenleaf), mean length at age and growth decreased, and size structure shifted to smaller size fish. Results from the multi-scale models indicate significant associations with both near-shore and land-use habitat types. Channel catfish were found at higher abundances in turbid areas with rock and coarse-woody debris, and a negative relationship was evident with aquatic vegetation, residential development and agriculture land-use. Trophic relationships indicated that intra-specific competitive interactions were evident. These results provide further evidence that density-dependent mechanisms likely reduced both survival and growth of stocked fish in Lake Lone Chimney. It also suggests that both habitat and relative stock size should be considered before stocking advanced size fingerlings.

TABLE OF CONTENTS

LIST OF TABLES

Chapter V

LIST OF FIGURES

Chapter III

Chapter IV

LIST OF APPENDICES

CHAPTER I

INTRODUCTION TO THE DISSERTATION

Channel catfish *Ictalurus punctatus* is a common sport fish species found in waterbodies

throughout much of the United States (Hubert 1999). Stocking has become a management staple

used to enhance fisheries that have low natural recruitment due to poor spawning habitat and

because of high susceptibility of stocked fry to predation from predators like largemouth bass

Micropterus salmoides (Marzolf 1957; Santucci et al. 1994). Many state agencies report stocking

channel catfish at a broad range of sizes and densities depending on the type of impoundment

under consideration (Michaletz and Dillard 1999). Stocking fingerlings less than 100 mm total

length (TL) has had the least amount of success so fish are now being reared to greater sizes (>

175 mm TL) in order to increase survival and contribution to the fishery, but this comes at a

significant financial investment by the management agency. Understanding mechanisms that

may influence success or failure of stocking is an imperative part of the management process

because success will likely vary by impoundment. Yet, only a few studies have evaluated

contribution (Siegwarth and Johnson 1998; Odenkirk 2002), others only evaluated mechanistic

relationships (Michaletz 2009), and none have evaluated the effects that stocking may have on

resident populations.

Although stocking fish may increase the local population size, stocking success is often

measured as the number of fish that contributed to both the population and angler harvest.

1

In order to achieve both, mechanisms that influence growth and survival of channel catfish need to be considered during the management process. Reduced growth can increase the time it takes for a fish to recruit to angler harvest and increased mortality can make it uneconomical to continue stocking channel catfish. Although stocking channel catfish at higher than needed rates can increase the size of the local population, mechanisms like availability of suitable habitat or competition can significantly decrease stocking success in light of the increased population size. The inability to correctly identify the consequences associated with stocking channel catfish reflects the paucity of information currently available to fishery scientists.

Channel catfish have long been perceived as a "broad-niched species" that is not generally associated with specific environmental conditions (Layher and Maughan 1985). However, many populations still required supplemental stocking due to the unquestionable lack of spawning habitat (Michaletz 2009), suggesting that habitat still plays a significant role in regulating channel catfish populations. For example, Fischer et al. (1999) found that channel catfish in a small Missouri impoundment exhibited a distribution that was aggregated instead of random, supporting the notion that channel catfish were associated with certain, yet unmeasured environmental conditions. Furthermore, many studies that have examined habitat use of channel catfish have largely ignored scale (Layher and Maughan 1985; Hubert 1999; Phelps et al. 2011) even though observed patterns will likely change with resolution from fine to coarse-scales (Wiens 1989; Miranda and Killgore 2011).

The initial transition from a pellet food diet to natural forage is likely a critical period that contributes to stocking success. Introducing fish that are not locally adapted can experience reduced growth and survival (Caroffino et al. 2008; Araki and Schmid 2010). Thus, intraspecific and interspecific trophic-level interactions likely play a role in survivorship and growth in early life stages of stocked channel catfish. Competitive relationships with other species like bluegill, which shares a similar diet (Mitzner 1989; Michaletz 2006) can affect channel catfish stocking

success. If a competitive (i.e., both intra- and inter-specific) interaction exists, then the intensity of the association should show a density-dependent response following stocking of channel catfish.

Little is known about the ecology and factors that drive stocking success of channel catfish in lentic systems. Thus, the overarching goal of this study was to assess the effectiveness of stocking advanced size channel catfish in medium size Oklahoma reservoirs and determine multiple environmental factors related to success. Using multiple reservoirs, I evaluated these four objectives in subsequent chapters:

- Quantify contribution and fitness components (i.e., growth in length and weight) related to stocking channel catfish.

- Evaluate the effects of a stocking manipulation on channel catfish population characteristics using a before-after-control-impact (BACI) design.

- Determine habitat associations of channel catfish in reservoirs at multiple spatial scales.

- Determine trophic structure of stocked and wild channel catfish in relation to other species comprising a subset of the food web.

REFERENCES

Araki, H., and C. Schmid. 2010. Is hatchery stocking a help or harm? Evidence, limitations and future directions in ecological and genetic surveys. Aquaculture S2-S11.

Carroffino, D. C., L. M. Miller, A. R. Kapuscinski, and J. J. Ostazeski. 2008. Stocking success of local-origin fry and impact of hatchery ancestry: monitoring a new steelhead (*Oncorhynchus mykiss*) stocking programs in a Minnesota tributary to Lake Superior. Canadian Journal of Fisheries and Aquatic Sciences 65:309-318.

Fischer, S. A., S. Eder, and E. D. Aragon. 1999. Movements and habitat use of channel catfish in blue catfish in a small impoundment in Missouri. Pages 239-255 *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.

Hubert, W. A. 1999. Biology and management of channel catfish. Pages 3-22 *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.

Layher, W. G., and O. E. Maughan. 1985. Relations between habitat variables and channel catfish populations in prairie streams. Transactions of the American Fisheries Society 114:771-781.

Marzolf, R. C. 1957. The reproduction of channel catfish in Missouri ponds. Journal of Wildlife Management 21:22-28.

Michaletz, P. H., and J. G. Dillard. 1999. A survey of catfish management in the United States and Canada. Fisheries 24:6-11.

Michaletz, P. H. 2006. Prey resource use by bluegill and channel catfish in small impoundments. Fisheries Management and Ecology 13:347-354.

Michaletz, P. H. 2009. Variable responses of channel catfish populations to stocking rate: density-dependent and lake productivity effects. North American Journal of Fisheries Management 29:177-188.

Miranda, L. E., and K. J. Kilgore. 2011. Catfish spatial distribution in the free-flowing Mississippi River. Pages 521-534 *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.

Mitzner, L. 1989. Assessment of maintenance-stocked channel catfish in Iowa lakes. Iowa Department of Natural Resources, Federal Aid in Sport Fish Restoration, Completion Report F-94-R-8. Des Moines, IA: Iowa Department of Natural Resources, 32 pp.

Odenkirk, J. S. 2002. Stocking size and population dynamics of channel catfish in Virginia impoundments. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 56:65-74.

Phelps, Q. E., S. J. Tripp, J. E. Garvey, D. P. Herzog, R. A. Hrabik, D. E. Ostendorf, J. W. Ridings, and J. W. Crites. 2011. Juvenile channel catfish habitat use in the Middle Mississippi River. Pages 535-543 *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.

Santucci, V. J., D. H. Wahl, and T. W. Storck. 1994. Growth, mortality, harvest, and cost-effectiveness of stocked channel catfish in a small impoundment. North American Journal of Fisheries Management 14:781-789.

Siegwarth, G. L., and J. E. Johnson. 1998. Assessment of stocking catchable-size channel catfish

    in the Buffalo River, Arkansas. North American Journal of Fisheries Management 18:96-

    103.

Wiens, J. A., 1989. Spatial scaling in ecology. Functional Ecology 3:385-397.

CHAPTER II

EFFECTIVENESS OF A STOCK ENHANCEMENT PROGRAM USING 178-MM CHANNEL

CATFISH *ICTALURUS PUNCTATUS* IN TWO OKLAHOMA RESERVOIRS

Introduction

Channel catfish *Ictalurus punctatus* natural recruitment is limited in impoundments

because of inadequate spawning habitat and high predation on juveniles (Marzolf 1957;

Krummrich and Heidinger 1973; Spinelli et al. 1985; Storck and Newman 1988; Michaletz et al.

2008). Stock enhancement is the principal management technique used by fishery biologists to

establish or sustain channel catfish stocks (Michaletz and Dillard 1999). Evaluation of these

hatchery-release programs have indicated mixed success (Siegwarth and Johnson 1988; Odenkirk

2002). Stocking small fry (< 100 mm total length (TL)) tends to be less successful because

vulnerability to predation is high (Michaletz et al. 2008). To reduce the influence of recruitment

bottlenecks that limit survival and contribution to the fishery (Michaletz 2009), management

agencies produce advanced-size fingerlings (> 175 mm TL), but this comes at a huge investment

by the management agency.

The reliance on expensive stocking programs has prompted many agencies to evaluate

the efficiency of stocking to ensure it improves the fishery. Much of the existing information on

channel catfish stocking programs has only been evaluated in small impoundments (< 200 ha),

requiring stocking relatively few fish (Santucci et al. 1994; Shaner et al. 1996; Michaletz and

Stanovich 2005; Michaletz et al. 2008; Michaletz 2009). Stocking success was quantified by subsequently sampling fish populations, assessing angler success, and looking for pre- and post-stocking changes. This information is not easily extrapolated to larger systems and the lack of information on the fate of stocked fish (e.g., survival and growth; which is dependent on the ability to accurately distinguish between hatchery and wild fish) is needed to quantify success in order to refine stock enhancement programs (Blankenship and Leber 1995; Lorenzen 2005).

Batch-marking fish using oxytetracycline (OTC; $C_{22}H_{24}N_2O_9 \cdot HCL$) has been an effective technique to distinguish between stocked and wild fish for many species (e.g., walleye *Sander vitreus* (Brooks et al. 1994), striped bass *Morone saxatilis* (Secor et al. 1991), crappie *Pomoxis* spp. (Isermann et al. 2002), and yellow perch *Perca flavescens* (Brown et al. 2002)), but has rarely been used for ictalurids (i.e., Murie et al. 2006; Stacell and Huffman 1994). Of the two studies that have applied OTC to ictalurids, only one used the chemical to identify marked fish (Murie et al. 2006), and the other evaluated the susceptibility to photosensitivity in channel catfish after administering OTC interperitoneally (Stacell and Huffman 1994). Both of these studies handled the fish individually; however, Stewart and Long (2011) successfully marked 100% of channel catfish fingerlings using OTC immersion, demonstrating the potential to batch-mark multitudes of fish that can be used to quantify stocking success on a much larger scale.

In this chapter I evaluate the effects of a single stocking event using advanced size (~178 mm TL) channel catfish. The objectives of this study were to (1) evaluate the use of OTC as a technique to identify channel catfish, (2) quantify the contribution of hatchery-released fish to the resident population, (3) and estimate growth (i.e., length and weight) of stocked fish.

Study Site

The study reservoirs were selected because they qualified for stocking based on Oklahoma Department of Wildlife Conservation (ODWC) criteria. The criterion is based on

channel catfish catch rate information from annual ODWC experimental gill net surveys. The

two reservoirs selected for this study were lakes Lake Lone Chimney (223 ha) and Greenleaf (372

ha). Lake Lone Chimney is a eutrophic reservoir in Pawnee County, Oklahoma, with 27 km of

shoreline, and has an average Secchi depth of 46 cm, and a maximum depth of 42 m (OWRB

2011; Figure 1). Lake Greenleaf is a eutrophic reservoir located in Muscogee County, Oklahoma,

with 29 km of shoreline, an average Secchi depth of 84 cm, and a maximum depth of 40 m

(OWRB 2011; Figure 1). Neither reservoir has been stocked with channel catfish since 1997.

Methods

Approximately 44,000 channel catfish fingerlings (~100 mm TL) were marked with OTC

by immersion at Byron Fish Hatchery following methods of Stewart and Long (2011). Briefly,

this process involved four interconnected tanks (1,420 L) with a re-circulating system to agitate

the water and reduce waste build up. Channel catfish were randomly divided among four tanks

and immersed for 6 h in a 700-mg L^{-1} solution of OTC hydrochloride, buffered to a pH of 7.0

with sodium phosphate (dibasic, Na_2HPO_4), and covered with a tarp to prevent degradation of the

OTC (Choate 1964; Trojnar 1973; Kayle 1992).

After immersion, tanks were assessed to quantify marking mortality determined as the

number of observed dead. Live fish were moved to outside ponds until reaching an average total

length of 178 mm (approximately 150 d old, 30 d post-marking) and stocked in lakes Lone

Chimney ($N = 16,836$; 75.5 ha^{-1}) and Greenleaf ($N = 20,513$; 55.1 ha^{-1}) in October 2010 at rates

determined by Oklahoma Department of Wildlife Conservation. Fifty fish from the transport

tanks were obtained at the time of stocking to verify OTC mark presence. Lapilli otoliths (Long

and Stewart 2010) were removed, embedded in epoxy, mounted on slides, and sanded to the core

following methods by Stewart et al. (2009). Un-marked otoliths from age-0 channel catfish ($N =$

50) were randomly mixed with the otoliths from marked fish to act as a control to estimate

9

marking efficacy. Each otolith was observed for an OTC mark with an epi-fluorescent compound microscope (Motic BA 400T-FL, Motic Incorporation LTD, Hong Kong) equipped with a 100-W ultraviolet (Hg arc) light source and fluorescent filter (495 dichroic mirror, 470 excitation filter, and 515-nm IF barrier filter).

To estimate stocking contribution, channel catfish populations in each reservoir were sampled from May to August 2011 and 2012 using tandem hoop nets (three nets per series, each 3.4-m long with 25-mm-bar mesh and seven 0.8-m hoops that tapered toward the cod end [Miller Net and Twine Co., Inc., Memphis, Tennessee]). The throats were constricted to prevent fish escapement by using nylon zip ties (Porath et al. 2011), and set at 16 randomly selected sites (Figure 1) (Stewart and Long 2012). Nets were fished parallel to shore at depths less than 4 m, baited with 1 kg of ground cheese logs (Boatcycle, Inc., Henderson, Texas) and left undisturbed for 72 h. Captured channel catfish were measured (nearest mm), weighed (nearest g), and otoliths were removed from up to 200 systematically selected individuals (every 5th fish measuring less than 325 mm in 2011 and 400 mm in 2012) to determine origin (i.e., wild or stocked). The threshold size of fish selected for OTC determination was increased in 2012 to account for growth between sampling years. Otoliths were examined twice by a single reader in random and non-consecutive order to determine OTC mark presence. If the first two examinations disagreed, a third examination was made. Mark longevity was also evaluated and defined as the time in weeks between the time fish were marked and capture in the wild (Isermann et al. 2002).

Mark detection can be significantly influenced by factors like reader experience, number of read attempts, and fading of OTC rings as time since marking increases. Therefore, mark detection rate was determined from a mixed sample containing 50 marked otoliths and 50 unmarked otoliths of similar aged fish. Known marked otoliths and unmarked otoliths were incidentally discarded during a lab move and not available during this time. The next best option was to use otoliths collected from fish one-year post-mark (deemed by the author as having a

visible OTC ring). This method, although atypical, is still useful and accounts for fading of the OTC ring over time, which is not accounted for when evaluating otoliths from recently marked fish. Mark detection of "good" otoliths was determined by two individuals (Reader 1 had 7 years of experience and Reader 2 had < 1 year of experience) who independently assessed the mixed sample three times. The estimates from the lesser experienced reader, coupled with estimates from the experienced reader, were used in an attempt to simulate the potential range of the mark detection probability. Reader experience was used to calculate a weighted average detection rate. Thus, overall average detection rate probability (P_{beta}) was formulated using a likelihood function,

$$f\left(P_{beta} \mid \alpha, \beta\right) = \frac{\Gamma\left(\alpha + \beta\right)}{\Gamma\left(\alpha\right)\Gamma\left(\beta\right)} P^{\alpha-1}\left(1 - P\right)^{\beta-1}$$

which was formulated as the probability density function of a beta distribution (Hutchings 2005), defined by the boundary of $0 \leq P \leq 1$ (Forbes et al. 2011). The $\Gamma(x)$ is the gamma function that acts as a normalizing constant that bounds the total probability to one. The shape parameters ($\alpha = 67.01, \beta = 2.31$) define the shape of the curve and were maximum likelihood estimates obtained by fitting the distribution to the weighted average detection estimates.

The proportion of marked fish (i.e., stocked) in the sub-sample, after correcting for detection probability, was then applied to the entire sample at individual 1-cm length bins. Relative contribution (% stocked) was then determined using the equation (Cook and Lord 1978; Brown and Sauver 2002):

$$C = \left(M \Big/ \left(T \times P_{beta}\right)\right) \times 100$$

where C is the estimated stocking contribution (%), M is the number of marked fish in the sample, T is the total number of fish in the sample, and P_{beta} is the weighted average detection rate probability.

Growth of stocked channel catfish in each reservoir was expressed using mean total length from the time fish were marked, stocked, and captured during the sampling periods. Growth in length was expressed using a von Bertalanffy growth model (Ricker 1975):

$$L_a = L_\infty \left(1 - \exp\left(-k \left(Age_i - t_0 \right) \right) \right),$$

where L_a is the predicted length at age, L_∞ is the theoretical maximum size, k is the Brody-growth coefficient, and t_0 is theoretical time at age zero. The variation, σ^2, in the model was associated with variability in observed length (l_a) and the parameters (i.e, L_∞, k, and t_0) were maximum likelihood estimates and the error distribution was assumed to be normally distributed.

Data Analysis

To determine if population indicators like mean length of the entire sample or performance (i.e., relative contribution and growth (length and weight)) of stocked fish differed between impoundments, repeated measures analyses using generalized least-square (GLS) models were used (*gls* function within the *nlme* package in R; Pinheiro et al. 2011). Prior to analysis, data were transformed to meet assumptions of normality. Relative contribution (%) was arcsine-square root transformed, relative abundance was $\log_{10}(catch + 1)$ transformed, and mean length and weight was $\log_{10}$-transformed. Models were structured to analyze fixed effects of reservoir, year, and a two-way reservoir $\times$ year interaction. The temporal heterogeneity in the variance structure of month within year was accounted for using an autoregressive-1 covariance structure. All analyses were conducted using R program (R Development Core Team 2005).

Results

Initial survival during the immersion period was estimated to be 100%. All channel catfish collected at time of stocking ($N = 50$) were marked and averaged 180.8 mm TL (SD = 4.8). Post-stocking OTC detection probabilities after one year ranged from 97% to 98% for

12

Reader 1 and 91% to 93% for Reader 2. The overall weighted average detection probability was 97% and was used to correct stocking contribution estimates.

Contribution estimates were variable between reservoirs, ranging from 3% to 98% (Figure 2 to 4). Contribution from stocking was generally greater in Lake Greenleaf (84% to 98%) than Lake Lone Chimney (4% to 35%) ($F_{1,13} = 231.41$, $P < 0.001$), despite the higher stocking rate used in Lake Lone Chimney. Contribution estimates in 2011 increased from 3% to 28% in Lake Lone Chimney, whereas, contribution increased from 84% to 98% in Lake Greenleaf. Contribution estimates did not increase between 2011 and 2012 ($F_{1,13} = 1.63$, $P = 0.26$) and the interaction between reservoir and year was not significant ($F_{1,12} = 2.26$, $P = 0.16$).

Catch rates of channel catfish in both reservoirs were variable (Figure 5) but overall higher in Lake Lone Chimney ($N = 7,348$) than Lake Greenleaf ($N = 2,262$) ($F_{1,252} = 94$, $P = 0.001$). Catch rates did not increase in concert with increased contribution of stocked fish between 2011 and 2012 ($F_{1,253} = 0.69$, $P = 0.41$), and the interaction between lake and year was not significant ($F_{1,252} = 0.01$, $P = 0.94$). At Lake Lone Chimney, the month to month variation in mean relative abundance was high and changed by 42% in some cases and ranged from 33 to 81 fish per series. At Lake Greenleaf, catch rates initially increased and remained consistent in 2011, a trend was not evident in 2012.

There was a significant reservoir by year interaction for overall mean length of channel catfish caught in hoop net samples ($F_{1,12} = 19.31$, $P < 0.001$). The average length of channel catfish caught was different between reservoirs in both years and declined in both lakes from May to August 2011 (Figure 6). At Lake Greenleaf, average length was higher in 2012 than 2011 (Tukey HSD, $P < 0.05$). Average length of fish increased from 260 mm to 345 mm from August 2011 to May 2012, whereas mean length continued to decline at Lake Lone Chimney (Tukey HSD, $P < 0.05$).

Regarding stocked fish only, growth in length was greater in Lake Greenleaf then Lake Lone Chimney (Figure 3, 4, and 7). The significant reservoir by year interaction ($F_{1,12} = 21.26$, $P < 0.001$) was attributed to channel catfish stocked in Lake Greenleaf. Both reservoirs were stocked with fish that averaged 180 mm TL in October 2010, but average length of stocked fish in Lake Greenleaf was greater than those stocked in Lake Lone Chimney by May 2011. Mean length of stocked fish in Lake Lone Chimney did not change from August 2011 to May 2012 (Tukey HSD, $P > 0.05$), indicating no growth during that period compared to stocked fish at Lake Greenleaf, where length increased from 2011 to 2012 (Figure 3, 4, and 7) (Tukey HSD, $P < 0.05$).

Similarly, average weight of stocked fish in Lake Greenleaf was significantly greater than those stocked in Lake Lone Chimney by May 2011 (Figure 8). The significant reservoir by year interaction ($F_{1,12} = 110.77$, $P < 0.001$) was attributed to channel catfish stocked in Lake Greenleaf. Overall, average weight of stocked fish in Lake Lone Chimney and Lake Greenleaf increased by 21 g and 146 g from May 2011 to August 2011. Average weight did not increase for stocked fish in Lake Lone Chimney (Tukey HSD, $P > 0.05$), compared to fish stocked at Lake Greenleaf (Tukey HSD, $P < 0.05$).

Discussion

This is the first study that has evaluated the direct contribution of OTC marked channel catfish to a larger impoundment (> 100 ha). The ability to use OTC to mass-mark channel catfish fingerlings was critical to the success of this project, and the utility was similar to that reported for scaled freshwater fish species (Brooks et. al. 1994; Unkenholz et al. 1997; Heidinger and Brooks 1998; Isermann et al. 2002; Jenkins et al. 2002; Hoffman and Bettoli 2007; Colvin et al. 2008). Marking success was high (100%) and although not directly assessed, OTC mark quality appeared good throughout my two year study period, similar to what has been found with other species (Secor et al. 1991; Brooks et al. 1994; Unkenholtz et al. 1997; Isermann et. al. 2002). As

a result of my OTC marking trials, a new avenue of experimental research on channel catfish should be available for other researchers to pursue. Moreover, by marking and directly following OTC marked fish, new insights into channel catfish stocking programs became apparent.

Estimates of stocking success for channel catfish stocked in larger impoundments are largely lacking, which is surprising because channel catfish is one of the most stocked species in the US (Michaletz and Dillard 1999). For example, studies in small (< 65 ha) impoundments in Virginia reported contribution rates from 0-91% (Odenkrik 2002). Alternatively, contribution in the Buffalo River, Arkansas was 40% (Siegwarth and Johnson 1998). These estimates suggest that a one-size-fits-all stocking agenda is impractical. Moreover, the primary difference between two reservoirs in my study appeared to be the abundance of wild channel catfish suggesting that density-dependent effects can regulate recruitment dynamics of stocked channel catfish (Michaletz 2009). This is not surprising given that factors like predation, competition, and habitat can be important variables that likely affect performance of stocked fish (Blankenship and Leber 1995).

Growth is important for survival of stocked fish because vulnerability to predation is significantly reduced when growth is fast (Schlosser 1987; Jenkins et al. 1999; Mathews et al. 2001). The reduced growth of stocked fish at Lake Lone Chimney relative to Lake Greenleaf was surprising because both impoundments were eutrophic (52 and 53 TSI; OWRB 2006) with apparently similar fish communities. Most likely, resources could have become limiting at Lake Lone Chimney as a result of stocking, which increased intraspecific interactions (Michaletz 2006; Michaletz 2009). The high density of wild channel catfish at Lake Lone Chimney went undetected in previous assessments by the ODWC, probably a result of habitat and sampling interactions, making it seem appropriate for stocking at that time. The ODWC's standard protocol used gill nets for sampling channel catfish, which underestimates small fish (Sullivan and Gale 1999; Michaletz and Sullivan 2002). Complicating those previous estimates, Lake Lone

Chimney has a preponderance of standing timber habitat where it is difficult to properly set gill nets but relatively easy to set tandem hoop nets used in this study. Regardless, Lone Chimney clearly had a resident channel catfish population that made it difficult for stocked channel catfish to integrate and recruit to the adult population, which seems to best account for the difference in outcomes between the two reservoirs in this study. Future studies on the trophic ecology of stocked channel catfish would be useful to assess competitive potential in reservoirs.

An interesting, yet ancillary finding, was the pattern of average length and weight of stocked fish in Lake Greenleaf between June and July. Length-at-maturity for channel catfish is approximately 300 mm TL (Hesse et al. 1982; Hubert 1999; Stewart *In Press*), which was the size that stocked fish in Lake Greenleaf was approaching in May 2012. Plausibly, the consistent decline in body weight without decline in total length in July could suggest that stocked fish in Lake Greenleaf were maturing and spawning as soon as one year post-stocking, although I have no evidence to support this besides patterns in declining weight.

Stocking success was poor at Lake Lone Chimney compared to Lake Greenleaf and an approach that considers ecological patterns could help optimize stocking efforts (Blankenship and Leber 1995; Lorenzen 2005; Lorenzen et al. 2010). This would also require catch rates that are consistent and reflect population changes so that trends can be identified (e.g., Price and Peterson 2010). Many gear efficiency studies have indicated that hoop nets can provide precise estimates of relative abundance of channel catfish (Michaletz and Sullivan 2002; Flammang and Schultz 2007; Flammang et al. 2011; Neely and Dumont 2011; Richters and Pope 2011; Wallace et al. 2011; Stewart and Long 2012). Capture efficiency (calculated from mark-recapture estimates) is generally consistent during the summer sampling periods (Buckmeier and Schlechte 2009), but these estimates may reflect only the fraction of the population that was susceptible to capture (Vokoun and Rabeni 1999). Because in this study, catch rates were variable and the fluctuations could not be precisely identified. Management assessments that rely only on relative abundance

trends could be misguided by trends caused by changes in catchability rather than actual

population changes. Future studies that evaluate catchability instead of efficiency (or precision)

are needed because relative abundance from hoop nets has limited potential to be an indicator to

quantify stocking success.

Moreover, my results suggest that trends in mean total length cannot be used to measure

success of stocking. Hypothetically, one could look at the trends in mean total length and

conclude that the stocking was successful at Lake Lone Chimney because mean total length

declined over time after fish were stocked. This would suggest that stocked fish, which were

relatively small, were contributing more to the catch and reducing overall mean total length. In

fact, however, because we could identify stocked fish with OTC rings, we know the exact

opposite effect occurred where stocked fish comprised a relatively small proportion of the total

population (3-35%). Furthermore, I would conclude that the stocking program at Lake Lone

Chimney should not be repeated because those fish were unable to acclimate to their environment

and grow to a harvestable size within a reasonable time frame. The high success of OTC marking

found by this study should be a robust tool that will allow fishery managers to better assess their

stocking program.

REFERENCES

Blankenship, H. L., and K. M. Leber. 1995. A responsible approach to marine stock enhancement. American Fisheries Society Symposium 15:67-175.

Brooks, R. C., R. C. Heidinger, and C. C. Kohler 1994. Mass-marking otoliths of larval and juvenile walleye by immersion in oxytetracycline, calcein, or calcein blue. North American Journal of Fisheries Management 14:143-150.

Brown, M. L., J. L. Powell, and D. O. Lucchesi. 2002. In-transit oxytetracycline marking, non-lethal mark detection, and tissue residue depletion in yellow perch. North American Journal of Fisheries Management 22:236-242.

Brown, M. L., and T. St. Sauver. 2002. An assessment of yellow perch, *Perca flavescens*, stocking contributions in eastern South Dakota. Fisheries Management and Ecology 9:225-234.

Buckmeier, D. L., and J. W. Schlecte. 2009. Capture efficiency and size selectivity of channel catfish and blue catfish sampling gears. North American Journal of Fisheries Management 29:404-416.

Choate J. 1964. Use of tetracycline drugs to mark advanced fry and fingerling brook trout (*Salvelinus fontinalis*). Transactions of the American Fisheries Society 93:303-311.

Colvin, N. E., C. L. Racey, and S. E. Lochmann. 2008. Stocking contribution and growth of largemouth bass stocked at 50 and 100 mm into backwaters of the Arkansas River. North American Journal of Fisheries Management 28:434-441.

Cook, R. C., and G. E. Lord. 1978. Identification of stocks of Bristol Bay sockeye salmon
Oncorhyncus nerka, by evaluating scale patterns with a polynomial discriminant
function. Fishery Bulletin 76:415-423.

Forbes, C., M. Evans, N. Hastings., and B. Peacock. 2011. Statistical Distributions, 4th edition.
John Wiley & Sons Inc., Hoboken, New Jersey.

Flammang, M. K., and R. D. Schultz. 2007. Evaluation of hoop-net size and bait selection for
sampling channel catfish in Iowa impoundments. North American Journal of Fisheries
Management 27:512-518.

Flammang, M. K., R. D. Schultz, and D. N. Cashatt. 2011. Utility of Tandem hoop nets for
indexing channel catfish structure and growth. Pages 545-555 *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.

Heidinger, R. C., and R. C. Brooks. 1998. Relative survival and contribution of saugers stocked
into the Peoria Pool of the Illinois River, 1990-1995. North American Journal of
Fisheries Management 18:374-382.

Hesse, L. W., Q. P. Bliss, and G. J. Zuerlein. 1982. Some aspects of the ecology of adult fishes
in the channelized Missouri River with special reference to the effects of two nuclear
power generating stations. Pages 225-276 *in* L. W. Hesse, G. L. Hergenrader, S. Lewis,
S. D. Reitz, and A. B. Schlesinger, editors. The Middle Missouri River, Missouri River
Study Group, Norfolk, Nebraska.

Hoffman, K. J., and P. W. Bettoli. 2005. Growth, dispersal, mortality, and contribution of largemouth bass stocked into Chickamauga Lake, Tennessee. North American Journal of Fisheries Management 25:1518-1527.

Hubert, W. A. 1999. Biology and management of channel catfish. Pages 3-22 *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.

Hutchings, J. A., 2005. Life history consequences of overexploitation to population recovery in Northwest Atlantic cod (*Gadus morhua*). Canadian Journal of Fisheries and Aquatic Sciences 62:824-832.

Isermann, D. A., P. W. Bettoli, S. M. Sammons, and T. N. Churchill. 2002. Initial poststocking mortality, oxytetracycline marking, and year-class contribution of black-nosed crappies stocked into Tennessee reservoirs. North American Journal of Fisheries Management 22:1399-1408.

Jenkins, T. M., Jr., S. Diehl, K. W. Kratz, and S. D. Cooper. 1999. Effects of the population density on individual growth of brown trout in streams. Ecology 80:941-956.

Jenkins, W. E., M. R. Denson, C. B. Bridgham, M. R. Collins, and T. I. J. Smith. 2002. Retention of oxytetracycline-induced marks on sagittae of red drum. North American Journal of Fisheries Management 22:590-594.

Kayle, K. A. 1992. Use of oxytetracycline to determine the contribution of stocked fingerling walleye. North American Journal of Fisheries Management 12:353-355.

Krummich, J. T., and R. C. Heidinger. 1973. Vulnerability of channel catfish to largemouth bass predation. Progressive Fish-Culturist 35:173-175.

Long, J. M., and D. R. Stewart. 2010. Verification of otolith identity used by fisheries scientist for aging channel catfish. Transactions of the American Fisheries Society 139:1775-1779.

Lorenzen, K. 2005. Population dynamics and potential of fisheries stock enhancement: practical theory for assessment and policy analysis. Philosophical transactions of the royal society B 360:171-189.

Lorenzen, K., K. M. Leber, and H. L. Blankenship. 2010. Responsible approach to marine stock enhancement: an update. Reviews in Fisheries Science 18:189-210.

Marzolf, R. C. 1957. The reproduction of channel catfish in Missouri ponds. Journal of Wildlife Management 21:22-28.

Mathews, W. J., K. B. Gido, and E. Marsh-Mathews. 2001. Density-dependent overwinter survival and growth of red shiners from a southwestern river. Transactions of the American Fisheries Society 130:478-488.

Michaletz, P. H., and J. G. Dillard. 1999. A survey of catfish management in the United States and Canada. Fisheries 24:6-11.

Michaletz, P. H., and K. P. Sullivan. 2002. Sampling channel catfish with tandem hoop nets in small impoundments. North American Journal of Fisheries Management 22:870-878.

Michaletz, P. H., and J. S. Stanovick. 2005. Relations among angler use, harvest, and stocking rates of channel catfish in Missouri impoundments. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 59:263-272.

Michaletz, P. H., M. J. Wallendorf, and D. M. Nicks. 2008. Effects of stocking rate, stocking size, and angler catch inequality on exploitation of stocked channel catfish in small

Missouri impoundments. North American Journal of Fisheries Management 28:1486-1497.

Michaletz, P. H. 2009. Variable responses of channel catfish populations to stocking rate: density-dependent and lake productivity effects. North American Journal of Fisheries Management 29:177-188.

Murie, D. J., D. C. Parkyn, W. F. Loftus, and L. G. Nico. 2006. Variable growth and longevity of yellow bullhead (*Ameiurus natalis*) in south Florida. Final Report to U.S. Geological Survey, Florida Integrated Science Center, Homestead, FL, pp. 40.

Neely, B. C., and S. C. Dumont. 2011. Effect of soak duration on precision of channel catfish catch with baited, tandem hoop nets. Pages 557-561 *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.

Odenkirk, J. S. 2002. Stocking size and population dynamics of channel catfish in Virginia impoundments. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 56:65-74.

OWRB (Oklahoma Water Resources Board). 2009. Beneficial Use Monitoring Program. OWRB.

http://www.owrb.ok.gov/quality/monitoring/bump/pdf_bump/Current/Lakes/2010-2011_LakesBUMPReport.pdf

Pinheiro, J, D. Bates, S. DebRoy, D. Sarkar, R Development Core Team (2011). nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-98, URL http://CRAN.R-project.org/package=nlme.

Porath, M. T., L. D. Pape, L. K., Richters, K. L. Pope, and M. A. Pegg. 2011. Influence of throat configuration and fish density on escapement of channel catfish from hoop nets. Pages 563-571 *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.

Price, A. L., and J. T. Peterson. 2010. Estimation and modeling of electrofishing capture efficiency for fishes in wadeable warmwater streams. North American Journal of Fisheries Management 30:481-498.

R Development Core Team (2010) R: a language and environment for statistical computing. R foundation for statistical computing. Vienna.

Richters, L. K., and K. L. Pope. 2011. Catch of channel catfish with tandem-set hoop nets and gill nets in lentic systems of Nebraska. Pages 573-580 *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.

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

Santucci, V. J., D. H. Wahl, and T. W. Storck. 1994. Growth, mortality, harvest, and cost-effectiveness of stocked channel catfish in a small impoundment. North American Journal of Fisheries Management 14:781-789.

Schlosser, I. J. 1987. A conceptual framework for fish communities in small warmwater streams. Pages 17-24 *in* W. J. Mathews and D. C. Henins, editors. Community and evolutionary

ecology of North American stream fishes. University of Oklahoma Press, Norman, Oklahoma.

Secor, D. H., M. G. White, and J. M. Dean. 1991. Immersion marking of larval and juvenile hatchery-produced striped bass with oxytetracycline. Transactions of the American Fisheries Society 120:261-266.

Shaner, B. L., M. J. Maceina, J. J. McHugh, and S. F. Cook. 1996. Assessment of catfish stocking in public fishing lakes in Alabama. North American Journal of Fisheries Management 16:880-887.

Siegwarth, G. L., and J. E. Johnson. 1998. Assessment of stocking catchable-size channel catfish in the Buffalo River, Arkansas. North American Journal of Fisheries Management 18:96-103.

Spinelli, A. J., B. G. Whiteside, and D. G. Huffman. 1985. Aquarium studies on the evaluation of stocking various sizes of channel catfish with established largemouth bass. North American Journal of Fisheries Management 5:138-145.

Stacell, M., and D. G. Huffman. 1994. Oxytetracycline-induced photosensitivity of channel catfish. Progressive Fish-Culturists 56:211-213.

Stewart, D. R., G. W. Benz, and G. D. Scholten. 2009. Weight-length relationships and growth data for blue catfish from four Tennessee waterbodies. Proceedings of the Annual Southeastern Association Fish and Wildlife Agencies 63:140-146.

Stewart, D. R., and J. M. Long. 2011. The efficacy of mass-marking channel catfish fingerlings by immersion in oxytetracyline. Proceedings of the Oklahoma Academy of Science 91:31-36.

Stewart, D. R., and J. M. Long. 2012. Precision of channel catfish catch estimates using hoop nets in larger Oklahoma reservoirs. North American Journal of Fisheries Management 32:1108-1112.

Stewart, D. R. *In Press*. Channel catfish *Ictalurus punctatus*. Pages xx-xx in M. Eberle, editor. Fishes of Kansas, University Press of Kansas, Lawrence.

Storck, T., and D. Newman. 1988. Effects of size at stocking on survival and harvest of channel catfish. North American Journal of Fisheries Management 8:98-101.

Sullivan, K. P., and C. M. Gale. 1999. A comparison of channel catfish catch rates, size distributions, and mortalities using three different gears in a Missouri impoundment. Pages 293-300 *in* E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. Chramm, Jr., and T. Coon, editors. Catfish 2000: proceedings of the international symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

Trojnar, J. R. 1973. Marking rainbow trout fry with tetracycline. Progressive Fish-Culturist 31:213-216.

Unkenholtz, E. G., M. L. Brown, and K. L. Pope. 1997. Oxytetracycline marking efficacy for yellow perch fingerlings and temporal assays of tissue residues. Progressive Fish-Culturists 59:280-284.

Vokoun, J. C., and C. F. Rabeni. 1999. Catfish sampling in rivers and streams: a review of strategies, gears, and methods. Pages 271-286 *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.

Wallace, B. C., D. M. Weaver, and T. J. Kwak. 2011. Efficiency of baited hoop nets for
sampling catfish in southeastern U.S. small impoundments. Pages 581-588 *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.
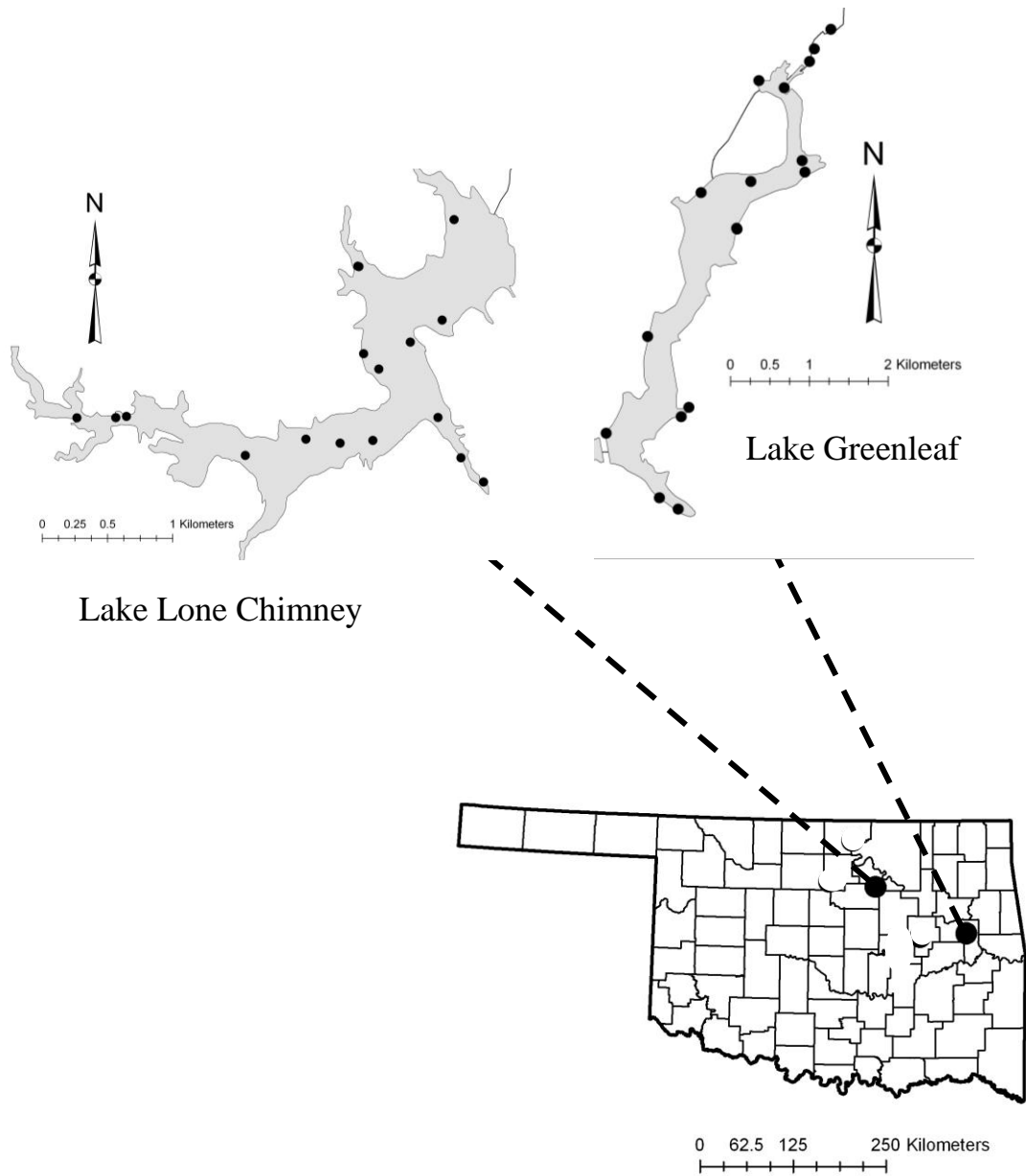
Figure 1. Map and location of lakes Lone Chimney and Greenleaf in Oklahoma.
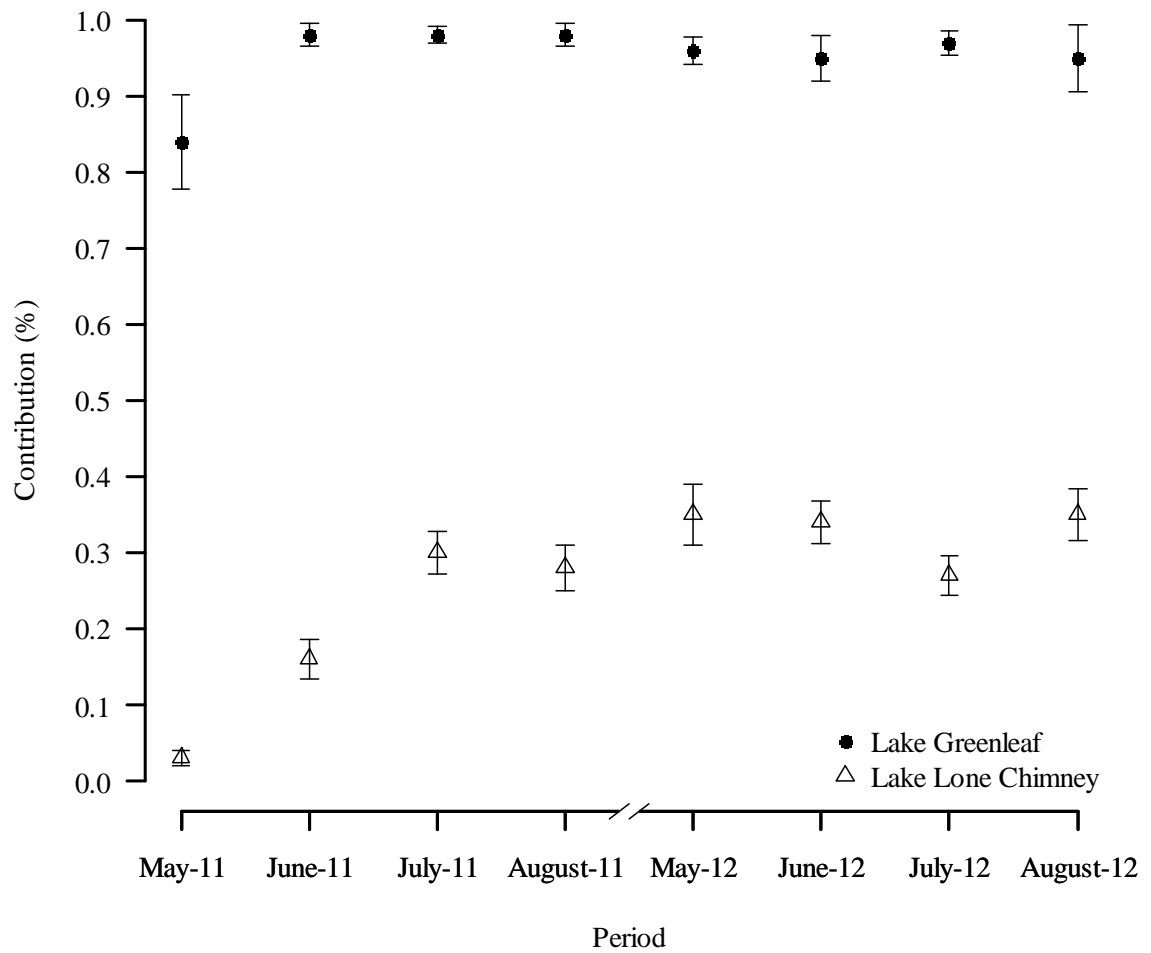
Figure 2. Contribution (%) and confidence intervals (± 95% CI) of stocked channel catfish *Ictalurus punctatus* to the adult populations at lakes Lone Chimney and Greenleaf from May-August, 2011 and 2012.
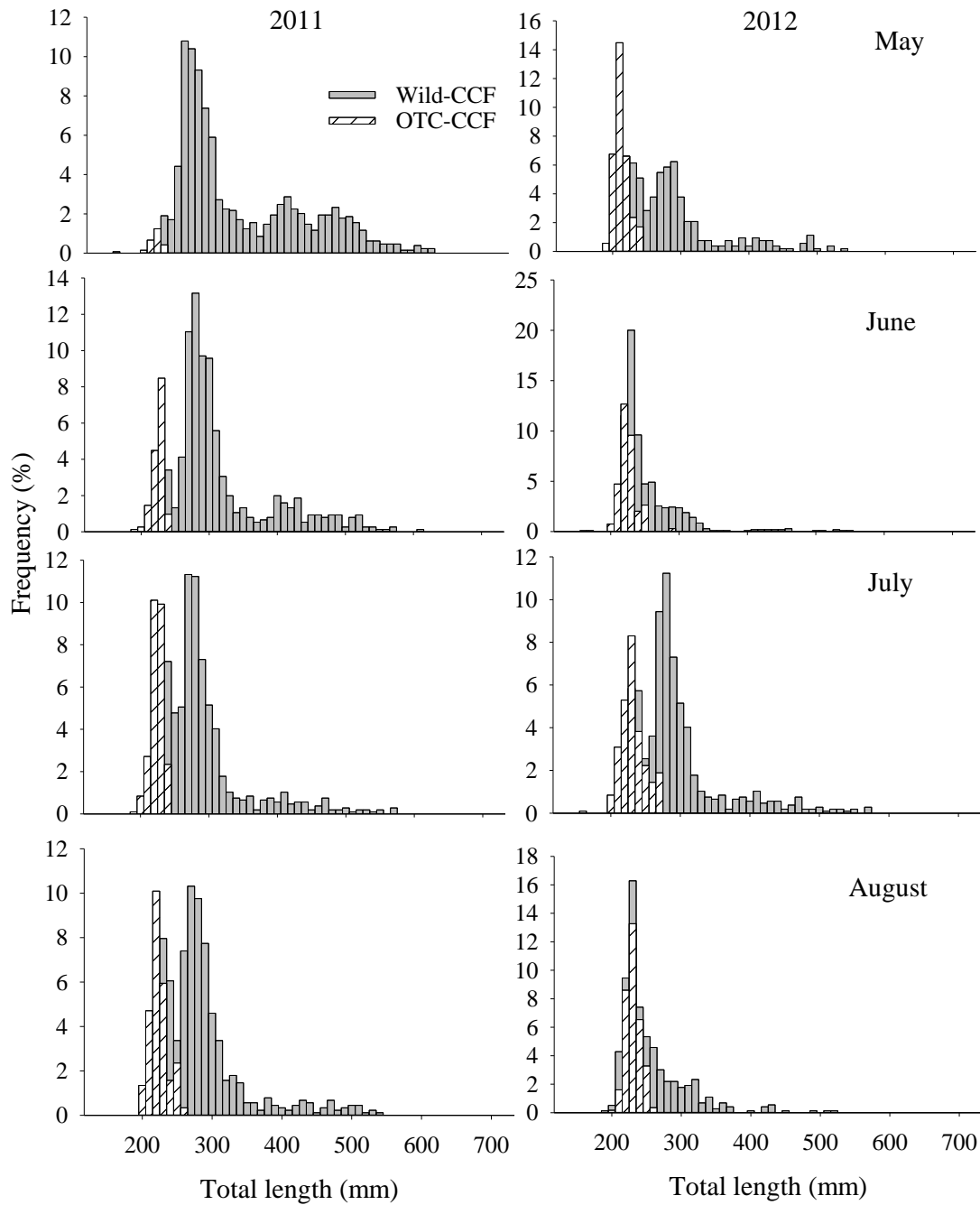
Figure 3. Length frequency distributions of stocked (oxytetracycline (OTC) marked) and wild channel catfish *Ictalurus punctatus* (CCF) in Lake Lone Chimney, Oklahoma (May-August of 2011 and 2012).
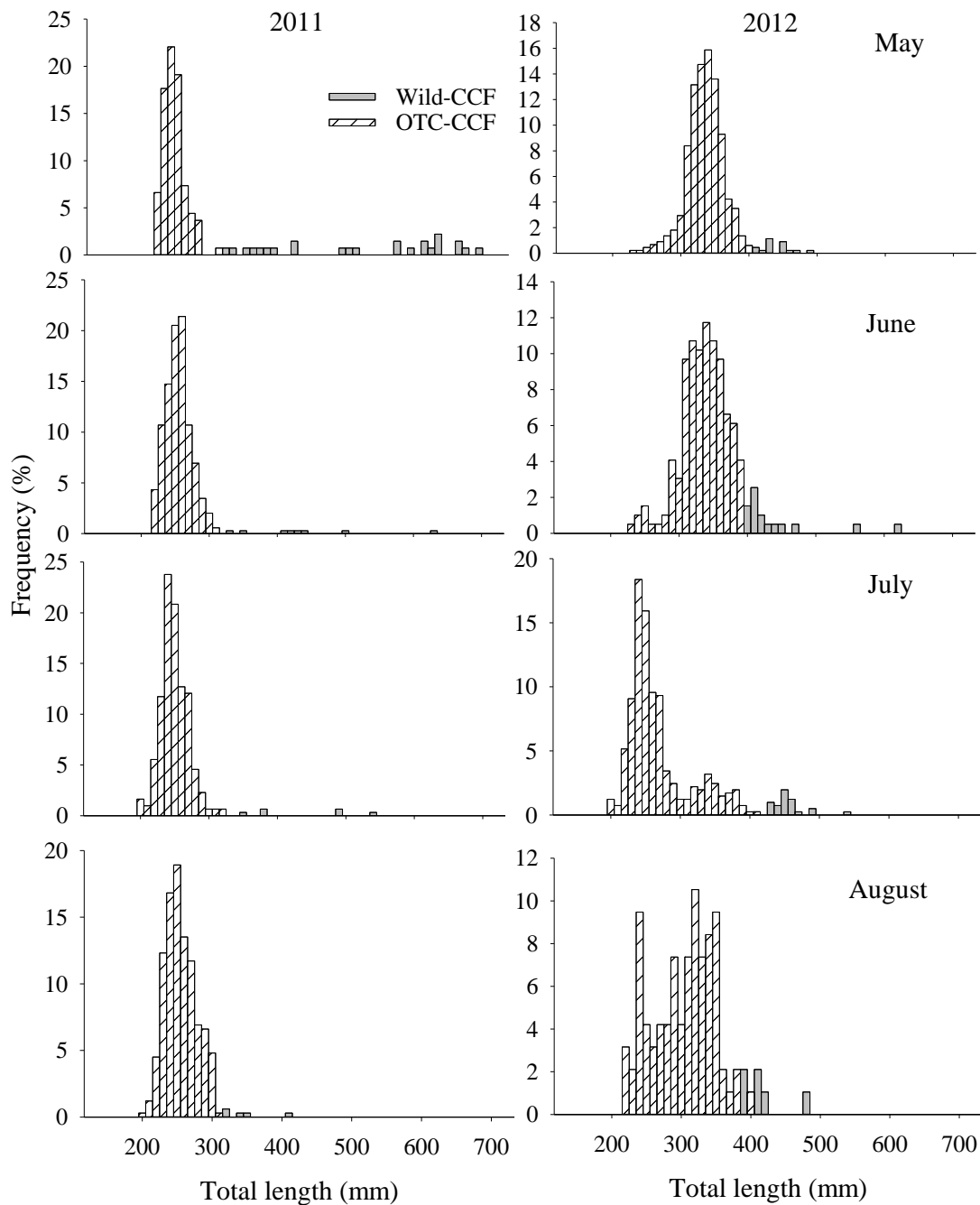
Figure 4. Length frequency distributions of stocked (oxytetracycline (OTC) marked) and wild channel catfish *Ictalurus punctatus* (CCF) in Lake Greenleaf, Oklahoma (May-August of 2011 and 2012).
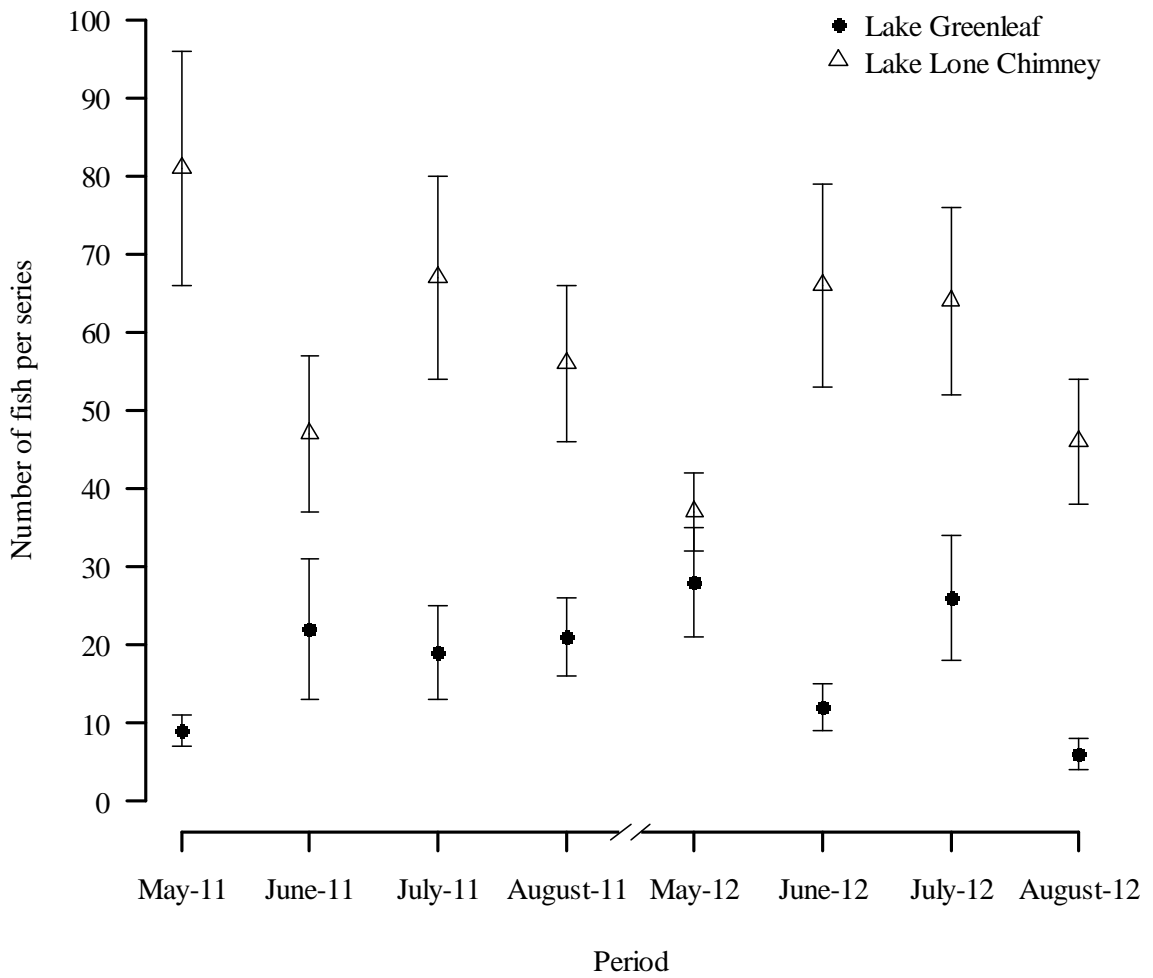
Figure 5. Catch rates (Number of fish per series) and confidence intervals (95% CI) of channel catfish *Ictalurus punctatus* captured at lakes Lone Chimney and Greenleaf in May-August, 2011 and 2012.
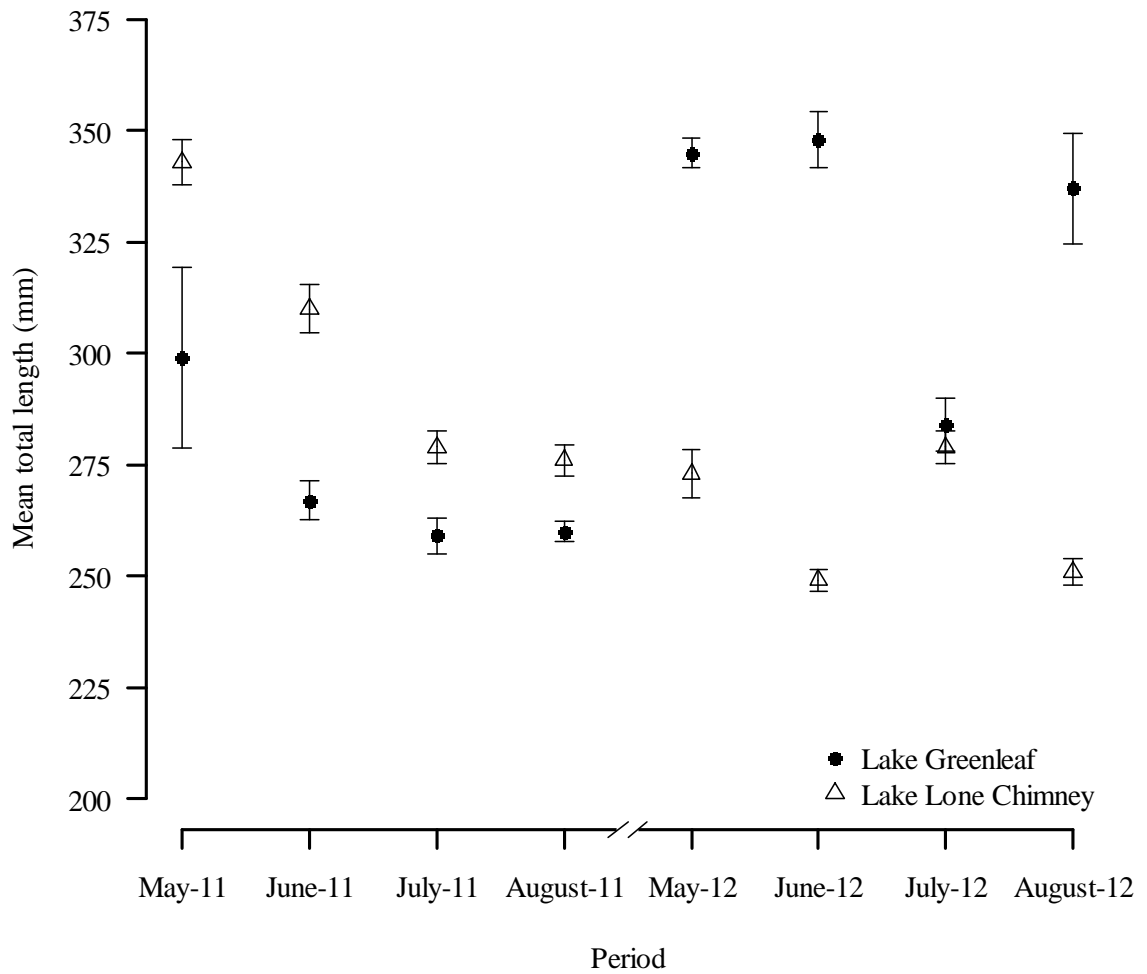
Figure 6. Mean total length (mm) and confidence intervals (95% CI) of channel catfish *Ictalurus punctatus* captured at lakes Lone Chimney and Greenleaf in May-August, 2011 and 2012.
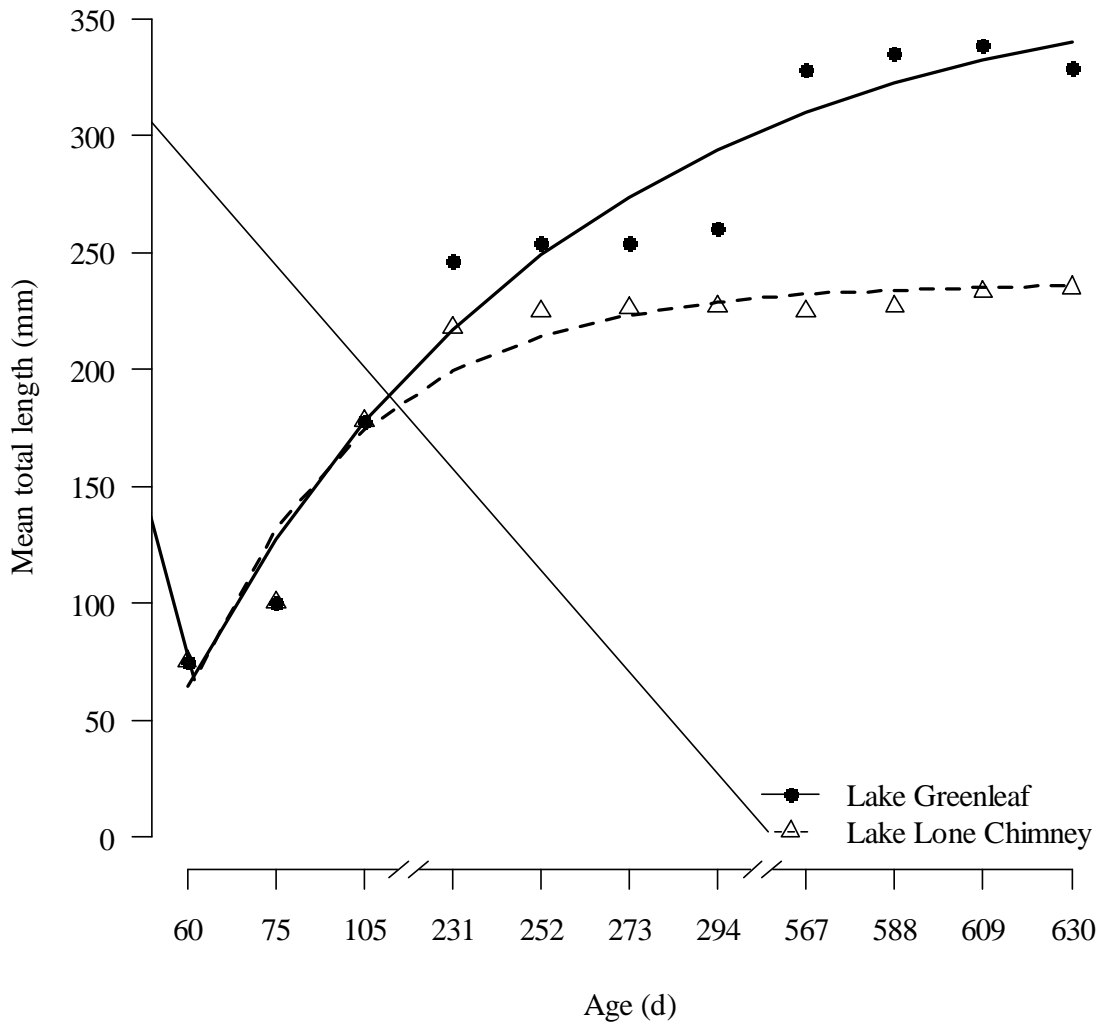
Figure 7. Stocked channel catfish *Ictalurus punctatus* von Bertalanffy growth curves for lakes Lone Chimney ($L_a = 235.7[1\text{-exp}(-0.012(Age_i - 0.0000064))]$) and Greenleaf ($L_a = 346.5[1\text{-exp}(-0.005(Age_i - 0.000027))]$).
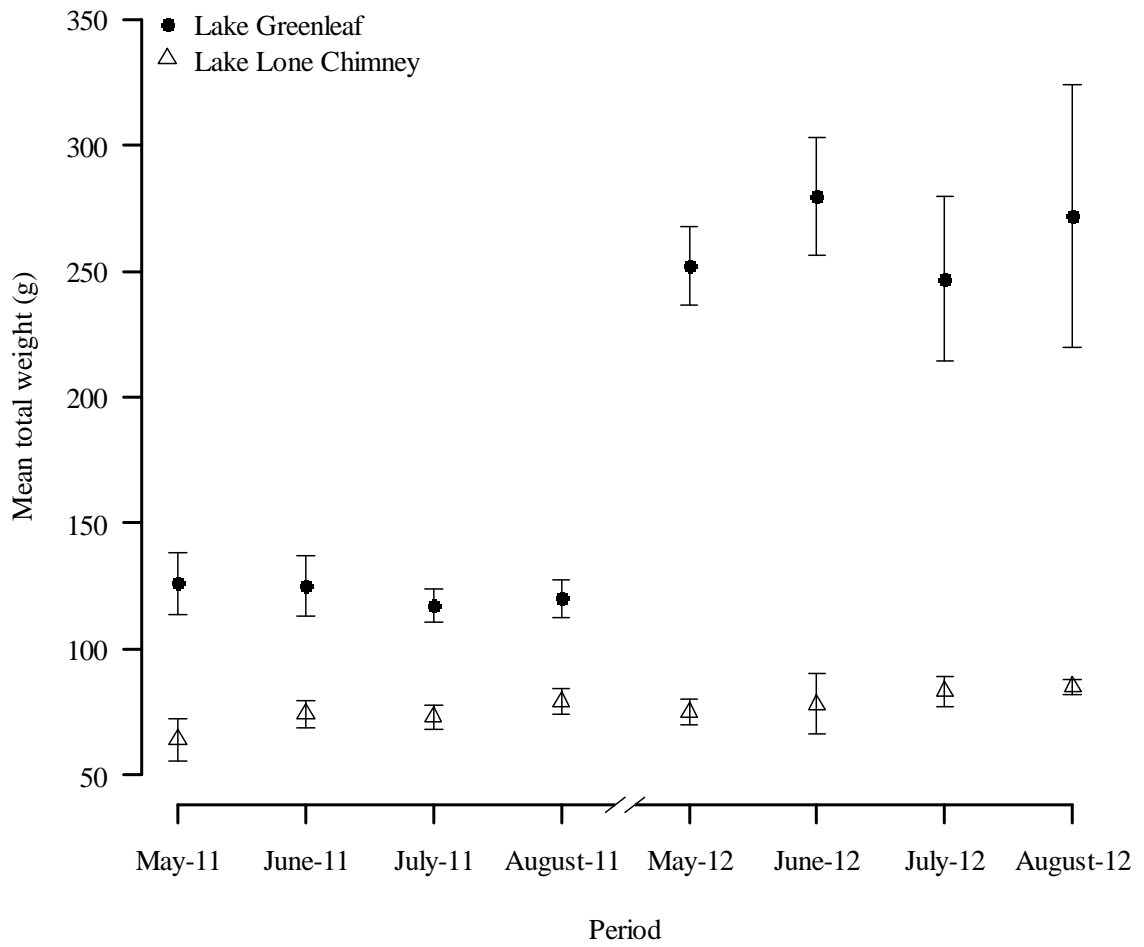
Figure 8. Mean total weight (g; ± 95% confidence intervals) of stocked channel catfish *Ictalurus punctatus* collected from lakes Lone Chimney and Greenleaf in May to August, 2011 and 2012.

CHAPTER III

EXPERIMENTAL STOCKING MANIPULATION OF 178-MM HATCHERY-REARED

CHANNEL CATFISH *ICTALURUS PUNCTATUS* IN SIX OKLAHOMA RESERVOIRS

Introduction

Artificial propagation is a management option employed to enhance many freshwater fish populations because of low natural reproduction (Michaletz and Dillard 1999). Stocking can provide fish for harvest in systems that naturally could not support a self-sustaining population (Michaletz and Dillard 1999). In particular, channel catfish *Ictalurus punctatus* populations are often not self-sustaining because of limited spawning habitat and heavy predation from species like largemouth bass *Micropterus* salmoides (Marzolf 1957; Krummrich and Heidinger 1973; Mestl 1983; Powell 1976; Michaletz et al. 2008). The financial investment of hatchery programs can be immense but many agencies continue to invest resources into stock enhancement methods without fully understanding factors influencing stocking success (i.e., recruitment and growth).

It is widely accepted that size at stocking influences the success of channel catfish stock enhancement programs. In general, stocking fry is the least effective (Mestl 1983; Dudash and Heidinger 1996; Howell and Betsill 1999). Stocking density has often been associated with angling success by assuming more fish stocked equals more fish caught (Michaletz and Stanovich 2005), likely resulting in overstocking in many situations. Tradeoffs between size at stocking

and survival can lead to density-dependent effects but many studies have only evaluated stocking in small impoundments (Howell and Betsill 1999; Mitzner 1999; Jackson and Francis 1999; Michaletz 2009). Little information exists on how channel catfish fisheries respond to stocking in larger reservoirs.

Understanding factors that influence both hatchery and wild fish is a critical component of population augmentation (Lorenzen 2005). Responsibly enhancing fisheries requires a holistic understanding that rarely exists in freshwater stocking programs (Cowx 1994). For instance, the few existing studies evaluating channel catfish stocking were conducted in systems that had been repeatedly stocked (e.g., Mitzner 1999; Michaletz 2009). Factors that influence hatchery fish or effects of stocking on wild conspecifics can not be evaluated using that experimental design. Additionally, few studies have determined the impact of stocking channel catfish from a single first time stocking event nor has any study evaluated the response of stocked populations when stocking is discontinued, which is equally important to understand (Blankenship and Leber 1995).

The lack of monitoring and failure to quantify recruitment success or failure of hatchery-released fish is the primary reasons for mixed success of stocking programs (Richards and Edwards 1986; Blankenship and Leber 1995). Experimental manipulation that evaluates both the impact of stocking fish and the response because of cessation of stocking would be useful to fisheries managers. This experimental design is important because it fully examines the range of effects that could occur with respect to density-dependent mechanisms (e.g., intraspecific competition). In this chapter, the effects of both stocking and cessation of stocking advanced size (~178 mm TL) channel catfish fingerlings under a typical regime employed by a state natural resource agency were investigated.

Study Site

Six study reservoirs were located throughout north-central and eastern Oklahoma (Figure 1). Lakes McMurtry (465 ha) and Ponca (326 ha) were eutrophic (57 TSI) with average Secchi depths of 47- and 78-cm (OWRB 2011). These two reservoirs had naturally high relative abundances of channel catfish (ODWC, unpublished data), and served as "control" reservoirs. Lakes Okemah (270 ha) and Okmulgee (270 ha) were mesotrophic (46 and 48 TSI) with average Secchi depths of 78- and 116-cm (ORWB 2011), and had artificially high relative abundances of channel catfish, the result of years of repeated stocking (ODWC, unpublished data). Lakes Lone Chimney (223 ha) and Greenleaf (372 ha) were eutrophic (53 and 52 TSI) with average Secchi depth of 67- and 111-cm (ORWB 2011) and supported low numbers of channel catfish (ODWC unpublished data) and had not been stocked since 1997.

Methods

The overall study design involved sampling for channel catfish in all reservoirs for three years, one year before stocking manipulation and two years after. The control lakes were not manipulated whereas the lakes with artificially high channel catfish numbers had their stocking program halted and the two lakes with naturally low numbers of channel catfish were stocked in 2010. Channel catfish fingerlings (~178 mm TL) were reared at Byron Fish Hatchery and stocked in lakes Lone Chimney ($N = 16,836$; 75.5 ha^{-1}) and Greenleaf ($N = 20,513$; 55.1 ha^{-1}) in October 2010. Channel catfish populations in all reservoirs were sampled at randomly selected sites with tandem hoop nets (three net per series, each 3.4-m long with 25-mm-bar mesh and seven 0.8-m hoops that tapered toward the cod end [Miller Net and Twine Co., Inc., Memphis, Tennessee]) in May pre- (2010) and post-stocking manipulation (2011 and 2012). The cords of the crow-foot throat for each net were constricted with nylon zip ties to prevent fish escapement (Porath et al. 2011). Each reservoir was sampled using eight hoop net series in 2010 and sixteen

series in 2011 and 2012 to increase precision in relative abundance estimates (Stewart and Long

(2012). Sampling sites remained fixed throughout the duration of the study. Nets were fished

parallel to shore at depths less than 4-m, baited with 1 kg of ground cheese logs (Boatcycle Inc.,

Henderson, Texas) and left undisturbed for 72 h. Captured channel catfish were measured

(nearest mm), weighed (nearest g), and a subsample of ten fish per 25-mm length interval was

sacrificed to obtain otoliths for age estimation.

Several population metrics were estimated at each reservoir each year: growth, size

distribution, body condition (i.e., relative weight), and relative abundance (i.e., catch-per-unit

effort). Age was estimated by counting annuli on lapilli otoliths (Long and Stewart 2010) that

were embedded in epoxy resin, sectioned in the transverse plane and examined under a stereo-

microscope (50× magnification, side illumination) by a single experienced reader (Stewart et al.

2009). Because age estimation is an interpretation of annuli, it is an imperfect measure of true

age (Dortel et al. 2013). To reduce age-estimation error, three independent estimates of the same

otolith were done (random and non-consecutive order) and precision among estimates was

assessed with coefficient of variation (CV).

Because otoliths of each fish were independently read three times and subsequent

interpretation may not always be consistent, growth estimates were modeled using nonlinear

maximum likelihood estimation of the von Bertalanffy growth model (VBGF; Ricker 1975). The

model was formulated to account for both process error (natural variation in length at age) and

observation error (age estimation error) when fitting the growth curve using AD Model Builder

(ADMB: Otter Research Ltd. 2005a):

$$L_i = L_\infty \left(1 - \exp\left[-k\left(T_i - t_0\right)\right]\right)$$

where L_i is the expected length at age for the ith individual, L_∞ is the theoretical maximum

length, k is the Brody growth coefficient, t_0 is theoretical age at length zero, and T_i is the age of

the ith individual (Cope and Punt 2007). The likelihood function for the growth model presented by Cope and Punt (2007) incorporates observation error from the multiple age estimates using a gamma distribution. Gamma distributions are frequently used to describe variation of skewed data sets that have high numbers of nonnegative ($0 \leq t_{ij} < \infty$) low values, and are appropriate for age sample data (Brynjarsdottir and Stefansson 2004). The shape (γ) and scale (β) parameters are greater than zero and the likelihood function is expressed as:

$$L = \prod_{i} \int \frac{1}{\sqrt{2\pi\sigma_{L,i}}} \exp\left[\frac{(l_i - L_i)^2}{2\sigma_{L,i}^2} \right] \prod_{j} \frac{1}{\sqrt{2\pi\sigma_{T,i}}} \exp\left[-\frac{(t_{ij} - T_i)^2}{2\sigma_{T,i}^2} \right] \frac{(T/\beta)^{(\gamma-1)} \exp\left[-(T/\beta) \right]}{\beta\Gamma(\gamma)} dT$$

where $t_{ij} = T_i + e_{T,ij}$, $e_{T,ij} \sim N\left(0, \sigma_{T,i}^2\right)$. The standard deviation of the age estimates for the i_{th} individual, $\sigma_{T,i}$, was based on the assumption that the CV was constant (i.e., $\sigma_{T,i} = CV_T T_i$ (Kimura and Lyons 1991; Piner et al. 2005, 2006; Cope and Punt 2007), estimated *a priori*, and incorporated into the nonlinear mixed effects model using the AD Model Builder RE module (ADMB-RE: Otter Research Ltd. 2005b; Skaug and Fournier 2006). Although autocorrelation exists among parameters of the von Bertalanffy growth equation, the Brody growth coefficient was used as an index to determine the effects of the stocking manipulation on growth parameters. Calculating and comparing Brody growth coefficients uses the entire age structure of the population so it may mask effects that might affect the younger, smaller classes of fish as a result of stocking juvenile fish. As a result, I also compared mean length at age from individual fish for all age classes five years and younger where sample sizes were sufficient for every year, reservoir, and age-class combination.

Measures of size distribution and body condition were also assessed because these population indices could be used to determine the impact of the stocking manipulation. Size distribution of channel catfish populations in each reservoir each year were assessed with proportional size distribution indices (PSD; Anderson and Neumann 1996):

$$PSD = \left(\frac{Q}{S}\right) \times 100$$

where: Q = number of quality-size ($\geq$ 410 mm; Brown et al. 1995) channel catfish in the sample,

S = number of stock-size ($\geq$ 280 mm; Brown et al. 1995) channel catfish in the sample.

Relative weight (W_r; Wege and Anderson 1978) was used as a measure of condition and was calculated as the proportion of measured body weight (W_t) to the estimated standard weight (W_s; Brown et al. 1995), based on length of the fish:

$$W_r = \left(\frac{W_t}{W_s}\right) \times 100$$

Data Analyses

For most analyses (i.e., relative abundance, mean total length and weight, relative weight, mean length at age), a generalized least-square (GLS) model with repeated measures was used to compare the effects of treatment (control, stock, and ceased-stock) and year and their interaction using the *gls* function within the *nlme* package in R (R Development Core Team 2005; Pinheiro et al. 2011). Reservoir within treatment was considered the within subject variable in the statistical model and the heterogeneous autoregressive covariance structure was adopted when modeling the repeated measures. Relative abundance, mean total length and weight were $\log_{10}$-transformed prior to analysis because assumptions of normality were not met. A Tukey's Honestly Significant Difference (HSD) test was conducted in instances of significances. To evaluate if PSD (%) changed across treatment, year, and the interaction, generalized linear mixed models using the *glmmPQL* function in the *MASS* package for R (Zuur et al. 2009; Venables and Ripley 2002) were analyzed with a binomial probability error distribution and logit link function.

Results

The experimental manipulation produced mixed results regarding relative abundance of channel catfish. The repeated-measures linear mixed model indicated a significant treatment × year interaction ($F_{4,9} = 5.10$, $P = 0.02$), indicating a significant change in catch rates after manipulation. Post-hoc analysis indicated a significant decline in catch rates for cease-stock lakes (TukeyHSD, $P < 0.05$). Relative abundance of cease-stock lakes (Okemah and Okmulgee) prior to the manipulation was similar to or greater than control lakes (McMurtry and Ponca) (Figure 2), and stocked lakes (Lone Chimney and Greenleaf) had generally lower relative abundance in comparison to control lakes (TukeyHSD, $P < 0.05$). Mean catch declined in both cease-stock lakes, which ranged between a 69% (Okemah) and 93% (Okmulgee) decrease in mean catch since 2010. As expected, mean catch increased (63%) at Lake Greenleaf after stocking was initiated, culminating in a 30× increase by 2012 (TukeyHSD, $P < 0.05$). However, mean catch rates of channel catfish at Lake Lone Chimney did not change by 2012 (TukeyHSD, $P > 0.05$).

The between-read CV for age estimates ranged from 89% to 97% and Brody growth coefficients (k) from the von Bertalanffy growth function were highly variable among reservoirs and over time (Figure 3). The growth coefficients did not change at Lake McMurtry (control) but increased from 2010 to 2012 for both cease-stock lakes, and decreased for one stocked lake (Lake Lone Chimney) (Figure 3). Growth patterns could not be calculated for Lake Greenleaf after 2010 because the population appeared to be entirely comprised of hatchery-age fish. Age structure after stocking manipulation was generally similar among reservoirs across time with two exceptions: 1) the minimum estimated age increased from two to four at Lake Okmulgee and 2) Lake Greenleaf comprised entirely of age-1 (2011) and age-2 (2012) channel catfish. The mixed-effect repeated measures model indicated that mean length at age-4 was significantly different among treatments ($F_{2,10} = 5.04$, $P = 0.03$), but year ($F_{2,10} = 0.63$, $P = 0.55$) and the interaction was

not significant ($F_{4,6} = 2.08$, $P = 0.20$). Mean length at age-4 ranged from 250 mm to 400 mm for control lakes, 262 mm to 371 mm for cease-stock lakes, and 285 mm to 321 for Lake Lone Chimney (Figure 4). Mean length at age-5 was not significantly different among treatments ($F_{2,10} = 0.04$, $P = 0.96$), year ($F_{2,10} = 1.45$, $P = 0.28$), or the interaction ($F_{4,6} = 0.51$, $P = 0.73$).

Mean total length was found to be different by a significant treatment by year interaction ($F_{4,9} = 12.98$, $P < 0.001$), the mean length of the population decreased by 64 mm for both control lakes and decreased 178 mm in the stocked lakes, whereas, mean length increased by as much as 96 mm at the cease-stock lakes (Figure 5). Proportional size distribution declined in stocked lakes and control lakes but increased in cease-stock lakes (*glmmPQL*; *t*=2.97, $P = 0.02$) (Figure 6). There was no difference in PSD values between control and ceased-stocked lakes (*glmmPQL*; *t*=1.83, $P = 0.10$).

Mean total weight was found to be different, indicated by a significant treatment by year interaction ($F_{4,9} = 5.59$, $P = 0.02$). Similar to mean length, the average weight of the population decreased for both control lakes but at different levels with the largest (~645 g) at Lake Ponca. Mean weight increased at both cease-stock lakes by 18 g to 365 g, but decreased by 274 g to 953 g in both stocked lakes (Figure 5). Relative weights averaged 90 and were significantly different among years ($F_{2,13} = 11.04$, $P < 0.001$), and among treatments ($F_{2,13} = 11.29$, $P < 0.001$), but the interaction of treatment with year was not significant ($F_{4,9} = 1.29$, $P = 0.34$).

Discussion

This study is one of the first to comprehensively examine the effects of channel catfish stockings with a full range of experimental manipulations. The effects of the one-time stocking event became increasingly noticeable two years post-impact and the populations generally responded as expected. Catch declined when stocking was ceased and that is not surprising given that hatchery fish are often released at higher numbers than what could be produced naturally

(Lorenzen 2005), which is often due to a lack critical of spawning habitat (Marzolf 1957; Michaletz 2009). Conversely, relative abundance increased as a result of the introduction of hatchery fish in at least one stocked population. As shown previously, contribution of hatchery fish in Lake Greenleaf was 98%, demonstrating that stocking can increase overall abundance (Chapter II). However, a similar response was not observed in Lake Lone Chimney, where stocking could not be identified as a factor that influenced abundance because very few (~3%) channel catfish caught were identified as hatchery origin (Chapter II).

Extreme climatic conditions from 2011 to 2012 induced significant changes in both control lakes and one stocked lake. During this period, most of Oklahoma experienced one of the worst droughts in 100 yr, which significantly affected water levels at three (McMurtry, Ponca, and Lone Chimney) of the six reservoirs. These reservoirs do not maintain a log of water levels, but water levels at Lake Lone Chimney for instance, a stocked lake, declined 3.5 m below average and was being reduced at a rate of 15 cm per month (J. Dooley, Lone Chimney Water Association, personal communication). This may have significant impacts on fish because abundance of fish is greatest in the littoral zone (Werner 1977; Brosse and Lek 2000), which is the habitat most affected during a drought period. Resource utilization and interactions of fishes that rely on the littoral zone can be greatly affected by drought (Mathews 1998). Body weight and body condition are key indicators of fish health and both metrics declined significantly during the drought period in lakes that were most affected by reduced water levels (McMurtry, Ponca, and Lone Chimney). Conversely, an increase in weight, instead of a decline, was observed at both cease-stock lakes, where water levels were less affected, and resource availability and competitive interactions remained relatively stable. Alternatively, these observed responses may have been the result of reduced density-dependent interactions as overall channel catfish populations declined through harvest and natural mortality over time (Michaletz 2009).

Density-dependence is known to affect channel catfish population characteristics like growth rates, condition, and survival, at least in small reservoirs (Hubert 1999; Mitzner 1999; Mosher 1999; Michaletz 2009) and my study suggests these results are also applicable in larger reservoirs. Because recruitment was experimentally manipulated at four reservoirs, any observed population response could be related to density-dependence. In particular, growth (as estimated from the population with Brody growth coefficient (k)), generally reacted inversely to the stocking manipulation and population abundance. At cease-stock lakes (Okemah and Okmulgee) in particular, growth increased as abundance declined. At stocked lakes, the pattern was less clear though. Lake Greenleaf contained only stocked fish post-stocking (i.e., a single year class), making it impossible to calculate k, however, stocked channel catfish grew quite rapidly, reaching a mean total length of 345 mm by May 2012 (Chapter II). In contrast, growth (k) and abundance of the entire channel catfish population at Lake Lone Chimney generally mirrored each other over time. But, stocked channel catfish at Lake Lone Chimney grew quite slowly (Chapter II), and growth of wild channel catfish (age-4 and age-5) decreased over time, generally supporting the hypothesis of density-dependent growth regulation.

Because channel catfish population characteristics are affected by density, caution must be taken to accurately characterize the resident population prior to stocking. Prior to this study, Lake Lone Chimney was identified as a reservoir that needed stocking based on relative abundance estimates determined by gill net samples (Kurt Kuklinski, ODWC), which is the primary method used by ODWC and many other state agencies to sample channel catfish (Richters and Pope 2011). After conducting this study, which used tandem hoop nets, it was evident that natural reproduction was occurring at Lake Lone Chimney because of high numbers of wild channel catfish (Chapter II); as a result, stocking seemed unnecessary in this reservoir. The resulting high catfish abundance in Lake Lone Chimney affected the ability to draw clear conclusions related to stocking. Although hoop nets have been found to provide relatively

precise estimates of relative abundance (e.g., Michaletz and Sullivan 2002; Richters and Pope 2011; Wallace et al. 2011; Stewart and Long 2012), inaccuracies are still likely because of changing catchability due to fish behavior (Price and Peterson 2010). Future studies that evaluate catchability of channel catfish instead of precision/efficiency would identify biases and limitations of hoop net relative abundance estimates, and thus provide more robust information to decision makers.

The underlying geology can strongly influence substrate composition and available cover (Frissel et al. 1986). Many of these reservoirs are located in different ecoregions and the local habitat conditions were probably not similar. This likely incorporated uncontrolled for heterogeneity. The added source of variance can affect fish assemblage dynamics (Pease et al. 2011), but little is known about habitat-use of channel catfish in reservoirs. Understanding how habitat and the surrounding land-use relate to channel catfish population characteristics is needed.

Using stock enhancement as a solution to low natural recruitment of channel catfish in larger reservoirs is feasible but should only be implemented with scientific justification. This would require a fishery manager to develop a management framework that identifies decisions and risks of stocking based on a holistic approach to stocking (Blankenship and Leber 2005). Information on relative stock size, habitat, performance (i.e., growth and survival) of stocked channel catfish, and ecosystem influences as identified by trophic impacts would reduce unnecessary stocking investments. The results from this study show that stock enhancement is not a "quick fix" solution and that broader aspects must be taken into consideration prior to stocking fish (Blankenship and Leber 2005; Lorenzen 2005; Lorenzen et al. 2010; Araki and Schmid 2010).

REFERENCES

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

Araki, H, and C. Schmid. 2010. Is hatchery stocking a help or harm? Evidence, limitations and future directions in ecological and genetic surveys. Aquaculture 308:S2-S11.

Baer, J., and A. Brinker. 2010. The response of a brown trout stocks and perception of anglers to cessation of brown trout stocking. Fisheries Management and Ecology 17:157-164.

Blankenship, H. L., and K. M. Leber. 1995. A responsible approach to marine stock enhancement. American Fisheries Society Symposium 15:167-175.

Brosse, S, and S. Lek. 2000. Modelling roach (*Rutilus rutilus*) microhabitat using linear and nonlinear techniques. Freshwater Biology 44:441-452.

Brown, M. L., F. Jaramillo, Jr., D. M. Gatlin, and B. R. Murphy. 1995. A revised standard weight (*Ws*) equation for channel catfish. Journal of Freshwater Ecology 10:295-302.

Brynjarsdottir, J., and G. Stefansson. 2004. Analysis of cod catch data from Icelandic groundfish surveys using generalized linear models. Fisheries Research 70:195-208.

Cope, J. M., and A. E. Punt. 2007. Admitting ageing error when fitting growth curves: an example using the von Bertalanffy growth function with random effects. Canadian Journal of Fisheries and Aquatic Sciences 64:205-218.

Cowx, I. G. 1994. Stocking strategies. Fisheries Management and Ecology 1:15-31.

Dortel, E., F. Massiot-Granier, E. Rivot, J. Million, J-P. Hallier, E. Morize, J-M Munaron, N. Bousquet, and E. Chassot. 2013. Accounting for age uncertainty in growth modeling, the

case study of yellowfin tuna (*Thunnus albacares*) of the Indian Ocean. PLoS ONE 8:e60886.

Dudash, M., and R. C. Heidinger. 1996. Comparative survival and growth of various size channel catfish stocked into a lake containing largemouth bass. Transactions of the Illinois State Academy of Science 89:105-111.

Flammang, M. K., and R. D. Schultz. 2007. Evaluation of hoop-net size and bait selection for sampling channel catfish in Iowa impoundments. North American Journal of Fisheries Management 27:512-518.

Howell, M. H., and R. K. Betsill. 1999. Evaluation of different sizes of advanced channel catfish fingerlings stocked in small Texas impoundments. Pages 461-465 *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.

Hubert, W. A. 1999. Biology and management of channel catfish. Pages 3-22 *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.

Jackson, J. J., and J. M. Francis. 1999. Evaluation of stocking three sizes of channel catfish in Nebraska small impoundments. Pages 487-492 *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.

Kimura, D. K., and J. J. Lyons. 1991. Between-reader bias and variability in the age-determination process. Fisheries Bulletin 89:53-60.

Krummich, J. T., and R. C. Heidinger. 1973. Vulnerability of channel catfish to largemouth bass predation. Progressive Fish-Culturist 35:173-175.

Long, J. M., and D. R. Stewart. 2010. Verification of otolith identity used by fisheries scientist for aging channel catfish. Transactions of the American Fisheries Society 139:1775-1779.

Lorenzen, K. 2005. Population dynamics and management of culture-based fisheries. Fisheries Management and Ecology 2:61-73.

Lorenzen, K, K. M. Leber, and H. L. Blankenship. 2010. Responsible approach to marine stock enhancement: an update. Reviews in Fisheries Science 18:189-210.

Marzolf, R. C. 1957. The reproduction of channel catfish in Missouri ponds. Journal of Wildlife Management 21:22-28.

Mathews, W. J. 1998. Patterns in freshwater fish ecology. Chapman and Hall, New York, NY.

Mestl, G. E. 1983. Survival of stocked channel catfish in small ponds. Master's thesis. Oklahoma State University, Stillwater.

Michaletz, P. H., and J. G. Dillard. 1999. A survey of catfish management in the United States and Canada. Fisheries 24:6-11.

Michaletz, P. H., and K. P. Sullivan. 2002. Sampling channel catfish with tandem hoop nets in small impoundments. North American Journal of Fisheries Management 22:870-878.

Michaletz, P. H., K. E. Doisy, and C. F. Rabeni. 2005. Influences of productivity, vegetation, and fish on macroinvertebrate abundance and size in Midwestern USA impoundments. Hydrobiologia 543:147-157.

Michaletz, P. H., and J. S. Stanovick. 2005. Relations among angler use, harvest, and stocking rates of channel catfish in Missouri impoundments. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 59:263-272.

Michaletz, P. H., M. J. Wallendorf, and D. M. Nicks. 2008. Effects of stocking rate, stocking size, and angler catch inequality on exploitation of stocked channel catfish in small Missouri impoundments. North American Journal of Fisheries Management 28:1486-1497.

Michaletz, P. H. 2009. Variable responses of channel catfish populations to stocking rate: density-dependent and lake productivity effects. North American Journal of Fisheries Management 29:177-188.

Mitzner, L. 1999. Assessment of maintenance-stocked channel catfish populations in Iowa lakes. Pages 467-474 *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.

Mosher, T. D. 1999. Characteristics of channel catfish in Kansas state fishing lakes: effects of watershed on growth. Pages 353-360 *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.

Otter Research Ltd. 2005a. An introduction to AD Model Builder Version 10.0. For use in non-linear modeling and statistics. Otter Research Ltd., Sydney, B.C.

Otter Research Ltd. 2005b. Random effects in AD Model Builder: ADMB-RE user guide. Otter
Research Ltd., Sydney, B.C.

OWRB (Oklahoma Water Resources Board). 2011. Beneficial Use Monitoring Program.
OWRB.

http://www.owrb.ok.gov/quality/monitoring/bump/pdf_bump/Current/Lakes/2010-
2011_LakesBUMPReport.pdf

Parrett, T. P., J. A. Marshall, and D. J. Bright. 1999. An investigation in the applicability of
length limits on the channel catfish populations in two small Ohio reservoirs. Pages 447-
454 *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.

Pease, A. A., J. M. Taylor, K. O. Winemiller, and R. S. King. 2011. Multiscale environmental
influences on fish assemblage structure in central Texas streams. Transactions of the
American Fisheries Society 140:1409-1427.

Piner, K. R., O. S. Hamel, J. I. Menkel, J. R. Wallace., and C. E. Hutchinson. 2005. Age
validation of canary rockfish (*Sebasates pinniger*) from off the Oregon coast (USA) using
the bomb radiocarbon method. Canadian Journal of Fisheries Aquatic Sciences 62:1060-
1066.

Piner, K. R., J. R. Wallace, O. S. Hamel, and R. Mikus. 2006. Evaluation of ageing accuracy of
bocaccio (*Sebastes paucispinis*) rockfish using bomb radiocarbon. Fisheries Research
77:200-206.

Powell, D. H. 1976. Channel catfish as an additional sport fish in Alabama's state-owned and managed public fishing lakes. Proceedings of the Annual Conference Southeastern Association of Game and Fish Commissioners 29:265-278.

Porath, M. T., L. D. Pape, L. K., Richters, K. L. Pope, and M. A. Pegg. 2011. Influence of throat configuration and fish density on escapement of channel catfish from hoop nets. Pages 563-571 *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.

Price, A. L., and J. T. Peterson. 2010. Estimation and modeling of electrofishing capture efficiency for fishes in wadeable warmwater streams. North American Journal of Fisheries Management 30:481-498.

R Development Core Team (2010) R: a language and environment for statistical computing. R foundation for statistical computing, Vienna.

Richters, L. K., and K. L. Pope. 2011. Catch of channel catfish with tandem-set hoop nets and gill nets in lentic systems of Nebraska. Pages 573-580 *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.

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

Santucci, V. J., D. H. Wahl, and T. W. Storck. 1994. Growth, mortality, harvest, and cost-effectiveness of stocked channel catfish in a small impoundment. North American Journal of Fisheries Management 14:781-789.

Shaner, B. L., M. J. Maceina, J. J. McHugh, and S. F. Cook. 1996. Assessment of catfish
    stocking in public fishing lakes in Alabama. North American Journal of Fisheries
    Management 16:880-887.

Skaug, H., and D. Fournier. 2006. Automatic approximation of the marginal likelihood in non-
    Gaussian hierarchical models. Computational Statistics and Data Analysis 51:699-709.

Stewart, D. R., G. W. Benz, and G. D. Scholten. 2009. Weight-length relationships and growth
    data for blue catfish from four Tennessee waterbodies. Proceedings of the Annual
    Southeastern Association Fish and Wildlife Agencies 63:140-146.

Stewart, D. R., and J. M. Long. 2012. Precision of channel catfish catch estimates using hoop
    nets in larger Oklahoma reservoirs. North American Journal of Fisheries Management
    32:1108-1112.

Siegwarth, G. L., and J. E. Johnson. 1998. Assessment of stocking catchable-size channel catfish
    in the Buffalo River, Arkansas. North American Journal of Fisheries Management 18:96-
    103.

Storck, T., and D. Newman. 1988. Effects of size at stocking on survival and harvest of channel
    catfish. North American Journal of Fisheries Management 8:98-101.

Tolonen, A. and J. Kjellman. 2001. Post-stocking perturbations in a population of subarctic
    whitefish, *Coregonus lavaretus* (L.): effects on growth, condition and cestode infection.
    Hydrobiologia 445:57-66.

Venables, W., and B. Ripley. 2002. Modern applied statistics with S. Springer, New York.

Wallace, B. C., D. M. Weaver, and T. J. Kwak. 2011. Efficiency of baited hoop nets for
    sampling catfish in southeastern U.S. small impoundments. Pages 581-588 *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.

Werner, E. E. 1977. Species packing and niche complementarity in three sunfishes. American

Naturalists 111:553-578.

Wege, G. J., and R. O. Anderson. 1978. Relative weight (*Wr*): a new index of condition for

largemouth bass. Pages 79-91 *in* G. Novinger and J. Dillard, editors. New approaches to

the management of small impoundments. American Fisheries Society, North Central

Deivision, Special Publications 5, Bethesda, Maryland.

Zuur, A. F., E. N. Ieno, N. J. Walker, A. A. Saveliev, and G. M. Smith. 2009. Mixed effects

models and extensions in ecology with R. Springer, New York.
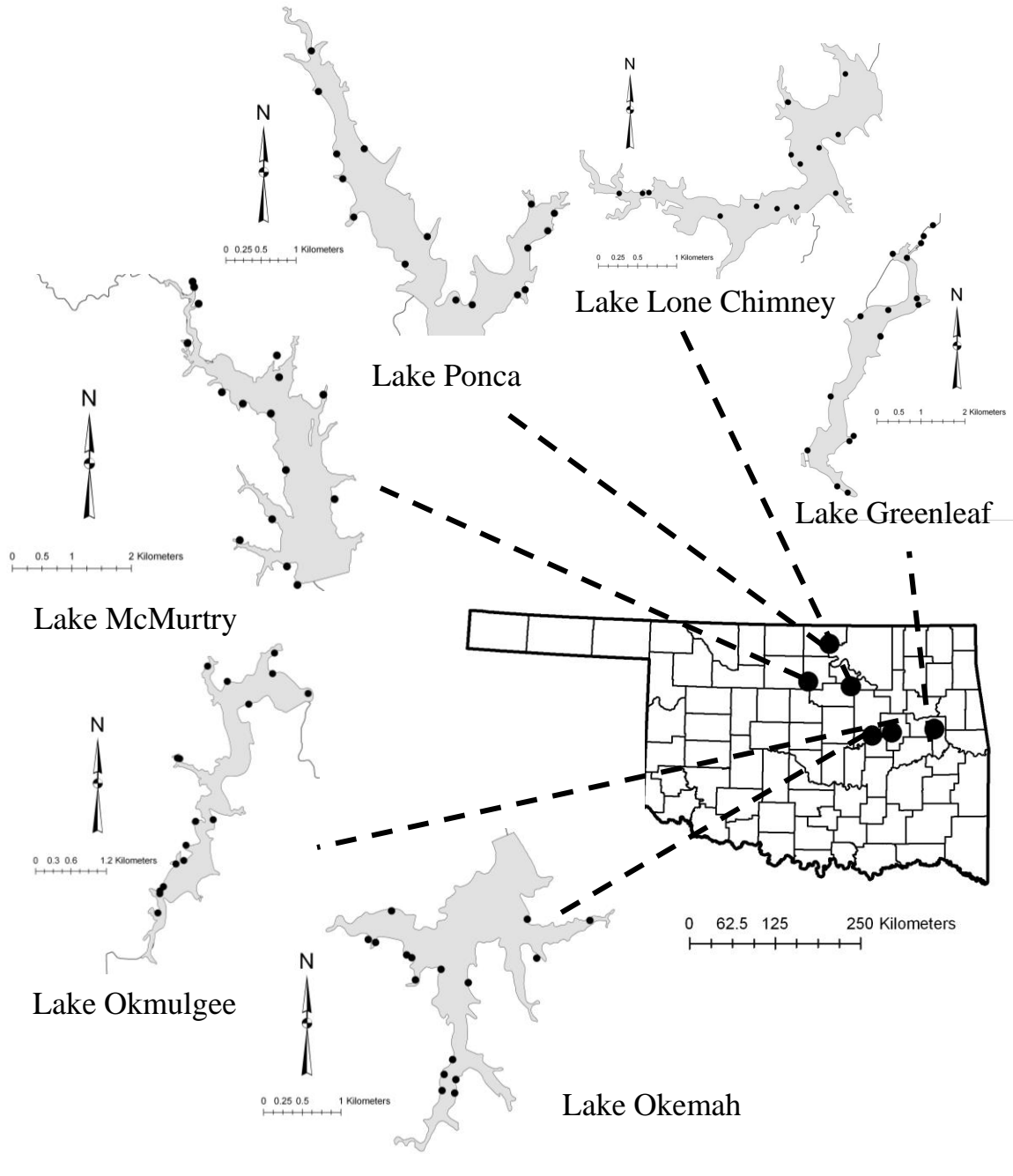
Figure 1. Map of Oklahoma and the location of sample sites within six study reservoirs (Control: McMurtry and Ponca; Cease-stock: Okemah and Okmulgee; Stock: Lone Chimney and Greenleaf) where an experimental stocking program of channel catfish *Ictalurus punctatus* was undertaken.
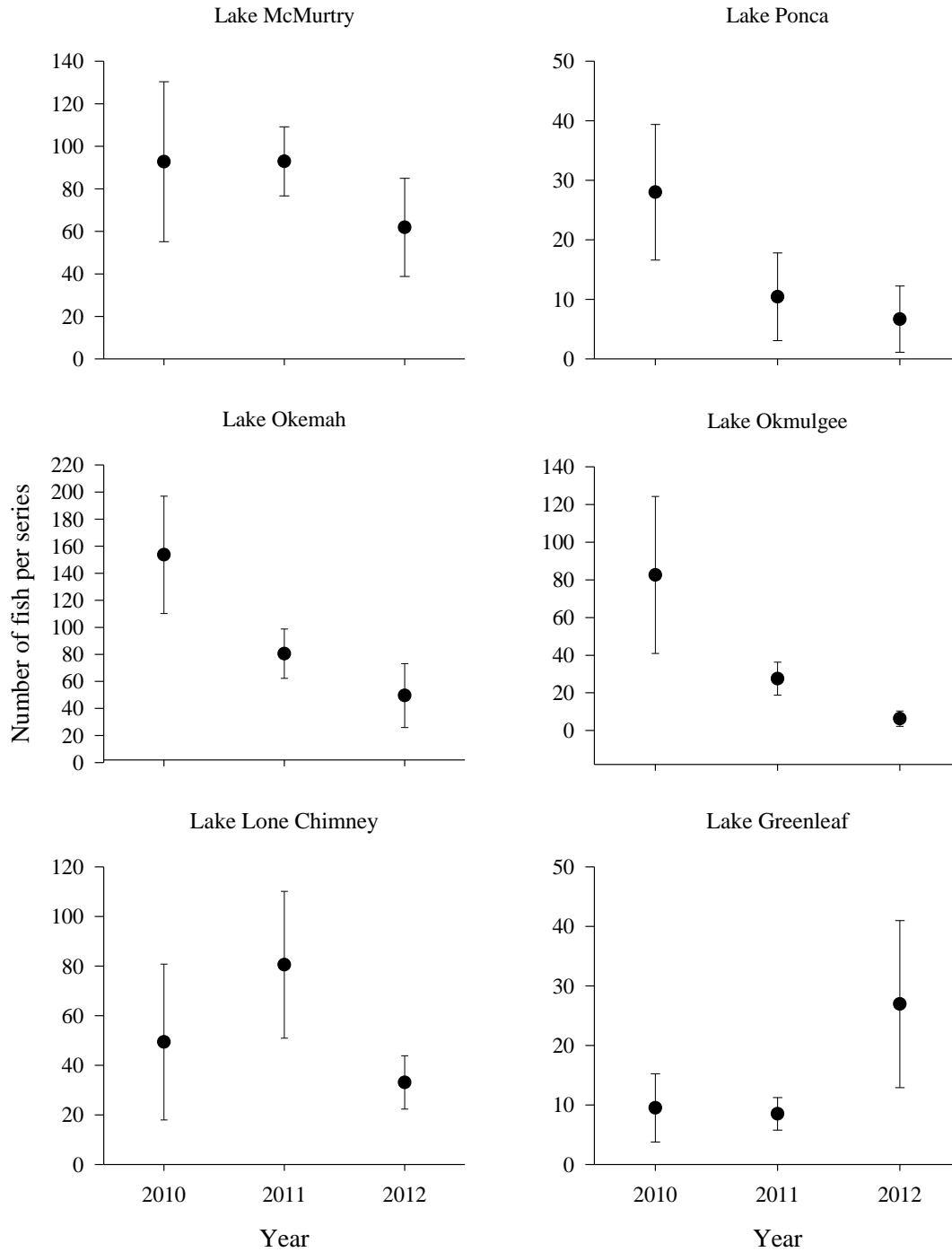
Figure 2. Mean relative abundance (± 95% CI) of channel catfish *Ictalurus punctatus* collected by tandem hoop net sets from six study reservoirs (Control: McMurtry and Ponca; Cease-stock: Okemah and Okmulgee; Stock: Lone Chimney and Greenleaf) from 2010 to 2012.
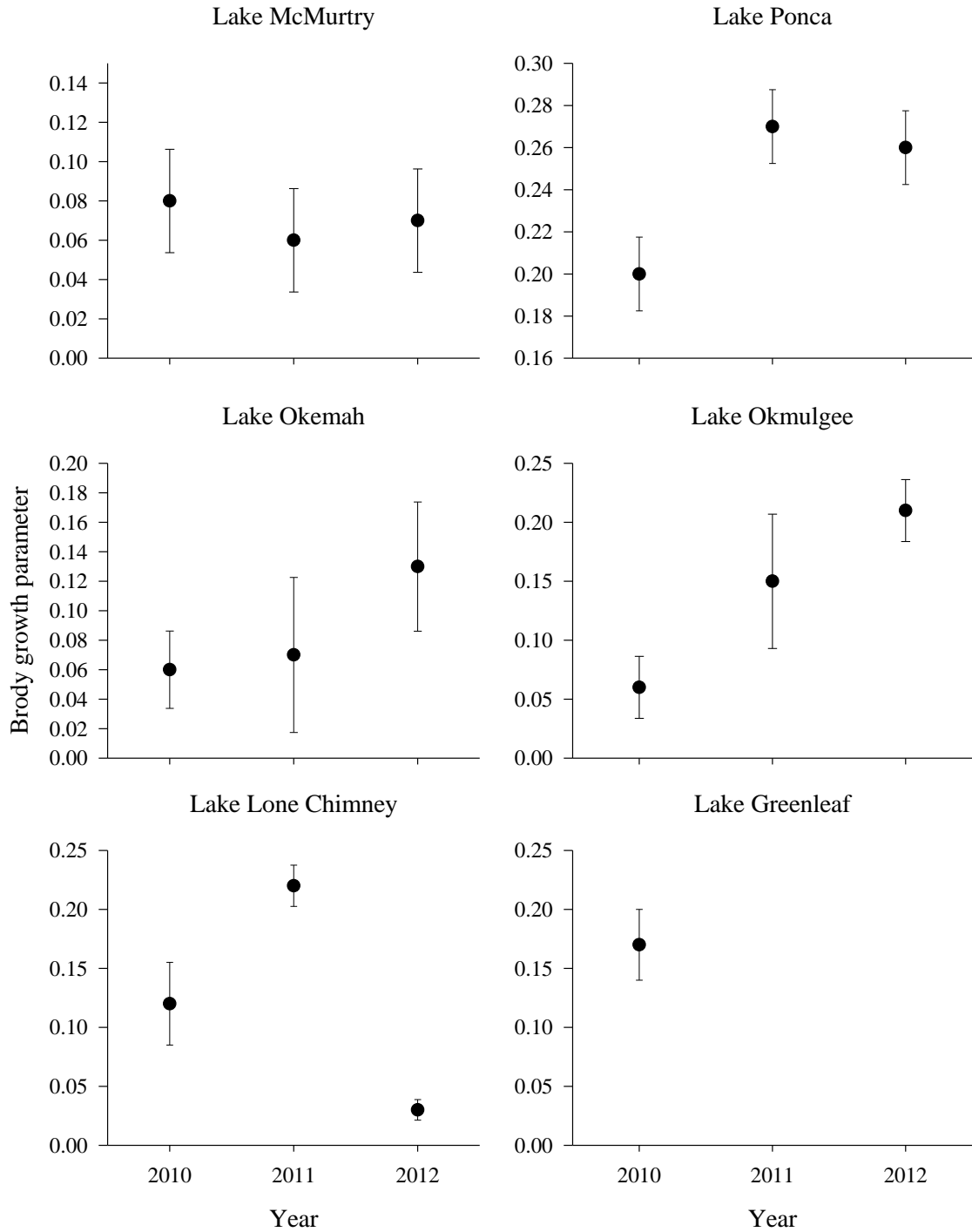
Figure 3. Brody growth parameter estimates (± 95% CI) for channel catfish *Ictalurus punctatus* from six study reservoirs (Control: McMurtry and Ponca; Cease-stock: Okemah and Okmulgee; Stock: Lone Chimney and Greenleaf) from 2010 to 2012. Estimates could not be calculated for Lake Greenleaf in 2011 and 2012 because only a single age class was detected.
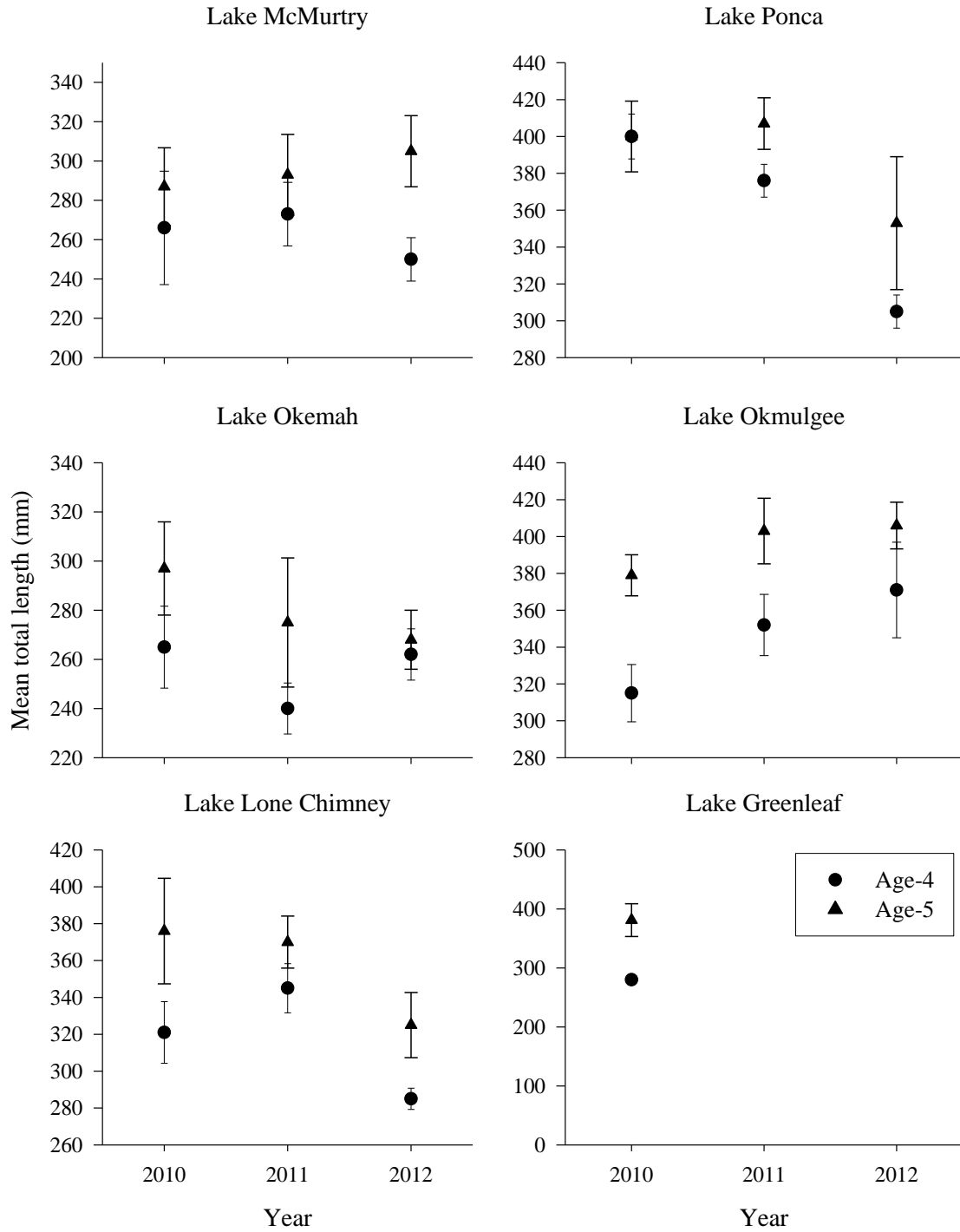
Figure 4. Mean total length (± 95% CI) at age-4 and age-5 channel catfish *Ictalurus punctatus* from six study reservoirs (Control: McMurtry and Ponca; Cease-stock: Okemah and Okmulgee; Stock: Lone Chimney and Greenleaf) from 2010 to 2012. Estimates could not be calculated for Lake Greenleaf in 2011 and 2012 because only a single age class was detected.
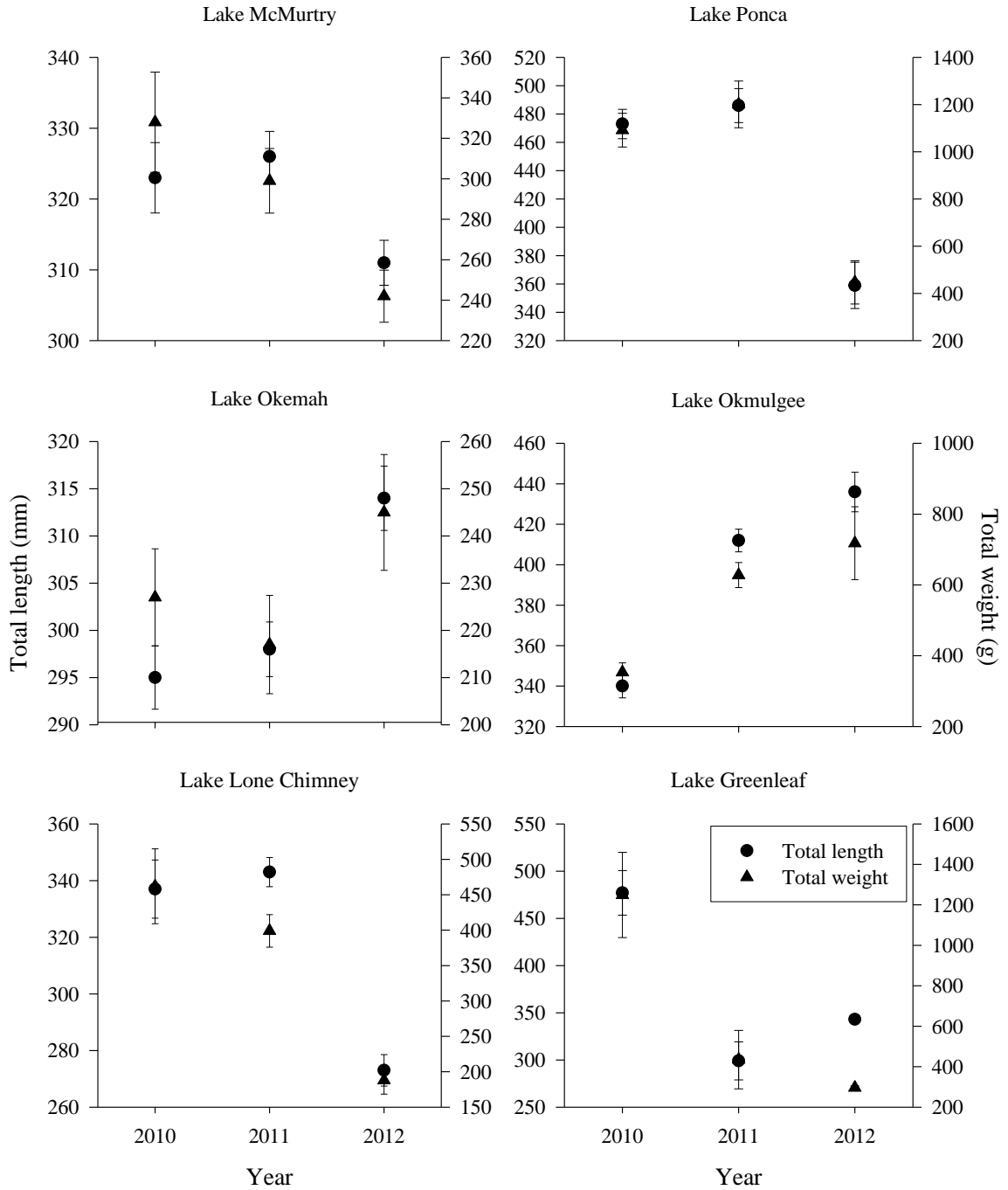
Figure 5. Mean total length (± 95% CI) and weight (± 95% CI) of channel catfish *Ictalurus punctatus* collected from six study reservoirs (Control: McMurtry and Ponca; Cease-stock: Okemah and Okmulgee; Stock: Lone Chimney and Greenleaf) from 2010 to 2012.
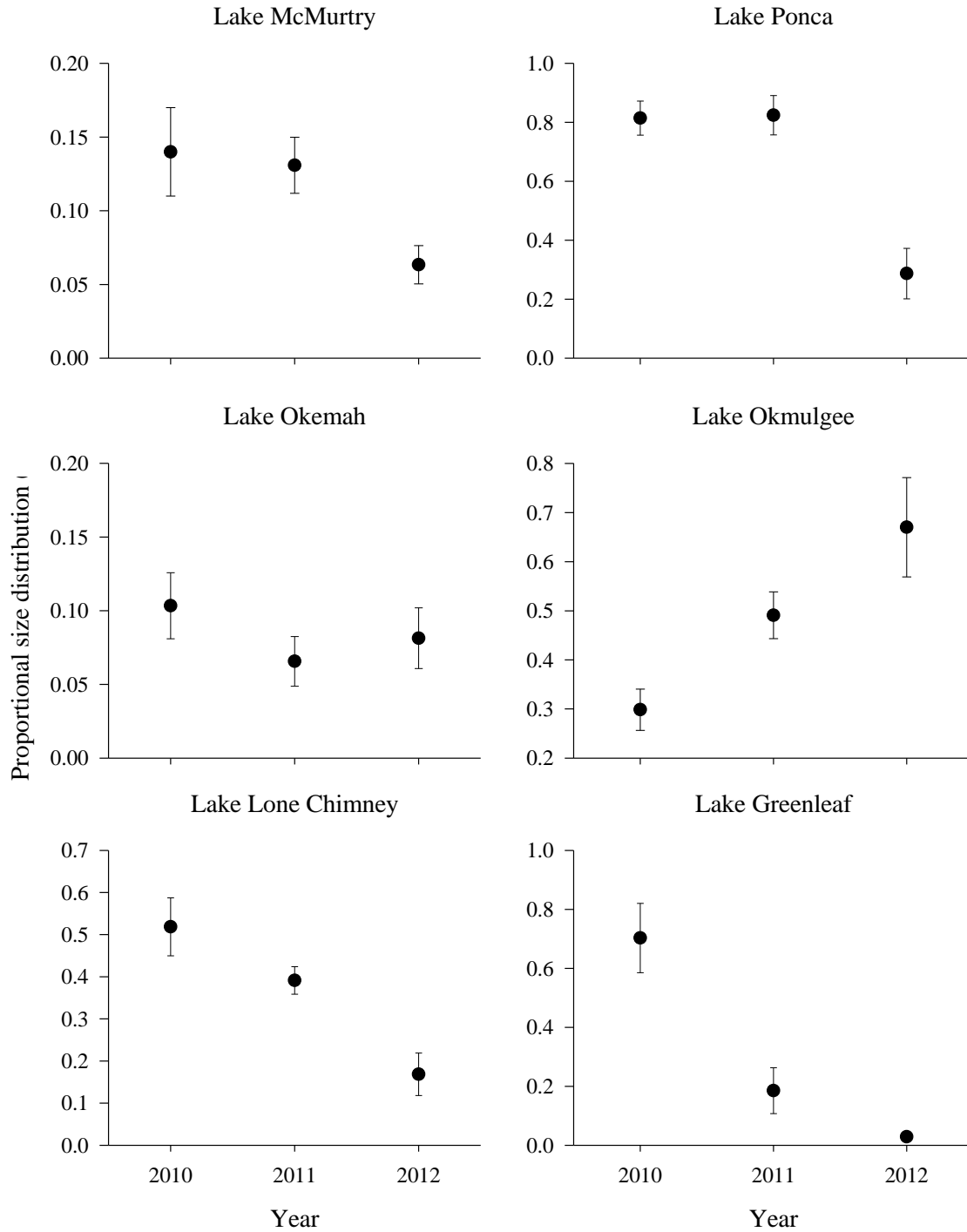
Figure 6. Proportional size distribution (± 95% CI) of channel catfish *Ictalurus punctatus* collected from six study reservoirs (Control: McMurtry and Ponca; Cease-stock: Okemah and Okmulgee; Stock: Lone Chimney and Greenleaf) from 2010 to 2012.

59
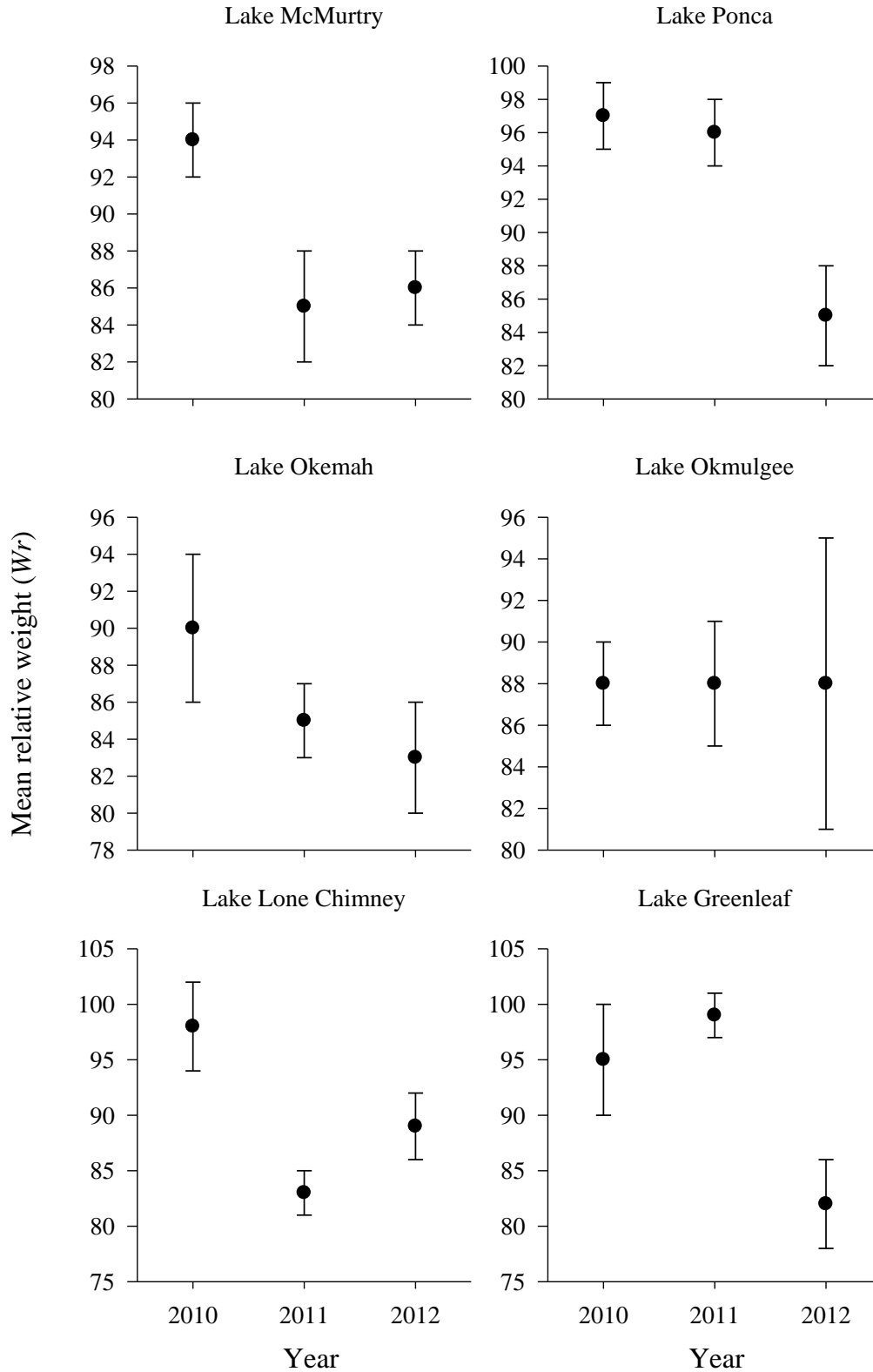
Figure 7. Mean relative weight (*W*ᵣ; ± 95% CI) of channel catfish *Ictalurus punctatus* collected from six study reservoirs (Control: McMurtry and Ponca; Cease-stock: Okemah and Okmulgee; Stock: Lone Chimney and Greenleaf) from 2010 to 2012.

CHAPTER IV

MODELLING CHANNEL CATFISH *ICTALURUS PUNCTATUS* HABITAT ASSOCIATIONS

IN SIX OKLAHOMA RESERVOIRS AT MULTIPLE SPATIAL SCALES

Introduction

Understanding how habitat influences spatial distributions and abundance of species is an

essential component of the management framework (Hayes et al. 1996). Near-shore habitat is

important for all life stages of many fish (Bohl 1980; Brosse and Lek 2000), where species

abundance and interactions are highest (Werner 1979; Werner and Hall 1979; Werner et al. 1983;

Savino and Stein 1982). Channel catfish *Ictalurus punctatus* habitat use has not been formally

described in lentic systems, even though habitat is cited as the principle factor that limits natural

recruitment (Michaletz 2009). State agencies invest many resources into channel catfish stock

enhancement programs but few have sough tot identify habitat associations that might mediate

abundance (Hubert 1999). Identifying species-habitat relationships and determining if they vary

with different life-history stages may play a useful role in explaining population dynamics of fish

(Olden and Jackson 2001).

The abundance and availability of near-shore habitat in aquatic ecosystems is linked to

riparian areas and the surrounding landscape (Jennings et al. 1999; Olden and Jackson 2001).

Land-use can reduce habitat complexity and disrupt important linkages between the terrestrial and

aquatic ecosystems (Christensen et al. 1996; Bettoli et al. 1993; Bartodziej 1999; Trial et al. 2001

Brewer and Rabeni 2011). These impacts include decreased recruitment of coarse-woody debris (Christensen et al. 1996), increased sedimentation and nutrient input (Jennings et al. 1999), and simplification of macrophyte communities (Bettoli et al. 1993; Olden and Jackson 2001). The interstitial spaces created by coarse-woody debris and rocky substrata are important spawning and rearing spaces for channel catfish (Scott and Crossman 1973; Braaten and Berry 1997; Hubert 1999; Kelsch and Wendel 2004). Anthropogenic modifications that decrease recruitment of coarse-woody debris and increase substrate embeddedness may alter predator-prey dynamics (Sass et al. 2006).

Because channel catfish possess the physiological ability to tolerate a wide range of conditions (Layher and Maughan 1985), researchers have described them as habitat generalists despite ample evidence to the contrary (Hubert 1999; Miranda and Kilgore 2011). Channel catfish commonly inhabit areas associated with coarse-woody debris and rock substrata in lotic systems (Harlan and Speaker 1956). Paragamian (1990) reported that channel catfish were found in higher abundances in areas with high habitat diversity. In reservoirs, channel catfish have been found to be more abundant in shallow water and coves (Fischer et al. 1999), but these studies were conducted in smaller impoundments, which may affect habitat affinity (Stewart and Long 2012). Presuming that channel catfish use habitat types uniformly could result in false conclusions and ignore important ecological mechanisms that influence channel catfish stock dynamics.

Most studies have evaluated channel catfish habitat-use at a single scale (Jackson and Jackson 1999; Driscoll et al. 1999; Phelps et al. 2010). The single scale design can prevent the identification of potentially important habitat structures. Because habitat characteristics vary spatially and temporally (Frissell et al. 1986), fish-habitat relationships should account for important spatial and temporal variability using a landscape design (Poizat and Pont 2003). Therefore, the objective of this study was to evaluate channel catfish habitat (i.e., near-shore and

land-use) relationships at multiple spatial scales in six Oklahoma reservoirs. The study was designed with the following objectives: 1) quantify habitat characteristics for six Oklahoma reservoirs; 2) to examine relationships between habitat and channel catfish abundance (all and sub-stock (< 280 mm total length (TL)) at three spatial scales (150-m, 500-m, and whole-lake).

Study Site

The study area included six reservoirs in Oklahoma (Figure 1) that ranged from 223-ha to 465-ha in surface area (Table 1). In general, the reservoirs were mesotrophic to eutrophic in nature and had different channel catfish stocks: lakes McMurtry and Ponca had self-sustaining stocks, whereas lakes Okemah, Okmulgee, Lone Chimney, and Greenleaf had a history of stocking in the last 1-3 years.

Methods

Channel Catfish Sampling

Channel catfish were sampled each May from 2010 to 2012 at randomly selected sites at each reservoir using tandem hoop nets (three net per series, each 3.4-m long with 25-mm-bar mesh and seven 0.8-m hoops that tapered toward the cod end [Miller Net and Twine Co., Inc., Memphis, Tennessee]), the throats of which were constricted with nylon zip ties to prevent fish escapement (Porath et al. 2011). Each reservoir was sampled with eight hoop net series in 2010 and 16 in 2011 and 2012 (Stewart and Long 2012). Nets were set parallel to shore at depths less than 4-m, baited with 1 kg of ground cheese logs (Boatcycle Inc., Henderson, Texas) and left undisturbed for 72 h. All channel catfish captured were counted and measured for total length (TL, mm).

Habitat Assessment

Water chemistry.— Before net setting, water transparency was measured at each sample site with a Secchi disk (cm). To measure reservoir productivity, surface water samples were collected annually from four regions of each reservoir in July to estimate chlorophyll-*a* (Chl-*a*, *μ*g/L) concentrations. Water samples were filtered within 24 hr of collection using 0.7 *μ*m Whatman GF/F glass fiber filters, frozen, and Chl-*a* concentrations were estimated with an Optimal Technologies Ratio-2 fluorometer (ALPHA 2005).

Near-shore habitat.—Near-shore habitat (substrate and cover) was determined at all reservoirs, except Lake Lone Chimney, in summer 2012 along a 100-m buffer from the shoreline using side-scan sonar technology (Kaeser and Litts 2010). Side-scan images were obtained with a Humminbird© 998c SI sonar unit, rectified using DrDepth® software, and imported into a geographic information system (GIS; ArcVIEW 9.3) (Kaeser and Litts 2010). Lake Lone Chimney did not have sufficient water depth to conduct side-scan sonar surveys in 2012 because of an intense drought that left sampling sites dry. Therefore, near-shore habitats types were delineated visually. Habitat types were classified using criteria similar to Kaeser and Litts (2010): fine sediment was identified as clay or sand material < 2 mm in diameter; bedrock-boulder and bedrock were defined as having a smooth texture surface that consisted of fractured blocks > 500 mm in diameter or having an unfractured surface; rocky-boulder and rocky material were types defined as being > 500 mm in diameter or rocky material > 2 mm and < 500 mm in diameter; aquatic vegetation was defined as any submergent, floating, or emergent macrophyte; coarse-woody debris was defined as any simple or complex woody structure that resided in or extended into the reservoir; and standing timber was classified as any area having visible timber stands.

Habitat validation.—For each of the five reservoirs where side-scan sonar was used to determine near-shore habitat, habitat types were validated at 100 randomly selected sites. Additionally, all sites classified as woody debris were inspected and substrates types not represented in the initial random sample were sought for verification. Substrate and cover types at shallow-water sites were verified directly by visual inspection, whereas habitats at deep-water sites were verified with an Ekman grab (e.g., fine sediment) or a four pronged grappling hook (e.g., coarse-woody debris). An error matrix of correctly and incorrectly identified habitats was analyzed using kappa analysis to determine classification accuracy (Congalton and Green 1999).

Surrounding land-use.—Land-use surrounding each lake was summarized using the latest 30-m resolution land-cover data (2006) from the Multi-Resolution Land Characteristics Consortium (Fry et al. 2011). Land-use data were clipped to a 1-km buffer around the boundary of each reservoir, and dominant land-cover types (residential development, agriculture, grassland, shrub, wetland, and forest) were tabulated for the whole-lake and at 150 and 500-m buffers around each sampling site.

Data Analyses

The relationships between channel catfish abundance and habitat variables were analyzed at three spatial scales to account for attraction to baited hoop nets and their roaming behavior, but the degree is unknown and has not been formally quantified. Buffers (150-m and 500-m) were created around each sampling site and percent habitat (near-shore and landscape variables) was calculated within the defined sampling unit. Buffers of these sizes were thought to provide meaningful information based on channel catfish movements (frequency of movement = 11%) and estimated home ranges (average size = 42.7 ha) in reservoirs (Fischer et al. 1999). Secchi depth measured at each sampling site was used as a variable at the fine (150-m buffer) scale. Productivity (i.e., annual mean Chl-*a*) measured from four regions from each reservoir was used

as a variable at the intermediate (500-m buffer) scale. Mean Secchi depth and Chl-*a* from all sampling sites were included as variables at the whole-lake scale.

Relationships between channel catfish abundance (total and sub-stock (< 280 mm TL)) and habitat (near-shore and land-use) were examined using negative binomial and zero-inflated negative binomial mixed models, which performs well with count data when the variance exceeds the mean and when a large proportion of zero data values are within the data set. For the 150-m and 500-m scale models, the natural logarithm of the total number of fish collected for a lake in that year was defined as the offset term. The random-intercept model was structured to account for variation associated with year and site within lake effects. Habitat variables (tabulated as proportions) were arcsine-square root transformed and all other variables were $\log_{10}$-transformed to meet assumptions of normality. Models were developed using the AD Model Builder (glmmADMB; Bolker et al. 2012) of the R program (R Development Core Team, 2010).

Candidate models at each spatial scale (150-m, 500-m, and whole-lake) were developed based on biological information (e.g., diversity of substrate and cover types) reported for channel catfish (see Hubert 1999), and compared using Akaike's Information Criterion (AIC$_c$; Akaike 1973; Burnham and Anderson 2002). Pearson correlation matrix was used to identify potential sources of collinearity and variables with correlations (> 0.30) were not included in the same model for each spatial scale (Graham 2003). Models of four or fewer variables were developed because complex models with large variables typically have limited conservation value and explanatory power (Burnham and Anderson 2002). Candidate models were ranked using AIC$_c$ and models with ΔAIC$_c \leq 4$ (defined as the difference between AIC$_c$ for a given model and the lowest value in a set) were considered plausible (Burnham and Anderson 2002). The set of candidate models were compared by calculating AIC$_c$ weights (measure of the relative probability of being the best model) and evidence ratios (Burnham and Anderson 2002). AICc weights (w_i) were calculated for model *i* as:

$$w_i = \frac{e^{\left(-\frac{1}{2}\Delta_i\right)}}{\sum\limits_{q=1}^{Q} e^{\left(-\frac{1}{2}\Delta_q\right)}}$$

where Δ_i is the difference between the AIC_c for the ith model and the minimum AIC_c. The

evidence ratio is a measure of the strength of evidence for the ith model and calculated as w_{max}/w_i,

where w_{max} is the largest weight for all candidate models and w_i is the weight of model i

(Burnham and Anderson 2002). Model validation was based on evaluating plots of residual

values versus fitted values (Bolker et al. 2012). Spearman's rank correlation (r_s) was used to

determine if there was a significant relationship between the observed and predicted values of the

most plausible model.

Results

Near-shore habitat and differed among reservoirs (Table 2), although fine sediment was

the dominant near-shore substrate type at all reservoirs (range 55% to 95%). Aquatic vegetation

was common (12-35%) at three reservoirs (lakes Okemah, Okmulgee, and Greenleaf), whereas

coarse-woody debris and standing timber was only common at Lake McMurtry (3%) and Lake

Lone Chimney (28%) and rocky habitat types were only common ($\geq$ 17%) at lakes Okmulgee and

Ponca. Overall, 516 sampling sites were assessed for habitat classification accuracy, which was

high (Kappa = 0.81) (Table 3) with most errors between signatures of rocky and boulder substrate

types. Agreement was only 23% and 63% for rock and bedrock boulder substrate types compared

to 94% and 95% for aquatic vegetation and rocky boulder.

Land-use around lakes Okemah, Okmulgee, and Greenleaf was mostly forest types (59-

80%), whereas grassland habitat was dominant at lakes McMurtry and Lone Chimney (Table 4).

Lake Ponca had the highest amount of developed land-use, approximately 2× greater coverage

then the next highest site (Lake Okmulgee).

A total of 11,082 channel catfish were collected during the study period of which 3,374 were sub-stock size (≤ 280 mm TL). Variation in channel catfish catch rates occurred among reservoirs. Lakes Okemah (97 fish series^{-1}), McMurtry (83 fish series^{-1}), and Lone Chimney (54 fish series^{-1}) had the highest catch rates, whereas lakes Okmulgee (39 fish series^{-1}), Ponca (15 fish series^{-1}), and Greenleaf (15 fish series^{-1}) were about one-half of the former.

The results from the Pearson correlation revealed many collinear variables (Table 5, 6, and 7). For all size groups combined, all competing models at the 150-m scale included agricultural land-use (Table 8). There were only two variables in the best competing model and included agriculture and aquatic vegetation. The model had a relative likelihood of 29% and there was a significant positive correlation between observed and predicted values ($r_s = 0.40$, $P < 0.05$). The most plausible model was 1.28 times more likely than the next best competing model. Based on parameter estimates, channel catfish abundance was significantly lower in areas associated with agriculture, aquatic vegetation, and clear water (i.e., increased Secchi depth) (Figure 2). Abundance was higher in areas associated with rocky boulder and less cover (i.e., more Fine sediment). For sub-stock size channel catfish, six competing models were identified, indicating that abundance channel catfish < 281 mm TL was negatively related to clear water areas (i.e., Secchi depth) that were associated with aquatic vegetation and rocky boulder (Figure 3). Sub-stock channel catfish were found in higher abundances in less complex areas (i.e., more fine sediment) with bedrock and coarse-woody debris. The best model included three habitat variables (aquatic vegetation, coarse-woody debris, and rock), was 2.86 times more likely than the other competing models, and there was a significant positive correlation between the observed and predicted values ($r_s = 0.25$, $P < 0.05$).

At the broader 500-m scale, six competing models were identified and the model with the lowest AIC$_c$ contained three covariates: aquatic vegetation, bedrock boulder, and agriculture (Table 9). The most plausible model was 2.34 times more likely than the next best performing

model and a significant positive correlation was evident between observed and predicted values ($r_s = 0.40$, $P < 0.05$). Similar to the local scale, agriculture and aquatic vegetation were negatively related, and bedrock boulder was positively correlated with channel catfish abundance (Figure 4). For sub-stock channel catfish, two models were found to be plausible and those models represented diversity of substrate types and less complex habitat, which included: bedrock, bedrock boulder, fine, rock, and coarse-woody debris. The model with the lowest AIC$_c$ was only 1.05 times more likely than the next model (Table 9). Significant correlations were found with aquatic vegetation, bedrock and fine sediment ($r_s = 0.26$, $P < 0.05$) (Figure 5).

At the lake scale, the most plausible model included aquatic vegetation, shoreline length, and developed land-use (Table 10). Correlation between observed and predicted values was high (all size groups, $r_s = 0.67$, $P < 0.05$; sub-stock, $r_s = 0.83$, $P < 0.05$). Channel catfish relative abundance was positively related to shoreline length and fine sediment (Figure 6). Negative associations with percent developed land-use and aquatic vegetation were found with most models, regardless of channel catfish size (Figure 7). Other variables included positive associations with bedrock and negative associations with Secchi depth.

Discussion

Channel catfish habitat associations at these different spatial scales likely reflect different responses to habitat at individual (e.g., foraging and predator avoidance) and population levels (e.g., reproduction and recruitment). Until now, most studies that have examined habitat use by channel catfish have done so by following individual animal movements and quantifying the habitats occupied (e.g., Fischer et al. 1999). While this is useful, it suffers from small sample sizes because, logistically, only a few individuals (~10-30) can be tagged and then tracked for a long period of time. Failure to account for different life stages would also result in missing habitat relationships with smaller size channel catfish. The multi-scale design used in the present

study was important in determining habitat associations with channel catfish because the number and types of habitat factors that influence channel catfish populations change with spatial scale.

At the local scale, habitat use tends to optimize the trade-off between foraging efficiency (in relation to prey availability and niche segregation among competing species), and predator avoidance (Fretwell and Lucas 1970; Werner and Hall 1979; Morris 1989; Shepherd and Litvak 2004). For example, interspecific interactions (i.e., predation and competition), although complex, can restrict species distributions in ways that affect population vital rates (i.e., decreased growth and increased mortality) (Pianka 2000). Conversely, intraspecific interactions can increase spatial distribution from profitable habitats to marginal habitat types (Morin 2011). For example, microhabitat (e.g., aquatic vegetation) can act as both a refuge and a foraging arena and numerous studies have used model species like bluegill *Lepomis macrochirus* to test those assumptions (Werner and Hall 1979; Crowder and Cooper 1979; Savino and Stein 1982; Werner et al. 1983).

The negative relationship between sub-stock channel catfish abundance and aquatic vegetation in particular, fits the profit-maximization theory and deserves future study. Aquatic vegetation is important for sunfishes (Centrarchidae; Crowder and Cooper 1979; Savino and Stein 1982), including largemouth bass (*Micropterus salmoides*), which both compete with and preys upon juvenile channel catfish (Marzolf 1957; Michaletz 2006; Michaletz 2009). Channel catfish juveniles may be highly susceptible to largemouth bass predation in aquatic vegetation (Marzolf 1957; Krummrich and Heidinger 1973), thus explaining the negative correlation between channel catfish abundance and aquatic vegetation. In a controlled setting, juvenile channel catfish responded to the presence of largemouth bass by decreasing movement and feeding rates, which negatively affected growth (Fine et al. 2011). Alternatively, foraging efficiency of channel catfish may be reduced through competition in vegetated habitats. The combination of both competition and predation threat likely renders aquatic vegetation less profitable for small

channel catfish (Fraser et al. 1995; Gilliam and Fraser 2001). However, neither of these hypotheses has been evaluated formally for this species.

In contrast to the local habitat patterns, 500-m scale (regional-scale) associations with channel catfish abundance illustrate the interplay between occupied habitats and adjacent land-use (Schlosser 1998; Haddad and Baum 1999; Gilliam and Fraser 2001). Patterns with near-shore and land-use habitat were similar for both channel catfish size groups. Channel catfish tend to be found in greater abundances in areas having high turbidity, less aquatic vegetation, and less agriculture land-use. A positive relationship between rocky substrata and channel catfish was evident for both sub-stock and all size classes combined. The interstitial spaces created by these habitats provide important spawning and juvenile rearing habitat (Stoeckel and Burr 1999; Brewer and Rabeni 2008; Daughtery et al. 2010). Moreover, these habitats likely have higher production of important prey items like benthic invertebrates (Beaty et al. 2006), which is not surprising because channel catfish occupy areas where prey is most abundant (Klaassen and Marzolf 1971; Hubert 1999).

At the lake scale, factors that predicted the abundance of all sizes and sub-stock channel catfish were similar (e.g.,, aquatic vegetation, shoreline length, and residential development). Channel catfish are often found in shallow-water areas and coves in impoundments, and longer shorelines likely equate to more abundant and higher diversity of shallow-water habitat that would benefit channel catfish (Edds et al. 2002). Some land-use types in adjacent habitats (e.g., residential development) can significantly alter a suite of ecosystem characteristics (e.g., nutrient levels and littoral zone function). The removal of riparian forests can reduce the addition of coarse-woody debris that is important source of habitat for littoral zone organisms (Francis and Schindler 2006). Coarse-woody debris additions can increase benthic macro-invertebrate production, provide refuge for prey, and potentially be important spawning structures for channel catfish (Hubert 1999). In lotic systems, channel catfish are more abundant in areas with more

coarse-woody debris and rocky substrate (Paragamian 1990; Coon and Dames 1991; Hubert 1999). My study is one of the first to demonstrate similarly patterns in reservoirs.

The use of hierarchical models would have provided a more parsimonious model set (Clark 2007). The area that is being sampled when using hoop nets is undefined and I can not precisely determine if 150-m is the area representing fine scale. Additionally, habitat was different among reservoirs and not all habitat types were represented equally, precluding random-slope inferences (Kuehl 2000). Studies that quantify the area being sampled would be useful when defining fish-habitat relationships. Although model prediction at the whole-lake scale was good ($r_s > 0.60$), increasing the number of reservoirs and habitat sampled would increase model performance at the 150-m and 500-m scale.

Additionally, there was a high degree of uncertainty between rock substrate and abundance, probably contributed to the low classification accuracy of rock. This has consistently plagued other studies that have used side-scan sonar to classify habitat (e.g., Kaeser and Litts 2010). In the future, rock type habitats should be grouped into one habitat type to account for low classification accuracy. This would improve the relationships between channel catfish abundance and rock substrata.

The results of this study show that interactions with land-use were apparent at all scales; something not examined previously. Relationships with aquatic vegetation in particular were observed across all scales; however, distinct patterns with habitats like coarse-woody debris would not have been observed if a single spatial scale was used. These models indicate that channel catfish clearly show habitat associations in reservoirs and that habitat should be taken into account when managing for channel catfish. It further suggests that the amount of interstitial space and land-use surrounding impoundments may play a role in mediating channel catfish abundance.

REFERENCES

Akaike, H. 1973. Information theory as an extension of the maximum likelihood principle. Pages 267-281 *in* B. N. Petrov and F. C Csaki, editors. Second International Symposium on Information Theory. Akademiai Kiado, Budapest.

American Public Health Association (ALPHA). 2005. Standard methods for the examination of water and wastewater. 21st ed. American Public Health Association. Baltimore (MD): Port City Press.

Bartodziej, B. 1999. A bid to revegetate an urban lake shoreland. LakeLine 19:10-29.

Beaty, S. R., K. Fortino, and A. E. Hershey. 2006. Distribution and growth of benthic macroinvertebrates among different patch types of the littoral zones of two arctic lakes. Freshwater Biology 51:2347-2361.

Bettoli, P. W., and J. E. Morris. 1991. Changes in the abundance of two Atherinid species after aquatic vegetation removal. Transactions of the American Fisheries Society 120:90-97.

Bohl, E. 1980. Diel pattern of pelagic distribution and feeding in planktivorous fish. Oecologia 44:368-375.

Bolker, B. H. Skaug, A. Magnusson, and A. Nielsen. 2012. Getting started with the glmmADMB package.

Braaten, P. J., and C. R. Berry Jr. 1997. Fish associations with four habitat types in a South Dakota prairie stream. Journal of Freshwater Ecology 12:477-489.

Brewer, S. K., C. F. Rabeni, S. P. Sowa, and G. Annis. 2007. Natural landscape and stream segment attributes influencing the distribution and relative abundance of riverine

smallmouth bass in Missouri. North American Journal of Fisheries Management 27: 326-341.

Brewer, S. K., and C. F. Rabeni. 2008. Seasonal and diel habitat shifts by juvenile ictalurids in a flow-regulated prairie river. American Midland Naturalists 159:42-54.

Brewer, S. K., and C. F. Rabeni. 2011. Interactions between natural-occuring landscape conditions and land use influencing the abundance of riverine smallmouth bass, Micropterus dolomieu. Canadian Journal of Fisheries and Aquatic Science 68:1922-1933.

Burnham, K. P., and D. R. Anderson. 2002. Model Selection and Inference: A practical information theoretic approach. New York: Springer-Verlag.

Christensen, D. L., B. R. Herwig, D. E. Schindler, and S. R. Carpenter. 1996. Impacts of lakeshore developed development on coarse woody debris in north temperate lakes. Ecological Applications 6:1143-1149.

Clark, J. S. 2007. Models for ecological data: an introduction. Princeton University Press.

Congalton, R. G., and K. Green. 1999. Assessing the accuracy of remotely sensed data: principles and practices. Boca Raton: Lewis Publishers.

Coon, T. G., and H. R. Dames. 1991. Catfish movement and habitat use in a Missouri River tributary. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 43:119-132.

Crowder, L. B., and W. E. Cooper. 1982. Habitat structural complexity and the interaction between bluegills and their prey. Ecology 63:1802-1813.

Daugherty, D. J., J. W. Schlechte, and R. W. Wienecke. 2011. Selection of interstice size by juvenile flathead catfish. Pages 485-493 *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.

Driscoll, M. T., H. L. Schramm, Jr., and W. R. Davis. 1999. Relative abundance of catfishes in main channel and secondary channel habitats in the lower Mississippi River. Pages 231-238 *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.

Edds, D. R., W. J. Mathews, and F. P. Gelwick. 2002. Resources use by large catfishes in a reservoir: Is there evidence for interactive segregation and innate differences? Journal of Fish Biology 60:739-750.

Fine, M. L., M. S. Mayo, and S. H. Newton. 2011. Largemouth bass predators reduce growth, feeding and movement in juvenile channel catfish. Ecology of Freshwater Fish 20:114-119.

Fischer, S. A., S. Eder, and E. D. Aragon. 1999. Movements and habitat use of channel catfish and blue catfish in a small impoundment in Missouri. Pages 239-255 *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.

Francis, T. B., and D. E., Schindler. 2006. Degradation of littoral habitats by developed development: woody debris in lakes of the Pacific Northwest and Midwest, United States. Ambio 35:274-280.

Fraser, D. F., J. F. Gilliam, and T. Yip-Hoi. 1995. Predation as an agent of population

   fragmentation in a tropical watershed. Ecology 76:1461-1472.

Fretwell, S. D., and H. L., Lucas. 1970. On territorial behavior and other factors influencing

   habitat distribution in birds. *Acta Biotheoretica* 19:136-156.

Frissel, C. A., W. J. Liss, C. E. Warren, and M. D. Hurley. 1986. A hierarchical framework for

   stream habitat classification: viewing streams in a watershed context. Environmental

   Management 10:199-214.

Fry, J. A,. G. Xian, S. Jin, J. A. Dewitz, C. G. Homer, Y. Limin, C. A. Barnes, N. D. Herold, and

   J. D. Wickham. 2011. Completion of the 2006 National Land Cover Database for the

   Conterminous United States. Photogrammeric Engineering and Remote Sensing 77:858-

   864.

Gelwicks, G. T., and G. A. Simmons. 2011. Range and seasonal movements of flathead catfish

   in the Iowa River, Iowa. Pages 443-453 *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.

Gilliam, J. F., and D. F. Fraser. 2001. Movement of corridors: enhancement by predation threat,

   disturbance, and habitat structure. Ecology 82:258-273.

Graham, M. H. 2003. Confronting multicollinearity in ecological multiple regression. Ecology

   84:2809-2815.

Haddad, N. M., and K. A. Baum. 1999. An experimental test of corridor effects on butterfly

   densities. Ecological Applications 9:623-633.

Hayes, D. B., C. P. Ferreri, and W. W. Taylor. 1996. Linking fish habitat to their population dynamics. Canadian Journal of Fisheries and Aquatic Sciences 53:383-390.

Hubert, W. A. 1999. Biology and management of channel catfish. Pages 3-22 *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.

Jackson, J. R., and D. C. Jackson. 1999. Macrohabitat use by catfishes in a southeastern United States Floodplain-River Ecosystem. Pages 215-222 *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.

Jacobs, K. E., W. D. Swink, and J. F. Novotny. 1987. Minimum tailwater flows in relation to habitat suitability and sport-fish harvest. North American Journal of Fisheries Management 7:569-574.

Jennings, M. J., M. A. Bozek, G. R. Hatzenbeler, E. E. Emmons, and M. D. Staggs. 1999. Cumulative effects of incremental shoreline habitat modification on fish assemblages in north temperate lakes. North American Journal of Fisheries Management 19:18-27.

Kaeser, A. J., and T. L. Litts. 2010. A novel technique for mapping habitat in navigable streams using low-cost side-scan sonar. Fisheries 35:163-174.

Katsiapi, M, A. D. Mazaris, E. Charalampous, and M. Moustaka-Gouni. 2012. Watershed land use types as drivers of freshwater phytoplankton structure. Hydrobiologia DOI 10.1007/s10750-012-1095-z.

Kelsch, S. W., and J. L. Wendel. 2004. Lotic habitat availability and use by channel catfish in the Red River of the North. Journal of Freshwater Ecology 19:473-484.

Klaassen, H. E., and G. R. Marzolf. 1971. Relationships between distributions of benthic insects and bottom-feeding fishes in Tuttle Creek Reservoir. Pages 385-395 *in* G. E. Hall, editor. Reservoir fisheries and limnology. American Fisheries Society, Special Publication 8, Bethesda, Maryland.

Kuehl, R. O. 2000. Design of experiments: statistical principles of research design and analysis. 2nd ed. California: Brookes/Cole 2000.

Krummich, J. T., and R. C. Heidinger. 1973. Vulnerability of channel catfish to largemouth bass predation. Progressive Fish-Culturist 35:173-175.

Layher, W. G., and O. E. Maughan. 1985. Relations between habitat variables and channel catfish populations in prairie streams. Transactions of the American Fisheries Society 114:771-781.

Marzolf, R. C. 1957. The reproduction of channel catfish in Missouri ponds. Journal of Wildlife Management 21:22-28.

Michaletz, P. H. 2006. Prey resource use by bluegill and channel catfish in small impoundments. Fisheries Management and Ecology 13:347-354.

Michaletz, P. H. 2009. Variable responses of channel catfish populations to stocking rate: density-dependent and lake productivity effects. North American Journal of Fisheries Management 29:177-188.

Miranda, L. E., and K. J. Killgore. 2011. Catfish spatial distribution in the free-flowing Mississippi River. Pages 521-534 *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.

Morin, P. 2011. Community Ecology, 2nd edition, Blackwell Science, Oxford.

Morris, D. W. 1989. Density-dependent habitat selection: testing the theory with fitness data. Evolutionary Ecology 3:80-94.

Olden, J. D., and D. A. Jackson. 2001. Fish-habitat relationships in lakes: gaining predictive and explanatory insight by using artificial neural networks. Transactions of the American Fisheries Society 130:878-897.

Olden, J. D., D. A. Jackson, and P. R. Peres-Neto. 2001. Spatial isolation in freshwater drainage lakes. Oecologia 127:572-585.

Paragamian, V. L. 1990. Characteristics of channel catfish populations in streams and rivers of Iowa with varying habitats. Journal of the Iowa Academy of Science 97:37-45.

Phelps, Q. E., S. J. Tripp, J. E. Garvey, D. P. Herzog, R. A. Hrabik, D. E. Ostendorf, J. W. Ridings, and J. W. Crites. 2010. Juvenile channel catfish habitat use in the Middle Mississippi River. Pages 535-543 *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.

Pianka, E. R. 2000. Evolutionary Ecology. 6th edition. Benjamin Cummings, San Francisco, CA, USA.

Piette, R. R., and A. D. Niebur. 2011. Movement of adult male flathead catfish in the upper Fox River and Wolf River systems determined by radiotelemetry. Pages 455-471 *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.

Poizat, G., and D. Pont. 1996. Multi-scale approach to species-habitat relationships: juvenile fish in a large river section. Freshwater Biology 36:611-622.

Porath, M. T., L. D. Pape, L. K., Richters, K. L. Pope, and M. A. Pegg. 2011. Influence of throat configuration and fish density on escapement of channel catfish from hoop nets. Pages 563-571 *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.

R Development Core Team (2010) R: a language and environment for statistical computing. R foundation for statistical computing, Vienna.

Sass, G. G., J. F. Kitchell, S. R. Carpenter, T. R. Hrabik, A. E. Marburg, and M. G. Turner. 2006. Fish community and food web responses to a whole-lake removal of coarse woody habitat. Fisheries 31:321-330.

Savino, J. F., and R. A. Stein. 1982. Predator-prey interactions between largemouth bass and bluegills as influenced by simulated, submersed vegetation. Transactions of the American Fisheries Society 111:255-266.

Schlosser, I. J. 1998. Fish recruitment, dispersal, and trophic interactions in a heterogeneous lotic environment. Oecologia 113:260-268.

Scott, W. B., and E. J. Crossman. 1979. Freshwater fishes of Canada. Bulletin 184. Fisheries Research Board of Canada, Ottawa.

Shepherd, T. D., and M. K. Litvak. 2004. Density-dependent habitat selection and the ideal free distribution in marine fish spatial dynamics: considerations and cautions. Fish and Fisheries 5:141-152.

Shroyer, S. M. 2011. Movement and site fidelity of flathead catfish in the Minnesota River. Pages 473-483 *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.

Stevens, E. D., and O. W. Tiemeier. 1961. Daily movement of channel catfish, Ictalurus punctatus (Rafinesque), in a farm pond. Transactions of the Kansas Academy of Science 64:218-224.

Stewart, D. R., and J. M. Long. 2012. Precision of channel catfish catch estimates using hoop nets in larger Oklahoma reservoirs. North American Journal of Fisheries Management 32:1108-1112.

Stoeckel, J. N., and B. M. Burr. 1999. A review of key reproductive traits and methods used to spawn Ictalurids. Pages 141-160 *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.

Trial, P. F., F. P. Gelwick, and M. A. Webb. 2001. Effects of shoreline urbanization on littoral fish assemblages. Journal of Lake and Reservoir Management 17:127-138.

Wagner, T., M. E. Benbow, T. O. Brenden, J. Qi, and R. Christian-Johnson. 2008. Buruli ulcer disease prevalence in Benin, West Africa: associations with land use/ cover and the identification disease clusters. International Journal of Health Geographics 7:25.

Werner, E. E. 1977. Species packing and niche complementarity in three sunfishes. American Naturalists 111:553-578.

Werner, E. E., and D. J. Hall. 1979. Foraging efficiency and habitat switching in competing sunfishes. Ecology 60:256-264.

Werner, E. E., G. G. Mittelbach, D. J. Hall, and J. F. Gilliam. 1983. Experimental tests of optimal habitat use in fish: the role of relative habitat profitability. Ecology 64:1525-1539.

Worthington, T. S., S. K. Brewer, T. B . Grabowski, and J. Mueller. 2013. Backcasting the decline of a vulnerable Great Plains reproductive ecotype: identifying threats and conservation priorities. Global Change Biology doi:10.1111/gcb. 12329.

Ziebell, C. D. 1973. Ultrasonic transmitters for tracking channel catfish. Progressive Fish-Culturist 35:28-32.

Table 1. Structural and abiotic characteristics of six Oklahoma reservoirs used to predict channel catfish *Ictalurus punctatus* abundance at the whole-lake scale.

| Reservoir | Lake Characteristics | | | | |
	Surface area (ha)	Shoreline length (km)	Maximum depth (m)	Secchi depth (cm, ± SD)	Chlorophyll-a (ug/L, ± SD)
McMurtry	467	29	16	43 ± 16	7.08 ± 0.22
Ponca	326	32	12	80 ± 16	22.70 ± 0.88
Okemah	299	45	14	56 ± 26	7.57 ± 0.60
Okmulgee	270	26	14	79 ± 20	8.34 ± 1.04
Lone Chimney	223	29	13	46 ± 14	10.12 ± 1.58
Greenleaf	372	27	14	69 ± 26	12.80 ± 0.22

Table 2. Habitat availability (% occurrence) measured within 100-m of shore from six Oklahoma reservoirs by side-scan sonar.

Reservoir	Habitat characteristics								
	Fine	Rocky boulder	Rocky	Bedrock boulder	Bedrock	Aquatic vegetation	Standing timber	Coarse woody debris	Other[†]
McMurtry	95.000	1.300	0.800	0.000	0.005	0.000	0.000	3.000	0.040
Ponca	63.000	19.000	9.000	0.400	0.002	9.000	0.000	0.080	0.000
Okemah	79.000	7.000	0.800	0.000	0.002	12.000	0.000	0.900	0.400
Okmulgee	63.000	17.000	0.300	0.000	0.200	20.000	0.000	0.070	0.100
Lone Chimney[a]	70.000	0.100	1.000	0.300	0.200	0.000	28.000	0.040	0.020
Greenleaf	55.000	6.000	2.000	0.000	0.010	35.000	0.000	2.000	0.100

† Non-natural occurring habitat (i.e., boat docks and fishing piers)
[a] Mapped visually on-site

Table 3. Error matrix of habitat classified within 100-m of shore from six Oklahoma reservoirs by side-scan sonar.

| Classified | Reference | | | | | | | Row total | Users accuracy |
	Fine	Rocky	Rocky boulder	Bedrock	Bedrock boulder	Aquatic vegetation	Course woody debris		
Fine	315	21	0	0	0	5	2	343	92%
Rocky	3	9	2	0	0	0	0	14	64%
Rocky boulder	4	10	37	0	0	0	0	51	73%
Bedrock	0	0	0	8	3	0	0	11	73%
Bedrock boulder	0	0	0	2	5	0	0	7	71%
Aquatic vegetation	0	0	0	0	0	81	0	81	100%
Course woody debris	1	0	0	0	0	0	8	9	89%
Column total	323	40	39	10	8	86	10	516	
Producers accuracy	98%	23%	95%	80%	63%	94%	80%	Overall accuracy	90%

Table 4. Select land use characteristics (%) estimated from a 1-km buffer surrounding six reservoirs in Oklahoma.

Reservoir	Habitat Characteristics					
	Residential developed	Forests	Grassland	Agriculture	Shrub	Wetlands
McMurtry	5.28	46.61	45.72	2.35	0.00	0.04
Ponca	17.89	9.56	41.62	15.79	2.31	12.84
Okemah	6.20	59.48	20.23	14.09	0.00	0.00
Okmulgee	8.59	69.23	14.07	8.11	0.00	0.00
Lone Chimney	4.64	20.59	66.97	7.80	0.00	0.00
Greenleaf	5.97	80.15	7.76	0.00	1.50	4.62

Table 5. Pearson correlations between each of the habitat variables measured at the 150-m scale from six reservoirs in Oklahoma.

	Habitat variables					
	Secchi depth	Bedrock boulder	Bedrock	Fine	Other	Rocky boulder
Secchi depth	1.00					
Bedrock boulder	0.04	1.00				
Bedrock	0.01	0.03	1.00			
Fine	-0.28	0.05	-0.12	1.00		
Other	0.04	-0.02	-0.03	0.07	1.00	
Rocky boulder	0.30	-0.06	0.06	-0.18	-0.04	1.00
Rocky	0.19	0.13	-0.05	-0.06	-0.07	0.16
Aquatic vegetation	0.27	-0.09	0.08	**-0.64**	-0.03	-0.14
Coarse-woody debris	-0.24	-0.05	-0.08	0.21	-0.03	-0.16
Developed	0.16	-0.05	**0.36**	-0.12	0.20	**0.41**
Forests	-0.07	-0.12	-0.04	0.14	-0.01	-0.08
Grassland	-0.21	0.20	-0.05	0.21	-0.02	-0.08
Agriculture	0.19	-0.02	-0.03	-0.20	-0.01	-0.03

Table 5. continued.

	Habitat variables						
	Rocky	Aquatic vegetation	Coarse-woody debris	Residential developed	Forests	Grassland	Agriculture
Secchi depth							
Bedrock boulder							
Bedrock							
Fine							
Other							
Rocky boulder							
Rocky	1.00						
Aquatic vegetation	-0.13	1.00					
Coarse-woody debris	-0.12	-0.14	1.00				
Residential developed	-0.05	0.07	-0.18	1.00			
Forests	-0.19	-0.01	0.20	-0.24	1.00		
Grassland	0.14	**-0.39**	-0.07	-0.13	**-0.56**	1.00	
Agriculture	-0.05	0.30	-0.06	-0.03	-0.21	-0.07	1.00

Table 6. Pearson correlations between each of the habitat variables measured at the 500-m scale from six reservoirs in Oklahoma.

	Habitat variables					
	Chlorophyll-a	Bedrock boulder	Bedrock	Fine	Other	Rocky boulder
Chlorophyll-a	1.00					
Bedrock boulder	0.27	1.00				
Bedrock	-0.24	0.02	1.00			
Fine	-0.14	0.01	-0.15	1.00		
Other	-0.19	-0.06	0.00	0.10	1.00	
Rocky boulder	0.25	0.12	0.12	-0.19	0.14	1.00
Rocky	**0.46**	0.10	-0.13	-0.04	-0.13	0.15
Aquatic vegetation	0.04	-0.11	-0.13	**-0.68**	-0.04	-0.06
Coarse-woody debris	-0.14	-0.08	-0.19	0.16	-0.08	-0.28
Residential developed	0.14	-0.05	0.10	-0.20	0.27	**0.55**
Forests	**-0.43**	-0.08	0.02	-0.13	0.27	0.00
Grassland	0.21	0.13	0.07	0.26	-0.27	-0.20
Agriculture	0.14	-0.06	-0.06	-0.17	-0.01	0.15

Table 6. continued.

	Habitat variables						
	Rocky	Aquatic vegetation	Coarse-woody debris	Residential developed	Forests	Grassland	Agriculture
Chlorophyll-a							
Bedrock boulder							
Bedrock							
Fine							
Other							
Rocky boulder							
Rocky	1.00						
Aquatic vegetation	-0.11	1.00					
Coarse-woody debris	-0.22	0.05	1.00				
Residential developed	0.02	0.13	-0.20	1.00			
Forests	**-0.35**	**0.33**	0.09	-0.03	1.00		
Grassland	0.13	**-0.50**	-0.11	-0.28	**-0.70**	1.00	
Agriculture	0.19	0.15	-0.17	**0.32**	**-0.35**	-0.10	1.00

Table 7. Pearson correlations between each of the habitat variables measured at the whole-lake scale from six reservoirs in Oklahoma.

	Secchi depth	Surface area	Shoreline length	Max depth	Chlorophyll-a	Bedrock boulder	Bedrock	Fine	Other
					Habitat variables				
Secchi depth	1.00								
Surface area	-0.22	1.00							
Shoreline length	-0.19	-0.12	1.00						
Max depth	**-0.54**	**0.68**	-0.08	1.00					
Chlorophyll-a	**0.59**	-0.06	-0.10	**-0.76**	1.00				
Bedrock boulder	0.15	**-0.40**	-0.07	**-0.81**	**0.76**	1.00			
Bedrock	0.02	**-0.71**	**-0.44**	-0.19	-0.29	0.13	1.00		
Fine	**-0.76**	**0.49**	**0.32**	**0.68**	**-0.52**	-0.26	-0.25	1.00	
Other	-0.10	-0.13	**0.84**	0.17	**-0.44**	**-0.52**	-0.27	0.17	1.00
Rocky boulder	**0.90**	-0.21	-0.04	**-0.52**	**0.58**	0.24	0.00	**-0.51**	-0.07
Rock	**0.53**	0.04	0.02	**-0.68**	**0.97**	**0.75**	**-0.40**	**-0.33**	**-0.38**
Aquatic vegetation	**0.61**	0.03	-0.19	-0.06	0.10	**-0.43**	-0.14	**-0.72**	0.20
Coarse-woody debris	**-0.47**	**0.91**	-0.09	**0.83**	**-0.36**	**-0.59**	**-0.59**	**0.53**	0.02
Residential developed	**0.72**	-0.05	0.01	**-0.66**	**0.88**	**0.63**	-0.24	**-0.36**	-0.30
Forests	0.13	0.22	-0.06	**0.55**	**-0.56**	**-0.92**	-0.06	-0.15	**0.47**
Grassland	**-0.57**	-0.15	-0.09	-0.17	0.11	**0.67**	0.26	**0.41**	**-0.49**
Agriculture	**0.32**	**-0.49**	**0.62**	**-0.64**	**0.42**	**0.53**	-0.03	-0.05	0.30

Table 7. continued.

	Rocky boulder	Rock	Aquatic vegetation	Coarse-woody debris	Residential developed	Forests	Grassland	Agriculture
				Habitat variables				
Secchi depth								
Surface area								
Shoreline length								
Max depth								
Chlorophyll-a								
Bedrock boulder								
Bedrock								
Fine								
Other								
Rocky boulder	1.00							
Rock	**0.59**	1.00						
Aquatic vegetation	**0.32**	-0.04	1.00					
Coarse-woody debris	**-0.54**	-0.30	0.07	1.00				
Residential developed	**0.83**	**0.93**	0.00	**-0.45**	1.00			
Forests	-0.07	**-0.63**	**0.74**	**0.41**	**-0.52**	1.00		
Grassland	**-0.41**	0.16	**-0.88**	-0.15	0.00	**-0.84**	1.00	
Agriculture	**0.55**	**0.52**	**-0.33**	**-0.70**	**0.63**	**-0.55**	0.16	1.00

Table 8. Results of negative binomial (NB) and zero-inflation (ZINB) mixed models† predicting channel catfish *Ictalurus punctatus* abundance (i.e., all size class combined and sub-stock size (< 281 mm total length)) in relation to habitat variables‡ at the 150-m scale from six reservoirs in Oklahoma.

Group	Secchi depth	Fine	Bedrock	Aquatic vegetation	Coarse-woody debris	Rock	Rock boulder	Residential developed	Agriculture	AIC_c	w	Evidence ratio
All				-					-	2103.00	0.29	1.00
	-						+		-	2103.50	0.22	1.28
		+							-	2103.90	0.18	1.57
				-				-	-	2105.00	0.11	2.72
				-		+	+		-	2105.50	0.08	3.49
		+						+	-	2105.90	0.07	4.26
	-								-	2106.70	0.05	6.36
Sub-stock				-	+	-				1160.00	0.47	1.00
				-						1162.10	0.16	2.86
		+								1162.50	0.13	3.49
	-									1163.00	0.10	4.48
				-	+					1163.80	0.07	6.69
			+	-	+					1164.00	0.06	7.39

† All models Δ < 4 are presented

‡ Positive and negative symbols represent variables that occurred in the model and specific sign of the coefficient.

Table 9. Results from negative binomial (NB) and zero-inflation (ZINB) mixed models† predicting channel catfish *Ictalurus punctatus* abundance (i.e., all size class combined and sub-stock size (< 281 mm total length)) in relation to habitat variables‡ at the 500-m scale from six reservoirs in Oklahoma.

Group	Fine	Bedrock	Bedrock boulder	Aquatic vegetation	Coarse-woody debris	Rock	Rocky boulder	Agriculture	AIC$_c$	w	Evidence ratio
All				-			+	-	2138.80	0.45	1.00
				-				-	2140.50	0.19	2.34
				-	+		+	-	2140.80	0.16	2.72
			+	-				-	2142.50	0.07	6.36
	+	+				-			2142.70	0.06	7.03
								-	2142.80	0.06	7.39
Sub-stock	+	+				-			1135.00	0.38	1.00
	+	+	+		+				1135.10	0.36	1.05
				-					1138.10	0.08	4.71
		+							1138.40	0.07	5.47
			+	-					1138.70	0.06	6.36
	+								1138.80	0.06	6.69

† All models Δ < 4 are presented
‡ Positive and negative symbols represent variables that occurred in the model and specific sign of the coefficient.

Table 10. Results of negative binomial (NB) mixed models† predicting channel catfish *Ictalurus punctatus* abundance (i.e., all size class combined and sub-stock size (< 281 mm total length)) in relation to habitat variables‡ at the whole-lake scale from six reservoirs in Oklahoma.

Group	Secchi depth	Fine	Bedrock	Bedrock boulder	Aquatic vegetation	Coarse-woody debris	Shoreline length	Residential developed	Agriculture	AIC_c	w	Evidence ratio
All					-		+	-		263.90	0.33	1.00
	-									264.90	0.20	1.65
		+								265.60	0.14	2.34
							+	-		265.90	0.12	2.72
					-			-		266.50	0.09	3.67
		+	+	-						267.30	0.06	5.47
		+	+						+	267.60	0.05	6.36
Sub-stock							+	-		208.20	0.35	1.00
					-		+	-		208.60	0.29	1.22
			+				+	-		210.10	0.13	2.59
						-	+	-		210.20	0.13	2.72
					-			-		212.00	0.05	6.69
	-									212.00	0.05	6.69

† All models Δ < 4 are presented

‡ Positive and negative symbols represent variables that occurred in the model and specific sign of the coefficient.
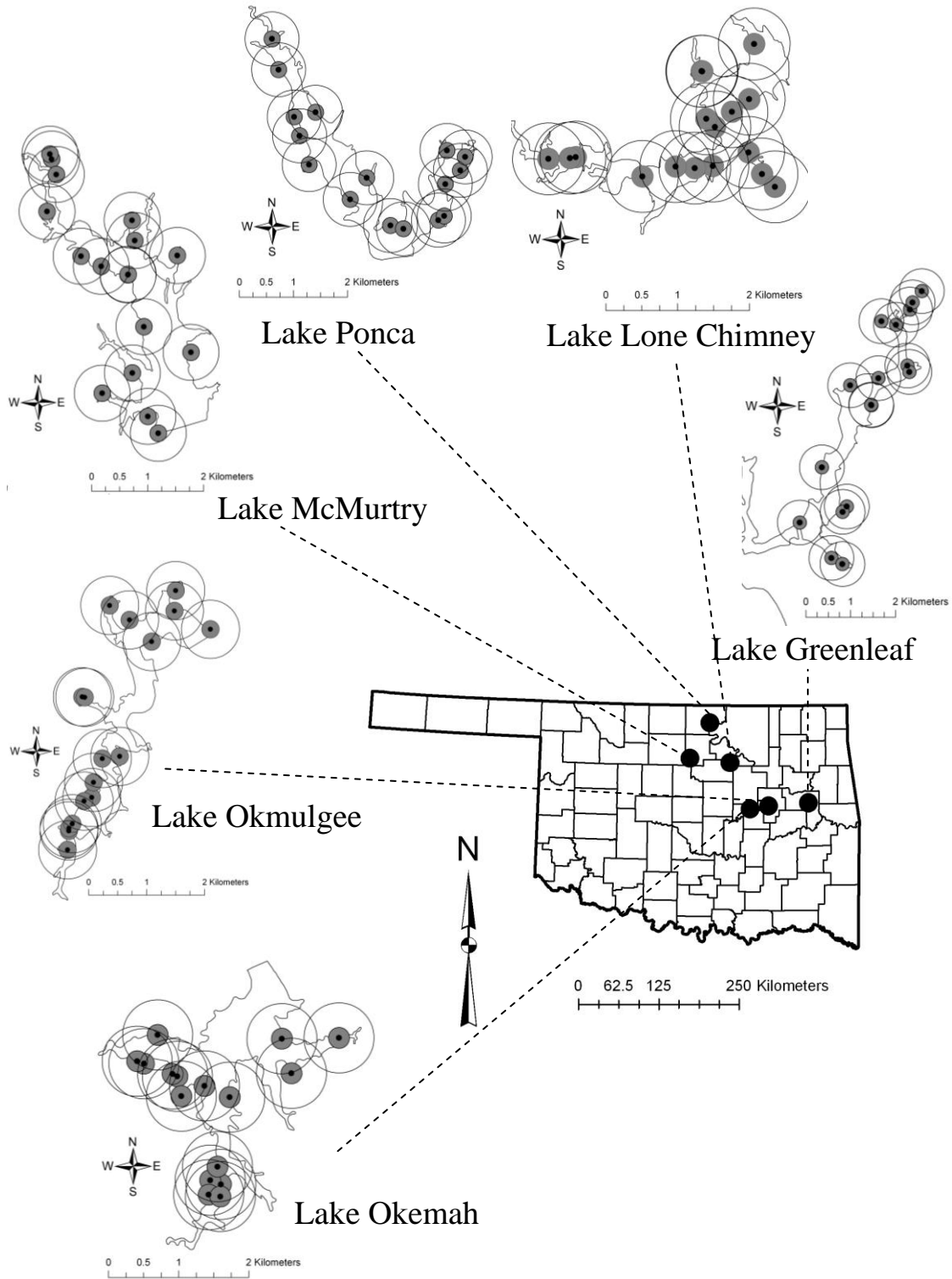
Figure 1. Map showing sampling sites and buffers (150 m and 500 m) for six Oklahoma reservoirs.
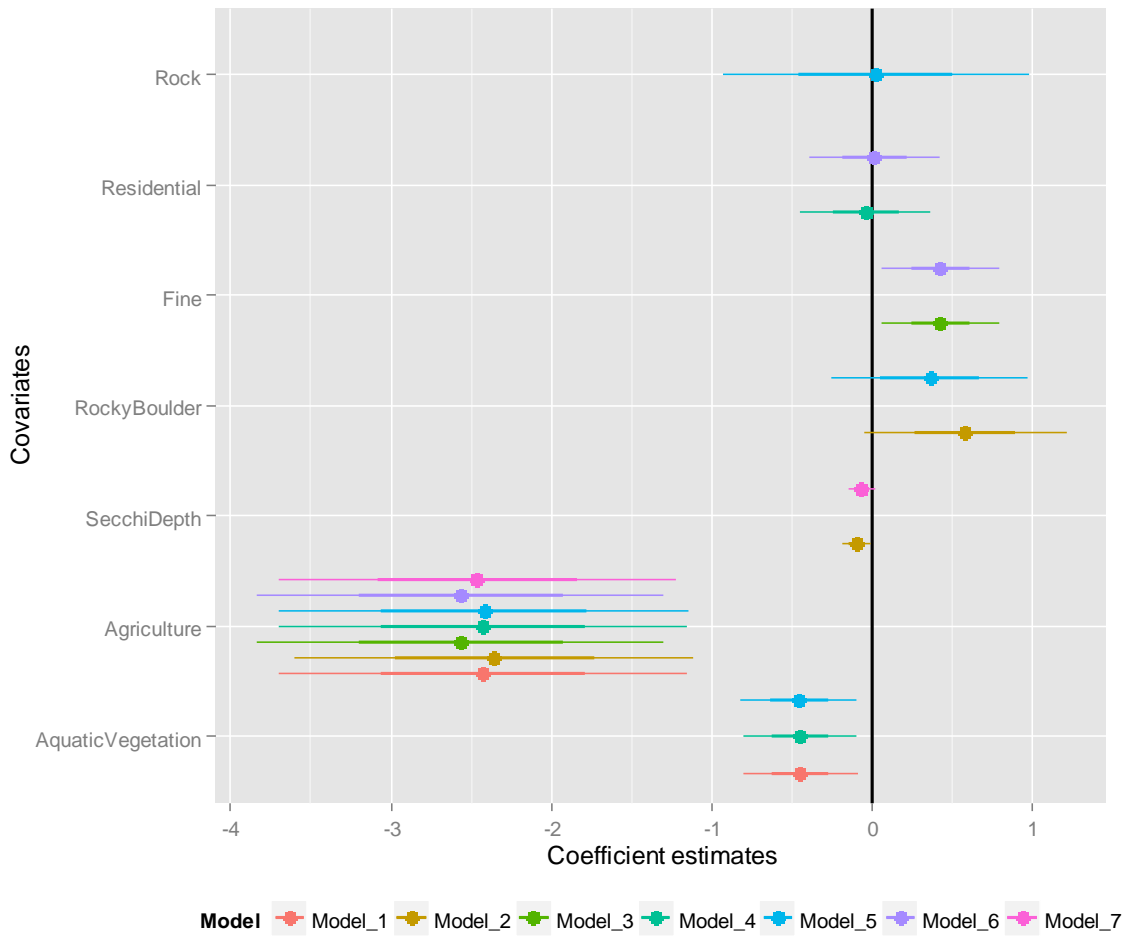
Figure 2. Coefficient plots from the negative-binomial mixed models showing the relationship of channel catfish *Ictalurus punctatus* abundance (all size groups considered) to habitat variables at the 150-m scale. Confidence intervals that span zero indicate no statistically significant effect at alpha = 0.05.
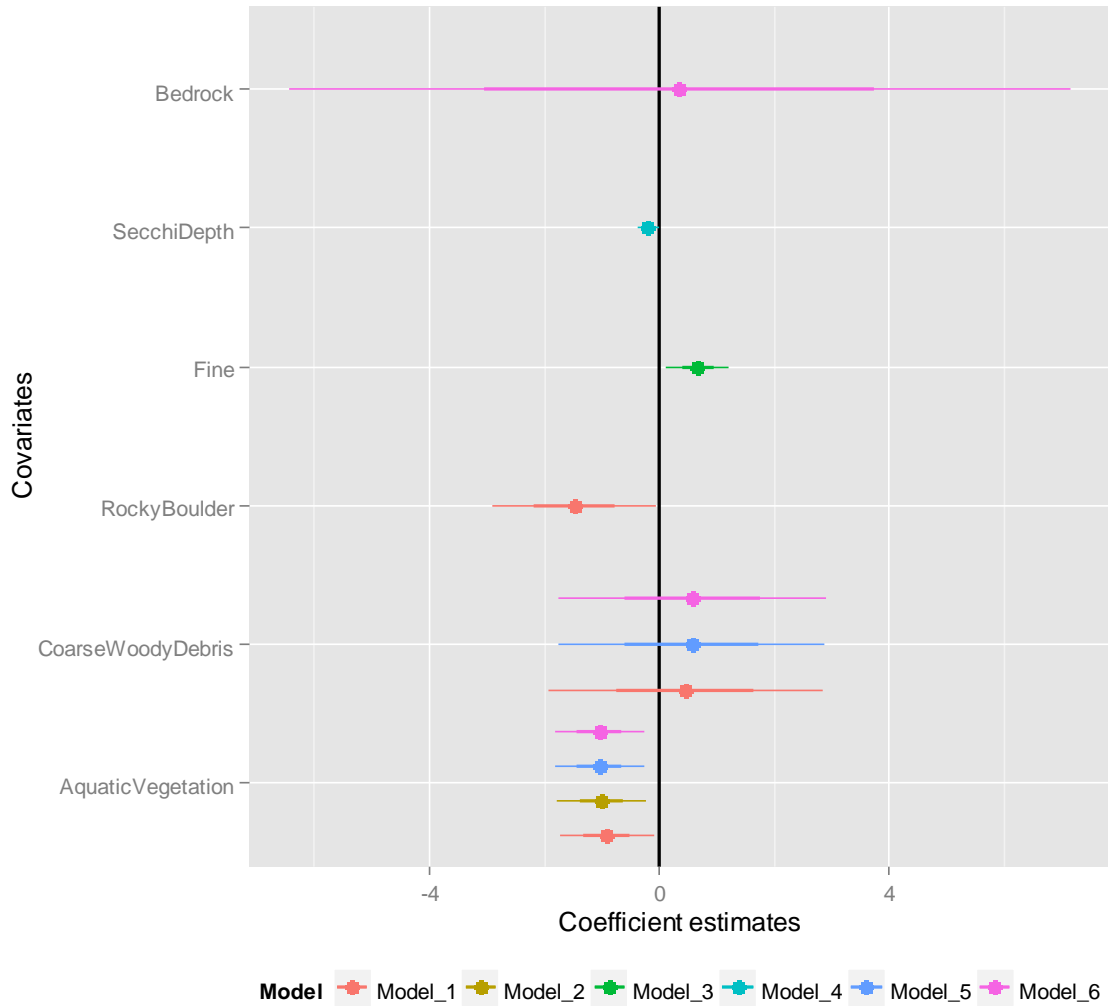
Figure 3. Coefficient plots from the zero-inflated negative-binomial mixed models showing the relationship of channel catfish *Ictalurus punctatus* abundance (< 280 mm total length) to habitat variables at the 150-m scale. Confidence intervals that span zero indicate no statistically significant effect at alpha = 0.05.
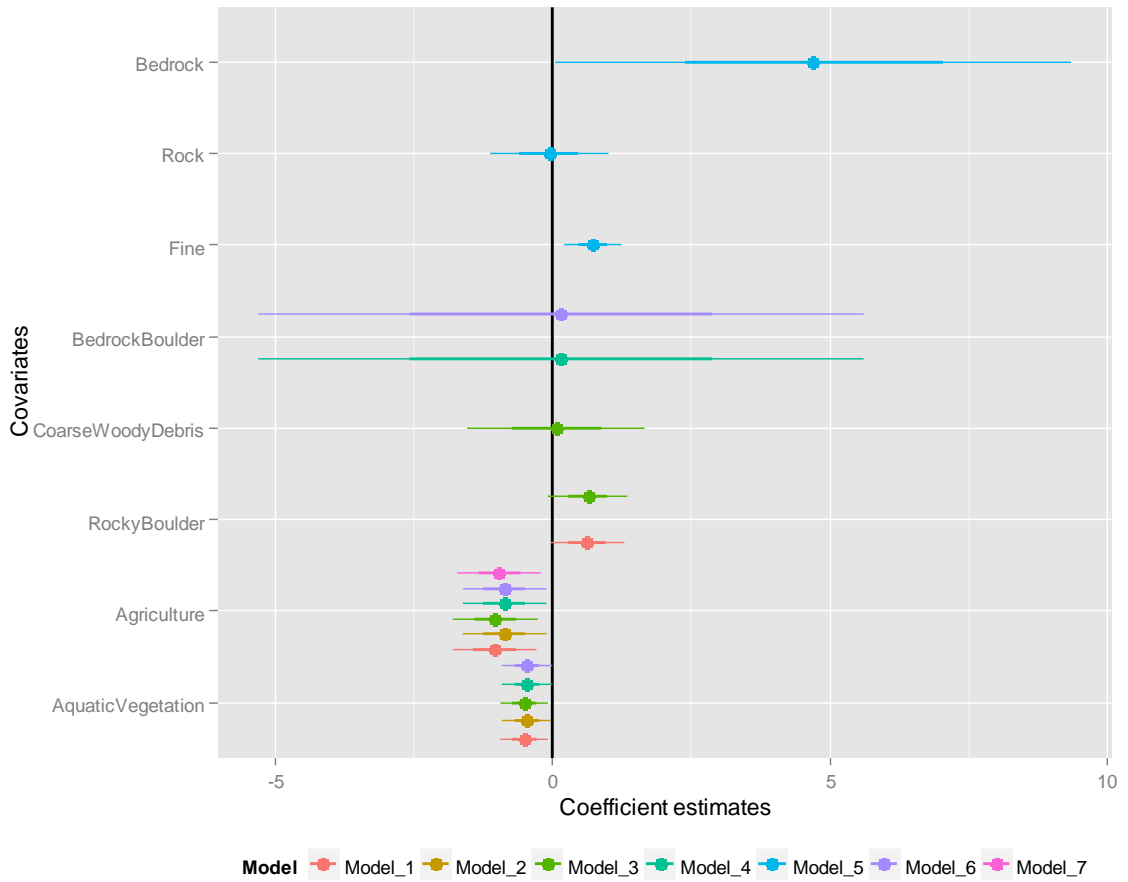
Figure 4. Coefficient plots from the negative-binomial mixed models showing the relationship of channel catfish *Ictalurus punctatus* abundance (all size groups considered) to habitat variables at the 500-m scale. Confidence intervals that span zero indicate no statistically significant effect at alpha = 0.05.
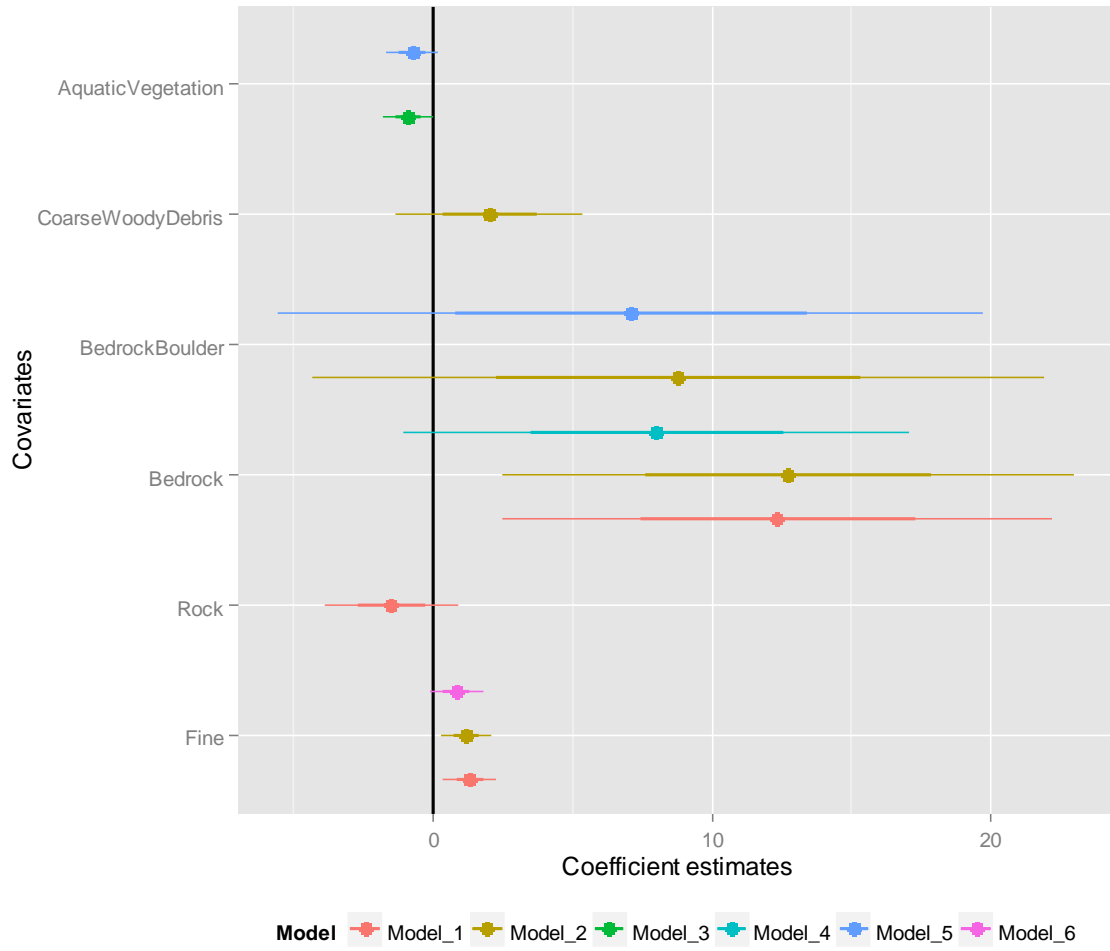
Figure 5. Coefficient plots from the zero-inflated negative-binomial mixed models showing the relationship of channel catfish *Ictalurus punctatus* abundance (< 280 mm total length) to habitat variables at the 500-m scale. Confidence intervals that span zero indicate no statistically significant effect at alpha = 0.05.
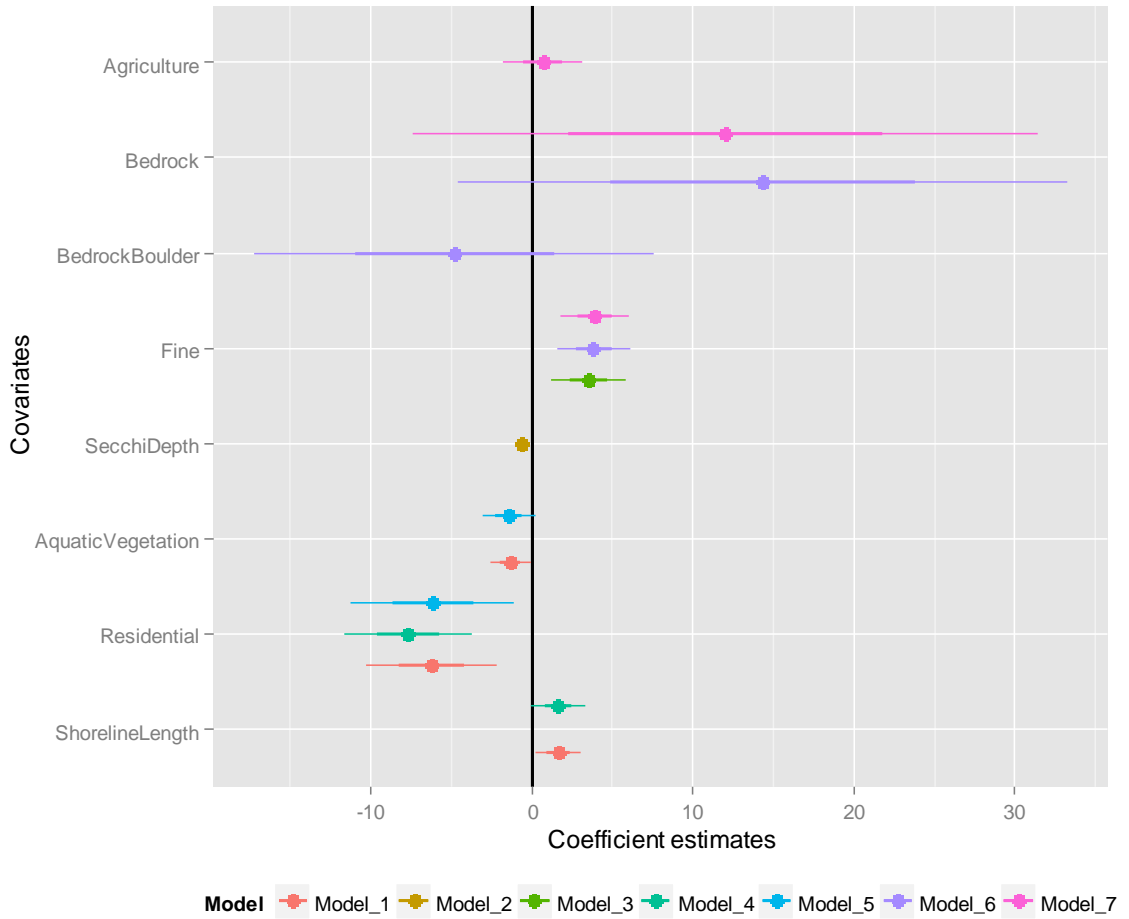
Figure 6. Coefficient plots from the negative-binomial mixed models showing the relationship of channel catfish *Ictalurus punctatus* abundance (all size groups considered) to habitat variables at the whole-lake scale. Confidence intervals that span zero indicate no statistically significant effect at alpha = 0.05.
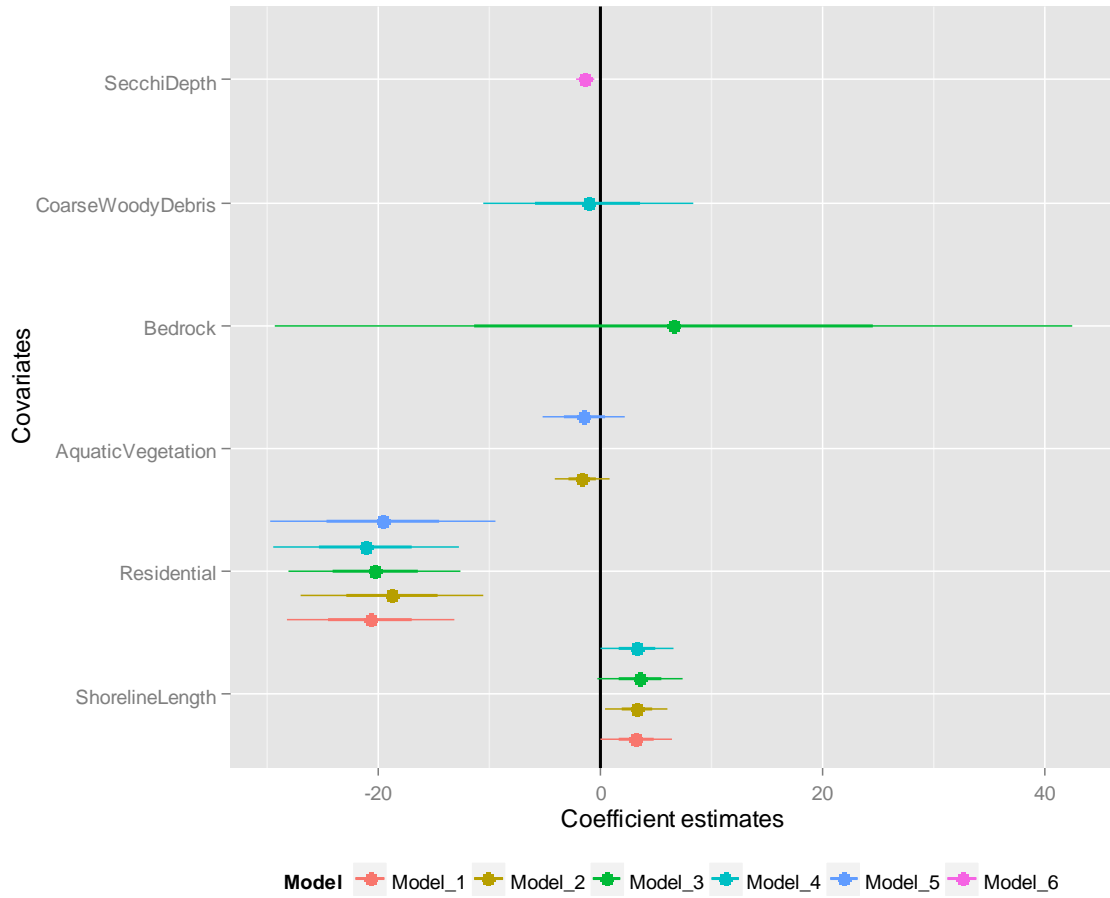
Figure 7. Coefficient plots from the negative-binomial mixed models showing the relationship of channel catfish *Ictalurus punctatus* abundance (< 280 mm total length) to habitat variables at the whole-lake scale. Confidence intervals that span zero indicate no statistically significant effect at alpha = 0.05.

CHAPTER V

TROPHIC ECOLOGY OF STOCKED AND WILD CHANNEL CATFISH *ICTALURUS*

PUNCTATUS COMPARED TO POTENTIAL PREDATORS AND COMPETING SPECIES IN

SIX OKLAHOMA RESERVOIRS

Introduction

Stocking fish is the primary management option used to manage channel catfish *Ictalurus punctatus* (Michaletz 2009; Chapter II). Stock enhancement has generally resulted in mixed success and increasing post-release survival is an important focus of stock enhancement research (Blankenship and Leber 1995). Stocking small fry (< 100 mm total length (TL)) tends to be less successful because vulnerability to predation is high (Michaeltz 2009). Stocking larger size fish (> 100 mm TL) can increase survival but stocking success (i.e., high contribution to the fishery and good growth) is not consistent (Siegwarth and Johnson 1998; Odenkirk 2002; Chapter II). Mechanisms like predation and competition (both inter- and intra-specific) likely play a major role in reducing survival of stocked channel catfish. Understanding factors that influence stocked fish post-stocking could be used to help refine these stock enhancement programs (Lorenzen 2005).

Channel catfish population characteristics are commonly associated with density-dependent mechanism (Michaletz 2009). High relative abundance generally results in decreased

size-structure, growth, and increased mortality (Michaletz 2009). Additionally, the abundance of resident channel catfish can also have a similar impact on stocking success (Chapter II). In Chapter II, stocking contribution and growth of advanced size fingerlings (178 mm TL) was significantly higher in a reservoir that had lower relative abundance of resident channel catfish. Those fish were able to reach lengths of 340 to 400 mm two-year post-stock, whereas fish stocked in a reservoir with an established resident population grew 46 mm (224 mm TL) in two years (Chapter II).

The ability of stocked fish to acclimate to a new environment is a critical period. The resident fish and reduced prey resources may make it difficult for stocked fish to acclimate post-stocking. Foraging success and predator avoidance is essential for survival of stocked fish (Hossain et al. 2002). Brennan et al. (2006) found that common snook *Centropomus undecimalis* did not acclimate to wild resources and survival was consequently lower. Diet studies indicate that stocked channel catfish are able to forage successfully (Siegwarth and Johnson 1998), but comparisons to other species or resident channel catfish were not made. A study that compares diets of stocked to resident channel catfish, and to other potentially competing species, would help identify factors that may influence post-release survival.

Diet studies require large samples collected over an extended period. All observed diet items are assumed to be assimilated equally, but that is intuitively invalid. Stable isotope (δ^{13}C and δ^{15}N) techniques are efficient (low sample sizes) and commonly used to understand food-web dynamics, elucidate trophic relationships among species (Post 2003), and provide long-term average of feeding trends reflecting assimilated dietary items (Post 2002). I was interested in understanding trophic relationships (based on stable isotope analysis) among stocked fish (identified by oxytetracyline [OTC] marks) and other species, including resident channel catfish. I specifically sought to identify potential prey items consumed and evaluate trophic relationships (i.e., theoretical trophic-niche space and trophic overlap) between stocked and resident channel

catfish; and identify trophic relationships of potential competitors and predators of channel catfish.

Study Site

The study area included six reservoirs in Oklahoma (Figure 1), ranging from 223 ha to 465 ha surface area. In general, the reservoirs were mesotrophic to eutrophic and had different abundances of channel catfish populations (Stewart and Long 2012; Chapter III). Lakes McMurtry (465 ha) and Ponca (326 ha) were eutrophic (57 TSI) with average Secchi depths of 47- and 78-cm (OWRB 2011), had relatively high numbers of resident channel catfish (ODWC, unpublished data), and served as "control" reservoirs. Lakes Okemah (270 ha) and Okmulgee (270 ha) were mesotrophic (46 and 48 TSI) with average Secchi depths of 78- and 116-cm (ORWB 2011), and had artificially high relative numbers of channel catfish, the result of years of repeated stocking (ODWC, unpublished data) until 2010 when stocking ceased for two years. Lakes Lone Chimney (223 ha) and Greenleaf (372 ha) were eutrophic (53 and 52 TSI) with average Secchi depth of 67- and 111-cm (ORWB 2011), supported low numbers of channel catfish (ODWC unpublished data) and was not stocked since 1997 until 2010 when approximately 20,513 and 16,836 fish were stocked in each (178-mm TL average length).

Methods

Each impoundment was sampled in August 2011and 2012. Channel catfish populations were sampled with tandem hoop nets (Stewart and Long 2012), whereas other fish species were collected with boat electrofishing (e.g., gizzard shad *Dorosoma cepedianum*, bluegill, white crappie, flathead catfish, longear sunfish *Lepomis megalotis* or redear sunfish *Lepomis micropholus* (2012 only), and largemouth bass (2012 only)). All fish were stored on ice after sampling and processed for stable isotope analysis the day of collection (see below). Aquatic vegetation from the littoral zone was taken by hand from each reservoir and benthic invertebrates

and Asian clam *Corbicula fluminea* were collected using an Ekman grab or by hand, washed of sediment and soaked in de-chlorinated water for 6 hr. Zooplankton were collected with a 75-μm mesh net and stored in distilled water for 6 hr (Feuchtmayr and Grey 2003; Schielke and Post 2010).

Dorsal muscle tissue from five channel catfish per proportional size distribution (PSD) categories (Anderson 1980; Gabelhouse 1984) per reservoir was collected for $\delta^{13}C$ (identification of an animals diet source (Post 2002)) and $\delta^{15}N$ (allows for determination of an animals trophic position (Post 2002)) isotope analysis. Fish, invertebrate and aquatic vegetation samples were dried for 48 hrs at 75°C, ground to powder using a mortar and pestle, and stored in aluminum containers (Jones et al. 1999). Samples were processed by the University of New Hampshire Stable Isotope Laboratory (~ $8 sample^{-1}, 2012 U.S. dollars) using a Costech ECS4010 elemental analyzer (Costech Analytical Technologies Inc, Valencia, CA) coupled to an DELTA$_{plus}$ XP isotope ration mass spectrometer (Thermo-Scientific, Bremen, Germany). Stable isotopes were expressed in delta notation (δ) measured as part per mille (‰) in reference to the respective international standards (Fry 2002),

$$\delta^{13}C, \delta^{15}N\ (‰) = [(R_{sample}/R_{standard} - 1)] \times 1,000$$

where R is the fraction of the heavy to light isotope (Fry 2002).

One of the goals of this study was to identify if trophic level and feeding ecology differed between wild and stocked fish, which were marked with oxytetracycline (OTC) (Stewart and Long 2011; Chapter II). Therefore, lapilli otoliths (Long and Stewart 2010) were removed from channel catfish collected from lakes where fish were stocked (Lone Chimney and Greenleaf), to assess for OTC marks. Otoliths were embedded in epoxy, mounted on slides, and sanded to the core (Stewart et al. 2009). Presence of an OTC mark was determined by examining otoliths with an epi-fluorescent compound microscope (Motic BA 400 T-FL, Motic Incorporation LTD, Hong

Kong) equipped with a 100-W ultraviolet (Hg arc) light source and fluorescent filter (495

dichroic mirror, 470 excitation filter, and 515-nm IF barrier filter).

Data Analysis

The stable isotope δ^{15}N of consumers is typically enriched by 3-4‰ from that of its' prey and

commonly used to estimate trophic position (TP) (Post 2002). Variability in δ^{15}N is corrected by

using a baseline signature representing the base of the food web,

$$TP_{[ij]} = \left(\frac{\delta^{15}N_{fish\,[ij]} - \delta^{15}N_{baseline\,[ij]}}{3.4} \right) + 2$$

where the ratio of the corrected δ^{15}N of fish in lake i in year j is divided by 3.4, which is the

trophic level increase in δ^{15}N and the addition of 2 because the baseline signature was from a

consumer (Post 2002).

Stable isotope values and TP were assessed for normality using a Shapiro-Wilk test.

Trophic position met the assumptions of normality ($W = 0.99$, $P > 0.05$), whereas both δ^{13}C and

δ^{15}N values were non-normally distributed and were transformed using the reciprocal ($1/\delta^{13}$C)

and square ((δ^{15}N)^2) transformations. A multivariate analysis of variance (MANOVA) was used

to test for significance among species, year, and lake effects on the mean transformed δ^{13}C and

δ^{15}N values using the Wilks' lambda statistic (Wilks 1932; Zar 1999). For channel catfish only,

an ANOVA was applied to check for significant reservoir and year effects of TP of both stocked

and then separately with all size classes combined. When significant ($P < 0.05$) differences were

found, a Tukey post-hoc test was applied.

Relative contributions of prey sources to diets of fish species were quantified with a

Bayesian mixing model in package SIAR (Parnell et al. 2008), which has the advantage of

incorporating variability of both prey and consumer isotope values into the mixture (Jackson et al.

2011). Contribution of the prey source to the consumer mixture was estimated by the posterior

probability distribution that was calculated from the model using the Markov-chain Monte Carlo

(MCMC) method (Jones et al. 2010). Additionally, ancillary sources of information like direct

measurement of stomach contents and published diet information was used to construct prior

information. The prior information can help reduce uncertainty in model parameter estimates and

dietary estimates (Moore and Semmens 2008). Care must be taken when incorporating prior

information because zeros and small error estimates can significantly change the median estimate.

To avoid this, uninformative priors of 5% to 10% were used in place of zeros and the variance

was never weighted less than 15%. Diet items were pooled to form 6 distinct prey sources:

aquatic vegetation (2-3 species), zooplankton (all species combined), benthic invertebrates (all

species combined), sunfish (2-4 species), catfish (2 species) and shad (1 species). Each model

was run for 1,000,000 iterations and the initial 50,000 iterations were discarded (i.e., burn-in

period) so that all estimates were reflective of the simulated chain at equilibrium. The remaining

iterations were thinned by 100 to reduce sample autocorrelation from the random posterior draws

(McCarthy 2007). Fractionation factors were assumed to be 1.0 ± 0.30‰ for $\delta^{13}C$ and $3.4 \pm$

0.30‰ for $\delta^{15}N$ (Post 2002).

To identify aspects of trophic structure from community level aspects, population metrics

were derived from the $\delta^{13}C$ and $\delta^{15}N$ and corresponding Euclidean distances (Layman et al. 2007;

Jackson et al. 2012). To estimate prey niche space of organisms, the standard ellipse (SEA_c),

corrected for small sample sizes, was calculated (Jackson et al. 2012). Mean distance of the

centroid (CD) was used to estimate variability and diversity of diets (Layman et al. 2007; Jackson

et al. 2012). The range of nitrogen (NR) and carbon (CR) that was exploited by the population

was calculated. Lastly, the standard deviation of nearest neighbor distance (SDNND), calculated

from the distances of each individual to its neighbor, and was used as an informative measure of

the variation of individuals in isotopic space.

Lastly, to evaluate possible ontogenetic shifts in carbon and nitrogen utilization for channel catfish, $\delta^{13}C$ and $\delta^{15}N$ were modeled as a function of log10-transformed fish length for each population. Random-intercept models with a random "Year" effect was used to account for random variation between years. All analyses were performed using the R program (R Development Core Team 2008).

Results

Isotopic values of basal resources like benthic invertebrates were significantly different over time for both $\delta^{15}N$ and $\delta^{13}C$ (Wilks' $\lambda = 0.02$, $F_{5,22} = 12.89$, $P < 0.01$), and changes in $\delta^{15}N$ and $\delta^{13}C$ in channel catfish signatures were evident by a significant two-way interaction between lake and year (Wilks' $\lambda = 0.02$, $F_{3,10} = 5.65$, $P < 0.05$). Channel catfish TP varied among impoundments and ranged between 2.81 and 3.85 (Figure 2). Channel catfish in lakes McMurtry and Okemah were at a lower trophic level compared to fish in lakes Okmulgee and Greenleaf. Channel catfish TP estimates were higher in 2012 than 2011 in all lakes except at Lake Lone Chimney, which was evident by a significant two-way interaction between lake and year ($F_{5,221} = 5.97$, $P < 0.001$). The TP of stocked fish ranged from 3.04 to 3.45, which was higher than the TP of conspecific wild channel catfish but the estimates did not change between lake or year ($F_{1,32} = 0.06$, $P = 0.25$). Stocked channel catfish in Lake Greenleaf were at a higher trophic level than stocked fish in Lake Lone Chimney ($F_{1,33} = 0.30$, $P < 0.05$).

The inclusion of the prior information reduced the amount of uncertainty in diet contribution estimates, and results from those models were reported herein. Diet items like benthic invertebrates, zooplankton, and sunfish were three prey resources that consistently contributed to channel catfish diets. As for stocked fish in Lake Greenleaf (Table 1), contribution of aquatic vegetation to diets declined from 2010 to 2012 (27% to 9%), while benthic invertebrates increased (32% to 50%), which was comparable to similar-size (< 280 mm TL) wild

fish (Table 2). Diets of fish stocked in Lake Lone Chimney consisted primarily of zooplankton and benthic invertebrates (Table 1), whereas similar-size wild channel catfish diets changed from aquatic vegetation, zooplankton, and benthic invertebrates in 2010 to zooplankton and fish in 2011 (Table 2). The proportional contributions of zooplankton, benthic invertebrates, and fish sources were similar between stock-size (Table 3) and quality-size (Table 4) channel catfish in all reservoirs except Lake Lone Chimney where contribution of fish to diets increased from 2011 to 2012.

The range of $\delta^{15}N$ and $\delta^{13}C$ exploited by channel catfish size groups varied among impoundments (Table 5) and was greatest for stocked channel catfish. The mean CD, a measure of variability and diversity of diet, was generally larger for smaller-size channel catfish, indicating a greater range in resource utilization. The smaller CD estimates for larger-size channel catfish suggest greater resource specialization and those estimates were comparable to other piscivorous fish species like white crappie and flathead catfish. The amount of individual variability, measured as SDNND, was generally lower for channel catfish compared to bluegill, white crappie, and largemouth bass. Isotopic niche area of channel catfish mostly overlapped with other channel catfish size groups (Figure 3 and 4). Overlap with species like bluegill ranged from 0-100% and isotopic niche area of quality-size channel catfish averaged 47% overlapped with bluegill. Overlap between hatchery-origin channel catfish and bluegill was estimated to be much lower (19%). The area of overlap between channel catfish and both longear and redear sunfish with channel catfish ranged from 0-67%, but was highly variable among impoundments. Overlap with isotopic niche areas of white crappie, flathead catfish, and largemouth bass was from 0% to approximately 47%.

Random-intercept linear regression models indicated few significant trends with channel catfish length and $\delta^{13}C$, whereas all models for $\delta^{15}N$ were significant except at Lake McMurtry (Table 6). Channel catfish trophic level was positively related to fish length at lakes Ponca,

110

Okmulgee, Lone Chimney, and Greenleaf, but not at Lake McMurtry. In contrast, carbon utilization was positively related to channel catfish length at lakes Okmulgee and Lone Chimney.

Discussion

Estimated contributions of prey to diets of stocked fish were comparable to resident channel catfish. This does not suggest that stocked fish were able to acclimate equally to their new environment. Intraspecific competition reduces growth and increase mortality in channel catfish populations (Michaletz 2009). The results of my study agree with these earlier findings. Abundance of channel catfish was greater in Lake Lone Chimney than in Lake Greenleaf (Chapter II). Diet overlap between stocked channel catfish and other species in Lake Greenleaf did not occur until age-2 (i.e., 2012, 2 years poststocking); whereas, models indicated a high degree of intraspecific isotopic niche overlap between stocked and wild fish in Lake Lone Chimney in both years of assessment. Moreover, growth of stocked channel catfish in Lake Greenleaf was high in contrast to growth in Lake Lone Chimney, strongly suggesting that intraspecific competition played a role. Thus, stocking channel catfish in reservoirs with a high abundance of natural occurring channel catfish could increase intraspecific competition and reduce stocking success.

The widest niche space occurred for organisms at intermediate trophic levels that foraged on zooplankton and aquatic invertebrates. A relatively narrower niche space was observed for piscivorous species. Channel catfish tended to be at lower trophic positions, feeding primarily on aquatic vegetation and benthic invertebrates; but the high δ^{15}N and δ^{13}C range indicated high dietary plasticity compared to other species. This generalist strategy may help reduce competition with other species despite the high level of isotopic overlap with bluegill, longear, and redear sunfish. These three sunfish (Centrarchidae) species typically inhabit aquatic vegetation (Crowder and Cooper 1979; Savino and Stein 1982), whereas channel catfish

abundance was negatively related with aquatic vegetation (Chapter IV). Competition between channel catfish and sunfish may be ameliorated because of the interplay between fish-habitat relationships.

Diet contributions revealed expected results and were comparable to what has already been reported (see Hubert 1999). Channel catfish were primarily omnivorous and diets consisted of aquatic vegetation and benthic invertebrates. Contribution of prey fishes was more common for the larger size groups. Although I found that zooplankton contributed to channel catfish diets, it is also likely that algae and detritus were being consumed incidentally while foraging on benthic invertebrates (Belusz 1968). Isotopic signatures of zooplankton closely resemble their diet, which consists of algae (Grey et al. 2001). It is also likely that zooplankton signature reflects the consumption of benthic material and not necessarily zooplankton itself. This has also been found in studies that used stable isotope methods to reconstruct diets of carp *Cyprinus carpio*, another well-known benthic forager (Britton et al. 2007; Weber and Brown 2013).

Weather and water levels changes may have also affected habitat availability, and therefore played a role affecting channel catfish trophic position and niche overlap. During this study, Oklahoma experienced one of the worst droughts in 100 years, significantly affecting water levels at three (McMurtry, Ponca, and Lone Chimney) of the six study reservoirs, with the changes at Lake Lone Chimney being the most drastic. Water levels at Lake Lone Chimney declined 3.5 m below average in 2012, at a rate of 15 cm per month (J. Dooley, Lone Chimney Water Association, personal communication), reducing surface area by 62%. The reduction in available habitat may have had significantly affected food web dynamics (Power 1992; Williams and Trexler 2006; Walters and Post 2008). For example, trophic position estimates declined in 2012 for channel catfish only at Lake Lone Chimney, although results from the Bayesian mixing models indicated that contribution of fish to channel catfish diets increased from 2011 to 2012. This apparent contradiction could be an artifact of baseline estimates that increased in 2012.

112

Drought can increase crowding, reduce availability of important littoral refuge for smaller fish, alter resource dynamics, and increase interactions (i.e., competition and predation) among species (Mathews 1998; Mathews and Mathews 2003). The shift in resource use was not evident in the other impoundments less affected by drought.

The results from this study provide a rationale that plausibly relates trophic-level interactions with both channel catfish stocking success (Chapter II) and stock characteristics (Chapter III). Stocked channel catfish in Lake Lone Chimney had higher trophic overlap with resident channel catfish and that likely reduced survival. My results further provide an understanding of trophic relationships with co-occurring fishes. Habitat is probably mediating these potential interspecific interactions. Incorporating these relationships into a management framework that considers habitat, along with relative stock size, should increase stocking success. This would require decision makers to manage from a holistic framework, instead of relying only on indices. When indices of abundance are used by themselves this can increase the risk associated with the stocking investment because the desired outcome may not be realized.

REFERENCES

Anderson, R. O. 1980. Proportional stock density (PSD) and relative weight (Wr); interpretative indices for fish populations and communities. Pages 27-33 in S. Gloss and B. Shupp, editors. Practical fisheries management: more with less in the 1980's. American Fisheries Society, New York Chapter, Bethesda, Maryland.

Baily, R. M., and H. M. Harrison, Jr. 1948. Food habits of the southern channel catfish *Ictalurus lacustris punctatus* in the Des Moines River, Iowa. Transactions of the American Figheries Society 75:110-138.

Belusz, L. C. 1968. The relationship of bottom organisms to the food chain of five fish species in the Connecticut River above the Holyoke Dam, Massachusetts. Master's thesis. University of Massachusetts, Amherst.

Brennan, N. P., M. C. Darcy, and K. M. Leber. 2006. Predator-fee enclosures improve post-release survival of stocked common snook. Journal of Experimental Marine Biology and Ecology 335:302-311.

Britton, J. R., R. R. Boar, J. Grey, J. Foster, J. Lugonzo and D. M. Harper. 2007. From introduction to fishery dominance: the initial impacts of the invasive carp *Cyprinus carpio* in Lake Naivasha, Kenya, 1999 to 2006. Journal of Fish Biology 71:239-257.

Brosse, S, and S. Lek. 2000. Modelling roach (*Rutilus rutilus*) microhabitat using linear and nonlinear techniques. Freshwater Biology 44:441-452.

Crowder, L. B., and W. E. Cooper. 1982. Habitat structural complexity and the interaction between bluegills and their prey. Ecology 63:1802:1813.

Durocher, P. P., W. C. Provine, and J. E. Kraai. 1984. Relationship between abundance of

    largemouth bass and submerged vegetation in Texas Reservoirs. North American Journal

    of Fisheries Management 4:84-88.

Ellison, D. G. 1984. Trophic dynamics of a Nebraska black crappie and white crappie

    population. North American Journal of Fisheries Management 4:355-364.

Feuchtmayr, H., and J. Grey. 2003. Effect of preparation and preservation procedures on carbon

    and nitrogen stable isotope determinations from zooplankton. Rapid Communications

    Mass Spectrometry 17:2605-2610.

Fine, M. L., M. S. Mayo, S. H. Newton, and E. N. Sismour. 2011. Largemouth bass predators

    reduce growth, feeding and movement in juvenile channel catfish. Ecology of

    Freshwater Fish 20:114-119.

Fischer, S. A., S. Eder, and E. D. Aragon. 1999. Movements and habitat use of channel catfish

    and blue catfish in a small impoundment in Missouri. Pages 239-255 *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.

Fry, B. 2002. Conservative mixing of stable isotopes across estuarine salinity gradients: A

    conceptual framework for monitoring watershed influences on downstream fisheries

    production. Estuaries 25:264-271.

Gabelhouse, D. W., Jr. 1984. A length-categorization system to assess fish stocks. North

    American Journal of Fisheries Management 4:273-285.

Grey, J., R. I. Jones, and D. Sleep. 2001. Seasonal changes in the importance of the source of organic matter to the diet of zooplankton in Loch Ness, as indicated by stable isotope analysis. Limnology and Oceanography 46:505-513.

Hill, T. D., W. G. Duffy, and M. R. Thompson. 1995. Food habits of channel catfish in Lake Oahe, South Dakota. Journal of Freshwater Ecology 10:319-323.

Hossain, M. A.R., M. Tanaka, and R. Masuda. 2002. Predator-prey interaction between hatchery-reared Japanese flounder juvenile, Paralichthys olivaceus, and sandy shore crab, Matuta lunaris: daily rhythms, anti-predator conditioning and starvation. Journal of Experimental Marine Biology 267:1-4.

Hubert, W. A. 1999. Biology and management of channel catfish. Pages 3-22 *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.

Jackson, A. L., R. Inger, A. C. Parnell, and S. Bearhop. 2011. Comparing isotopic niche widths among and within communities: SIBER – Stable Isotope Bayesian Ellipses in R. Journal of Animal Ecology 80:595-602.

Jackson, M. C., I. Donohue, A. L. Jackson, J. R. Britton, D. M. Harper, and J. Grey. 2012. Population-level metrics of trophic structure based on stable isotopes and their application to invasion ecology. PLoS ONE 7(2):e31757. doi:10.1371/journal.pone.0031757.

Jones, A. W., C. M. Dalton, E. S. Stowe, and D. M. Post. 2010. Contribution of declining anadromous fishes to the reproductive investment of a common piscivorous seabird, the double-crested cormorant (*Phalacrocorax auritus*). The Auk 127:696-703.

Krummich, J. T., and R. C. Heidinger. 1973. Vulnerability of channel catfish to largemouth bass predation. Progressive Fish-Culturist 35:173-175.

Layman, C. A., D. A. Arrington, C. G. Montana, and D. M. Post. 2007. Can stable isotope ratios provide for community-wide measures of trophic structure? Ecology 10:937-944.

Marzolf, R. C. 1957. The reproduction of channel catfish in Missouri ponds. Journal of Wildlife Management 21:22-28.

Mathews, W. J. 1998. Patterns in Freshwater Fish Ecology. Chapmann Hall: New York.

Mathews, W. J., and E. Marsh-Mathews. 2003. Effects of drought on fish across axes of space, time and ecological complexity. Freshwater Biology 48:1232-1253.

Mathur, D. 1972. Seasonal food habits of adult white crappie, *Pomoxis annularis* Rafinesque, in Conowingo reservoir. American Midland Naturalist 87:236-241.

McCarthy, M. A. 2007. Bayesian methods for ecology. Cambridge University Press, Cambridge, United Kingdom.

Michaletz, P. H. 2006. Prey resource use by bluegill and channel catfish in small impoundments. Fisheries Management and Ecology 13:347-354.

Michaletz, P. H., and J. S. Stanovick. 2005. Relations among angler use, harvest, and stocking rates of channel catfish in Missouri impoundments. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 59:263-272.

Michaletz, P. H., M. J. Wallendorf, and D. M. Nicks. 2008. The effects of stocking rate, stocking size, and anglers catch inequality on exploitation of stocked channel catfish in small Missouri impoundments. North American Journal of Fisheries Management 28:1486-1497.

Michaletz, P. M. 2009. Variable responses of channel catfish populations to stocking rate: density-dependent and lake productivity effects. North American Journal of Fisheries Management 29:177-188.

Mitzner, L. 1989. Assessment of maintenance-stocked channel catfish in Iowa lakes. Iowa Department of Natural Resoucres, Federal Aid in Sport Fish Restoration, Completion Report F-94-R-8. Des Moines, IA: Iowa Department of Natural Resources, 32 pp.

Moore, J. W., and B. X. Semmens. 2008. Incorporating uncertainty and prior information into stable isotope mixing models. Ecology Letters 11:470-480.

Olson, N. W., C. P. Paukert, D. W. Willis, and J. A. Klammer. 2003. Prey selection and diets of bluegill *Lepomis macrochirus* with differing population characteristics in two Nebraska natural lakes. Fisheries Management and Ecology 10:31-40.

OWRB (Oklahoma Water Resources Board). 2011. Beneficial Use Monitoring Program. OWRB.

http://www.owrb.ok.gov/quality/monitoring/bump/pdf_bump/Current/Lakes/2010-2011_LakesBUMPReport.pdf

Parnell, A., R. Inger, S. Bearhop, and A. L. Jackson. 2008. SIAR: Stable Isotope Analysis in R. http://cran.r-project.org/web/packages/siar/index.html

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.

Post, D., M. 2002. Using stable isotopes to estimate trophic position: Models, methods, and assumptions. Ecology 83:703-718.

Post, D. M. 2003. Individual variation in the timing of ontogenetic niche shifts in largemouth

    bass. Ecology 84:1298-1310.

Power, M. E. 1992. Top-down and bottom-up forces in food webs: do plants have primacy?

    Ecology 73:733-746.

R Development Core Team (2010) R: a language and environment for statistical computing. R

    foundation for statistical computing, Vienna.

Santucci, V. J., Jr., D. H. Wahl, and T. W. Storck. 1994. Growth, mortality, harvest, and cost-

    effectiveness of stocked channel catfish in a small impoundment. North American

    Journal of Fisheries Management 14:781-789.

Savino, J. F., and R. A. Stein. 1982. Predator-prey interaction between largemouth bass and

    bluegill as influenced by simulated, submersed vegetation. Transactions of the American

    Fisheries Society 111:255-266.

Schielke, E. G., and D. M. Post. 2010. Size matters: comparing stable isotope ratios of tissue

    plugs and whole organisms. Limnology and Oceanography: Methods 8:348-351.

Shaner, B. L., M. J. Maceina, J. J. McHugh, and S. F. Cook. 1996. Assessment of catfish

    stocking in public fishing lakes in Alabama. North American Journal of Fisheries

    Management 16:880-887.

Spinelli, A. J., B. G. Whiteside, and D. G. Huffman. 1985. Aquarium studies on the evaluation of

    stocking various sizes of channel catfish with established largemouth bass. North

    American Journal of Fisheries Management 5:138-145.

Stewart, D. R., G. W. Benz, and G. D. Scholten. 2009. Weight-length relationships and growth data for blue catfish from four Tennessee waterbodies. Proceedings of the Annual Southeastern Association Fish and Wildlife Agencies 63:140-146.

Stewart, D. R., and J. M. Long. 2011. The efficacy of mass-marking channel catfish Ictalurus punctatus fingerlings using oxytetracycline. Proceedings of the Oklahoma Academy of Science 91:31-36.

Stewart, D. R., and J. M. Long. 2012. Precision of channel catfish catch estimates using hoop nets in larger Oklahoma reservoirs. North American Journal of Fisheries Management 32:1108-1112.

Storck, T., and D. Newman. 1988. Effects of size at stocking on survival and harvest of channel catfish. North American Journal of Fisheries Management 82:98-101.

Tyus, H. M., and N. J. Nikirk. 1990. Abundance, growth and diet of channel catfish, *Ictalurus punctatus*, in the Green and Yampa Rivers, Colorado and Utah. Southwestern Naturalist 35:188-198.

Walters, A. W., and D. M. Post. 2008. An experimental disturbance alters fish size structure but not food chain length in streams. Ecology 89:3261-3267.

Weber, M. J., and M. L. Brown. 2013. Spatiotemporal variation of juvenile common carp foraging patterns as inferred from stable isotope analysis. Transactions of the American Fisheries Society 142:1179-1191.

Werner, E. E. 1977. Species packing and niche complementarity in three sunfishes. American Naturalists 111:553-578.

Wilks, S. S. 1932. Certain generalizations in the analysis of variance. Biometrika 24:471-494.

Williams, A. J., and J. C. Trexler. 2006. A preliminary analysis of the correlation of food-web

    characteristics with hydrology and nutrient gradients in the southern Everglades.

    Hydrobiologia 569:493-504.

Zar, J. H. 1999. Biostatistical Analysis.4th edition. Prentice-Hall. New Jersey, United States.

Table 1. Proportions (± credibility intervals (CI)) of prey sources in diets of stocked channel catfish *Ictalurus punctatus* caught from two Oklahoma reservoirs in 2011 and 2012.

Reservoir	Year	N	Prey source	No prior		Prior	
				95% CI	Median	95% CI	Median
Lone Chimney	2011	5	Aquatic Vegetation	0-34	17	0-29	11
			Zooplankton	0-37	17	0-35	17
			Benthic Invertebrates	0-43	22	7-57	28
			Sunfish	0-27	9	0-26	9
			Catfish	0-34	15	0-32	14
			Gizzard Shad	0-32	15	0-31	14
	2012	5	Aquatic Vegetation	-	-	-	-
			Zooplankton	0-41	22	0-31	13
			Benthic Invertebrates	0-42	26	11-46	30
			Sunfish	0-35	15	1-33	16
			Catfish	0-38	19	2-38	20
			Gizzard Shad	0-37	18	2-36	19
Greenleaf	2012	5	Aquatic Vegetation	15-38	26	17-38	27
			Zooplankton	3-59	31	2-48	25
			Benthic Invertebrates	2-46	26	13-52	32
			Sunfish	0-10	3	0-11	4
			Catfish	0-17	6	0-14	2
			Gizzard Shad	0-14	5	0-15	5
	2012	5	Aquatic Vegetation	0-20	5	0-21	9
			Zooplankton	1-47	24	0-33	13
			Benthic Invertebrates	17-66	42	28-68	50
			Sunfish	0-17	6	0-18	6
			Catfish	0-21	9	0-21	8
			Gizzard Shad	0-23	9	0-23	9

Table 2. Proportions (± credibility intervals (CI)) of prey sources in diets of sub-stock (≤ 280 mm) channel catfish *Ictalurus punctatus* caught from six Oklahoma reservoirs in 2011 and 2012.

Reservoir	Year	N	Prey source	No prior 95% CI	No prior Median	Prior 95% CI	Prior Median
McMurtry	2011	10	Aquatic Vegetation	0-11	3	0-6	1
			Zooplankton	15-72	44	21-65	43
			Benthic Invertebrates	5-67	37	21-68	44
			Sunfish	0-13	4	0-11	3
			Catfish	0-14	4	0-8	1
			Gizzard Shad	0-18	5	0-14	4
	2012	7	Aquatic Vegetation	0-14	5	0-9	2
			Zooplankton	16-51	33	8-43	27
			Benthic Invertebrates	0-45	24	15-65	38
			Sunfish	0-25	9	2-27	14
			Catfish	0-28	11	0-21	7
			Gizzard Shad	0-32	13	0-23	8
Ponca	2011	8	Aquatic Vegetation	0-9	4	0-9	4
			Zooplankton	3-73	51	27-63	47
			Benthic Invertebrates	0-52	26	10-59	34
			Sunfish	0-14	4	0-14	5
			Catfish	0-15	4	0-12	3
			Gizzard Shad	0-18	5	0-14	4
	2012	5	Aquatic Vegetation	0-19	4	0-24	6
			Zooplankton	26-64	49	21-64	48
			Benthic Invertebrates	2-27	17	8-33	19
			Sunfish	0-19	6	0-17	6
			Catfish	0-22	7	0-19	6
			Gizzard Shad	0-32	13	0-29	11

Table 2. continued.

Reservoir	Year	N	Prey source	No prior		Prior	
				95% CI	Median	95% CI	Median
Okemah	2011	7	Aquatic Vegetation	4-43	25	10-44	27
			Zooplankton	8-49	27	9-51	30
			Benthic Invertebrates	0-33	15	4-41	22
			Sunfish	0-24	7	0-20	5
			Catfish	0-25	8	0-15	2
			Gizzard Shad	0-29	12	0-26	8
	2012	7	Aquatic Vegetation	0-27	14	0-7	1
			Zooplankton	14-56	35	33-61	48
			Benthic Invertebrates	0-23	8	0-16	7
			Sunfish	0-27	11	0-30	13
			Catfish	0-22	8	0-21	4
			Gizzard Shad	1-38	20	0-45	21
Okmulgee	2011	0	-	-	-	-	-
	2012	0	-	-	-	-	-
Lone Chimney	2011	6	Aquatic Vegetation	0-35	18	0-30	12
			Zooplankton	0-32	15	0-30	15
			Benthic Invertebrates	1-39	22	9-47	26
			Sunfish	0-24	8	0-24	9
			Catfish	0-35	18	0-34	17
			Gizzard Shad	0-33	16	0-32	16
	2012	6	Aquatic Vegetation	-	-	-	-
			Zooplankton	0-39	20	0-27	5
			Benthic Invertebrates	0-36	21	5-44	29
			Sunfish	0-37	15	2-38	20
			Catfish	0-50	23	2-43	22
			Gizzard Shad	0-40	20	2-39	20
Greenleaf	2011	0	-	-	-	-	-
	2012	0	-	-	-	-	-

Table 3. Proportions (± credibility intervals (CI)) of prey sources in diets of stock-size (≥ 281 mm to ≤ 410 mm) channel catfish *Ictalurus punctatus* caught from six Oklahoma reservoirs in 2011 and 2012.

Reservoir	Year	N	Prey source	No prior 95% CI	No prior Median	Prior 95% CI	Prior Median
McMurtry	2011	9	Aquatic Vegetation	2-30	15	0-23	11
			Zooplankton	12-71	38	16-68	41
			Benthic Invertebrates	0-45	24	7-68	28
			Sunfish	0-15	4	0-14	4
			Catfish	0-16	5	0-11	3
			Gizzard Shad	0-25	8	0-25	8
	2012	11	Aquatic Vegetation	0-8	3	0-6	1
			Zooplankton	26-65	47	21-59	41
			Benthic Invertebrates	0-50	22	8-60	33
			Sunfish	0-19	7	0-20	9
			Catfish	0-21	7	0-15	4
			Gizzard Shad	0-24	9	0-22	8
Ponca	2011	5	Aquatic Vegetation	0-14	6	1-16	7
			Zooplankton	0-45	22	2-44	23
			Benthic Invertebrates	2-31	17	9-35	22
			Sunfish	5-45	26	9-45	27
			Catfish	0-8	4	0-7	3
			Gizzard Shad	0-46	23	0-37	16
	2012	5	Aquatic Vegetation	0-28	10	0-17	3
			Zooplankton	19-67	47	25-66	49
			Benthic Invertebrates	3-36	20	10-41	24
			Sunfish	0-14	4	0-16	6
			Catfish	0-17	5	0-13	3
			Gizzard Shad	0-27	10	0-26	9

125

Table 3. continued.

Reservoir	Year	N	Prey source	No prior 95% CI	No prior Median	Prior 95% CI	Prior Median
Okemah	2011	12	Aquatic Vegetation	12-38	26	11-35	24
			Zooplankton	25-54	40	25-53	40
			Benthic Invertebrates	0-31	13	5-37	20
			Sunfish	0-14	4	0-13	4
			Catfish	0-15	5	0-10	1
			Gizzard Shad	0-22	7	0-21	7
	2012	8	Aquatic Vegetation	8-37	23	1-35	23
			Zooplankton	6-44	25	3-44	24
			Benthic Invertebrates	0-29	14	5-36	20
			Sunfish	0-25	10	0-29	14
			Catfish	0-22	8	0-16	2
			Gizzard Shad	0-32	17	0-28	12
Okmulgee	2011	10	Aquatic Vegetation	7-50	29	13-52	32
			Zooplankton	9-61	35	0-49	26
			Ben Invertebrates	0-39	18	6-49	27
			Sunfish	0-12	3	0-11	3
			Catfish	0-16	4	0-13	3
			Gizzard Shad	0-21	6	0-17	4
	2012	0	-	-	-	-	-
Lone Chimney	2011	5	Aquatic Vegetation	0-34	17	0-29	11
			Zooplankton	0-31	13	0-26	9
			Benthic Invertebrates	0-36	19	10-50	28
			Sunfish	0-29	11	1-28	11
			Catfish	0-39	20	3-36	18
			Gizzard Shad	0-34	17	2-33	16
	2012	5	Aquatic Vegetation	-	-	-	-
			Zooplankton	0-39	18	0-26	3
			Benthic Invertebrates	0-35	12	0-38	17
			Sunfish	0-41	18	2-45	23
			Catfish	0-50	26	5-52	28
			Gizzard Shad	0-42	21	1-42	22
Greenleaf	2011	0	-	-	-	-	-
	2012	0	-	-	-	-	-

Table 4. Proportion (± credibility intervals (CI)) of prey sources in diets of quality-size (≥410 to ≤610 mm) channel catfish *Ictalurus punctatus* collected from six Oklahoma reservoirs in 2011 and 2012.

Reservoir	Year	N	Prey source	No prior		Prior	
				95% CI	Median	95% CI	Median
McMurtry	2011	6	Aquatic Vegetation	0-17	5	0-10	3
			Zooplankton	5-51	28	4-44	25
			Benthic Invertebrates	4-53	29	18-63	38
			Sunfish	0-27	11	1-29	14
			Catfish	0-28	11	0-21	6
			Gizzard Shad	0-29	10	0-25	8
	2012	5	Aquatic Vegetation	0-22	9	0-14	5
			Zooplankton	13-54	32	11-48	30
			Benthic Invertebrates	10-46	25	12-58	34
			Sunfish	0-24	8	0-24	9
			Catfish	0-26	9	0-20	6
			Gizzard Shad	0-29	11	0-27	11
Ponca	2011	5	Aquatic Vegetation	0-23	11	3-27	14
			Zooplankton	0-40	20	0-35	14
			Benthic Invertebrates	0-30	15	3-35	20
			Sunfish	5-45	25	4-41	23
			Catfish	0-10	4	0-8	1
			Gizzard Shad	0-42	22	3-46	24
	2012	10	Aquatic Vegetation	0-15	7	0-16	8
			Zooplankton	24-52	38	21-49	36
			Benthic Invertebrates	12-34	23	13-34	24
			Sunfish	0-17	6	0-17	6
			Catfish	0-21	7	0-17	4
			Gizzard Shad	0-33	15	2-37	19

Table 4. continued.

| Reservoir | Year | N | Prey source | No prior | | Prior | |
				95% CI	Median	95% CI	Median
Okemah	2011	0	-	-	-	-	-
	2012	6	Aquatic Vegetation	0-18	7	0-18	8
			Zooplankton	14-42	28	11-42	26
			Benthic Invertebrates	2-32	19	7-33	20
			Sunfish	0-31	17	5-35	20
			Catfish	0-28	15	0-25	11
			Gizzard Shad	0-27	14	0-27	13
Okmulgee	2011	11	Aquatic Vegetation	0-22	10	4-28	16
			Zooplankton	9-51	28	0-35	20
			Benthic Invertebrates	0-30	15	3-34	19
			Sunfish	0-26	12	4-31	18
			Catfish	0-31	17	0-29	16
			Gizzard Shad	0-32	16	0-28	12
	2012	11	Aquatic Vegetation	17-62	39	19-61	39
			Zooplankton	0-41	19	0-35	14
			Benthic Invertebrates	0-26	9	3-31	15
			Sunfish	0-24	9	0-25	9
			Catfish	0-26	10	0-27	11
			Gizzard Shad	0-23	7	0-20	5
Lone Chimney	2011	5	Aquatic Vegetation	0-35	18	0-26	5
			Zooplankton	0-28	13	0-21	3
			Benthic Invertebrates	2-35	20	14-47	30
			Sunfish	0-23	10	1-24	11
			Catfish	1-37	20	3-40	21
			Gizzard Shad	0-35	18	2-40	21

Table 4. continued.

Reservoir	Year	N	Prey source	No prior		Prior	
				95% CI	Median	95% CI	Median
Lone Chimney	2012	7	Aquatic Vegetation	-	-	-	-
			Zooplankton	0-30	11	0-18	2
			Benthic Invertebrates	0-21	3	0-12	4
			Sunfish	0-45	24	3-50	28
			Catfish	7-54	31	11-56	33
			Gizzard Shad	1-53	28	3-54	29
Greenleaf	2011	5	Aquatic Vegetation	0-26	12	2-28	15
			Zooplankton	0-36	19	0-29	13
			Benthic Invertebrates	3-40	23	11-46	27
			Sunfish	0-27	13	0-29	14
			Catfish	0-35	18	0-35	19
			Gizzard Shad	0-29	13	0-25	8
	2012	5	Aquatic Vegetation	0-22	7	1-24	12
			Zooplankton	1-36	20	0-27	12
			Benthic Invertebrates	5-45	25	14-47	29
			Sunfish	0-28	13	0-29	13
			Catfish	0-31	15	0-32	15
			Gizzard Shad	0-34	17	0-33	16

Table 5. Population metrics and isotopic niche overlap of channel catfish *Ictalurus punctatus* (hatchery (OTC), sub-stock (SS; < 280 mm), stock-size (≥ 281 to ≤ 410 mm), quality-size (≥ 411 to ≤ 610 mm)), bluegill (BLUE) *Lepomis macrochirus*, longear sunfish (LGSU) *Lepomis megalotis*, white crappie (WHCR) *Pomoxis annularis*, largemouth bass (LMB) *Micropterus salmoides*, and flathead catfish (FCF) *Pylodictis olivaris* collected from six Oklahoma reservoirs.

Reservoir	Year	Species	Layman metrics					Trophic overlap			
			NR	CR	CD	SDNND	SEA$_c$	OTC	SS	Stock	Quality
McMurtry	2011	SS	2.32	2.54	1.06	0.46	2.31	NA	-	54	22
		Stock	1.88	4.86	1.43	0.47	3.78	NA	54	-	19
		Quality	2.05	2.33	0.91	0.28	2.39	NA	22	19	-
		BLUE	0.51	0.52	0.26	0.23	0.18	NA	30	61	100
		WHCR	1.79	1.79	0.80	0.78	0.77	NA	0	0	44
		FCF	1.25	1.09	0.64	0.34	1.51	NA	0	0	0
	2012	SS	1.03	2.22	0.74	0.18	1.09	NA	-	42	41
		Stock	2.11	2.67	0.88	0.17	1.58	NA	42	-	53
		Quality	1.59	2.08	0.92	0.33	2.13	NA	41	53	-
		BLUE	2.14	1.61	0.94	0.12	2.23	NA	59	19	49
		LGSU	3.16	0.77	1.04	0.61	1.34	NA	0	0	0
		WHCR	0.57	2.13	0.81	0.20	0.94	NA	0	0	0
		LMB	3.46	3.25	1.52	1.20	5.38	NA	0	0	0
		FCF	1.32	1.49	0.77	0.30	1.57	NA	0	0	0
Ponca	2011	SS	2.42	1.28	0.67	0.53	1.31	NA	-	18	36
		Stock	0.92	1.72	0.68	0.36	0.94	NA	18	-	65
		Quality	2.51	3.36	1.24	0.65	3.49	NA	36	65	-
		BLUE	0.88	0.88	0.52	0.22	0.56	NA	32	38	100
		WHCR	1.47	1.77	0.67	0.71	0.15	NA	0	0	47
		FCF	0.34	0.96	0.28	0.17	0.58	NA	0	0	0
	2012	SS	1.47	0.75	0.58	0.18	0.73	NA	-	65	44
		Stock	0.98	1.53	0.62	0.50	1.07	NA	65	-	36
		Quality	2.91	2.15	0.82	0.45	1.67	NA	44	36	-
		BLUE	1.55	1.74	0.66	0.57	0.65	NA	1	0	8
		LGSU	0.27	0.99	0.33	0.05	0.17	NA	0	0	22
		WHCR	1.27	1.05	0.63	0.10	0.91	NA	0	0	0
		LMB	2.67	2.07	1.01	0.41	2.67	NA	0	0	0
		FCF	1.61	1.41	0.60	0.48	0.70	NA	0	0	0

NR = δ15N range; CR = δ13C range; CD = mean centroid distance

SDNND = standard deviation of mean nearest neighbor

SEA$_c$ = standard ellipse area corrected for small sample sizes.

Table 5. continued

Reservoir	Year	Species	NR	CR	CD	SDNND	SEA$_c$	OTC	SS	Stock	Quality
				Layman metrics					Trophic niche overlap		
Okemah	2011	SS	3.46	5.00	2.04	0.51	9.51	NA	-	100	-
		Stock	3.68	4.82	1.15	0.90	3.82	NA	100	-	-
		BLUE	1.72	0.84	0.59	0.35	0.92	NA	24	0	-
		WHCR	1.15	4.41	1.43	1.46	0.66	NA	0	0	-
		FCF	1.01	1.25	0.53	0.24	3.54	NA	5	4	-
	2012	SS	2.34	2.49	0.99	0.72	2.12	NA	-	62	2
		Stock	2.26	4.16	1.42	0.31	2.49	NA	62	-	0
		Quality	1.46	1.11	0.60	0.24	0.88	NA	2	0	-
		BLUE	3.14	1.24	1.14	0.38	2.35	NA	33	28	0
		LGSU	2.43	3.02	1.27	0.43	3.43	NA	23	25	0
		WHCR	3.71	2.00	1.04	0.93	3.33	NA	18	3	0
		LMB	1.29	1.16	0.83	0.12	1.27	NA	1	0	17
		FCF	0.78	4.46	1.33	0.53	1.39	NA	9	0	21
Okmulgee	2011	Stock	3.22	7.19	1.84	0.58	7.41	NA	-	-	0
		Quality	1.25	7.05	1.66	0.51	2.86	NA	-	0	-
		BLUE	3.72	1.62	1.46	0.38	3.96	NA	-	24	16
		WHCR	2.32	3.88	1.71	0.18	0.76	NA	-	4	17
		FCF	0.98	1.10	0.56	0.22	4.68	NA	-	0	18
	2012	Quality	4.16	5.64	1.72	0.66	6.12	NA	-	-	-
		BLUE	6.44	3.35	2.16	1.91	2.48	NA	-	-	97
		RESU	1.04	2.18	0.75	0.39	2.76	NA	-	-	67
		WHCR	1.28	3.23	1.01	0.54	1.15	NA	-	-	0
		LMB	1.17	4.07	1.08	0.95	2.73	NA	-	-	0
		FCF	1.92	2.31	1.04	0.34	2.84	NA	-	-	8

Table 5. continued.

Reservoir	Year	Species	Layman metrics					Trophic niche overlap			
			NR	CR	CD	SDNND	SEA$_c$	OTC	SS	Stock	Quality
Lone Chimney	2011	OTC	1.95	3.13	1.15	0.32	2.63	-	2	38	0
		SS	3.62	5.41	1.72	0.74	4.06	2	-	54	80
		Stock	4.69	3.36	1.96	0.17	7.48	38	54	-	43
		Quality	1.07	2.18	1.02	0.19	0.97	0	80	43	-
		BLUE	1.47	1.45	0.70	0.48	1.20	0	0	0	0
		WHCR	2.96	1.16	1.16	0.24	0.72	0	0	0	1
		FCF	1.02	1.10	0.56	0.11	2.33	0	0	0	0
	2012	OTC	2.82	4.69	1.92	0.41	6.87	-	100	62	66
		SS	2.14	2.18	0.84	0.44	2.04	100	-	47	11
		Stock	1.26	2.23	0.88	0.50	1.67	62	47	-	53
		Quality	1.93	0.79	0.67	0.06	0.68	66	11	53	-
		BLUE	1.25	1.29	0.65	0.17	0.95	6	0	10	3
		RESU	1.50	1.25	0.62	0.15	1.18	37	14	5	54
		WHCR	1.16	1.12	0.55	0.14	0.54	0	0	0	0
		LMB	3.78	1.45	1.21	0.46	3.48	0	0	0	0
		FCF	1.23	2.53	0.94	0.14	0.93	0	0	0	2
Greenleaf	2011	OTC	2.16	6.94	2.14	0.36	3.82	-	-	-	0
		Quality	2.38	3.89	1.39	0.25	1.27	0	-	-	-
		BLUE	1.39	3.01	0.92	0.88	1.64	0	-	-	68
		WHCR	1.90	2.54	1.09	0.71	1.97	6	-	-	36
		FCF	2.44	1.07	0.93	0.13	1.01	0	-	-	0
	2012	OTC	1.98	5.21	1.63	0.33	3.23	-	-	-	0
		Quality	0.80	2.86	0.81	0.51	1.26	0	-	-	-
		BLUE	1.86	3.41	1.32	0.39	4.80	70	-	-	75
		LGSU	1.37	1.12	0.63	0.45	1.00	11	-	-	0
		WHCR	1.66	0.93	0.57	0.26	0.99	0	-	-	0
		LMB	0.94	1.74	0.58	0.24	0.67	0	-	-	0
		FCF	0.85	1.62	0.50	0.30	0.77	0	-	-	0

Table 6. Summary of random-intercept models to predict trophic relationships with $\log_{10}$-transformed length of channel catfish *Ictalurus punctatus*.

Isotopic signature	Reservoir	N	Model parameter estimates		Variance components		P
			y-intercept (±SE)	slope (±SE)	Intercept	Residual	
$\delta^{15}N$	McMurtry	48	11.84 ± 1.67	0.08 ± 0.63	0.87	0.84	0.90
	Ponca	38	8.10 ± 1.71	1.58 ± 0.66	0.003	0.77	**0.03**
	Okemah	40	4.30 ± 3.73	3.02 ± 1.46	0.93	0.90	**0.05**
	Okmulgee	32	7.12 ± 4.51	6.54 ± 1.71	0.004	1.05	**< 0.01**
	Lone Chimney	44	3.36 ± 3.44	4.03 ± 1.35	1.11	1.09	**< 0.01**
	Greenleaf	20	2.39 ± 1.77	4.38 ± 0.71	0.001	0.56	**< 0.01**
$\delta^{13}C$	McMurtry	48	29.16 ± 1.95	1.17 ± 0.78	0.31	1.06	0.14
	Ponca	38	27.08 ± 2.66	0.54 ± 1.03	0.77	1.10	0.60
	Okemah	40	33.66 ± 5.38	2.27 ± 2.13	0.50	1.33	0.29
	Okmulgee	32	47.69 ± 7.89	7.73 ± 2.99	0.001	1.83	**0.02**
	Lone Chimney	44	9.85 ± 5.08	5.94 ± 2.04	0.37	1.65	**0.01**
	Greenleaf	20	29.00 ± 6.78	0.11 ± 2.65	1.98	2.03	0.97
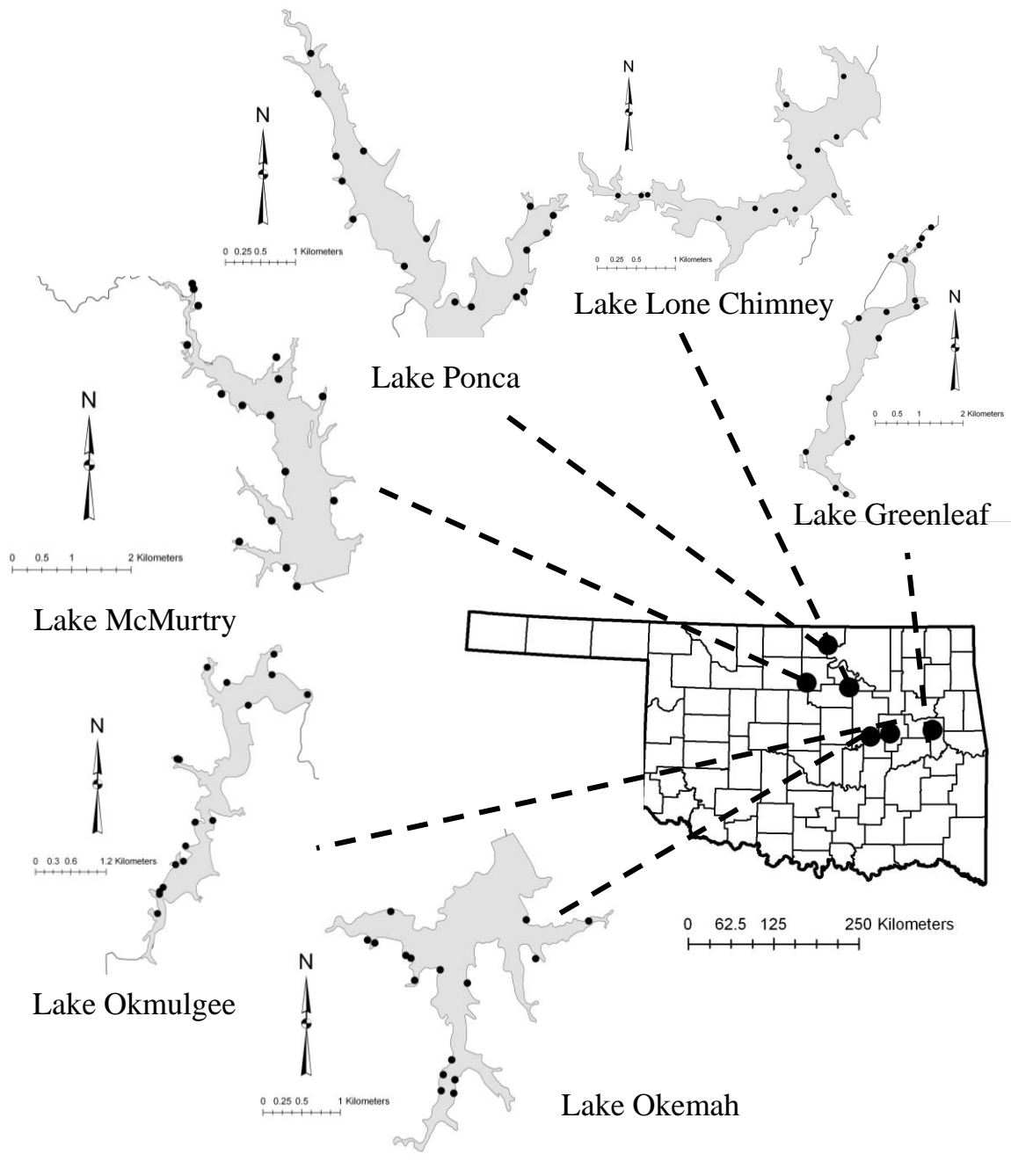
Figure 1. Map of Oklahoma and location of sample sites within six study reservoirs (Control: McMurtry and Ponca; Cease-stock: Okemah and Okmulgee; Stock: Lone Chimney and Greenleaf) where an experimental stocking program of channel catfish *Ictalurus punctatus* was undertaken.
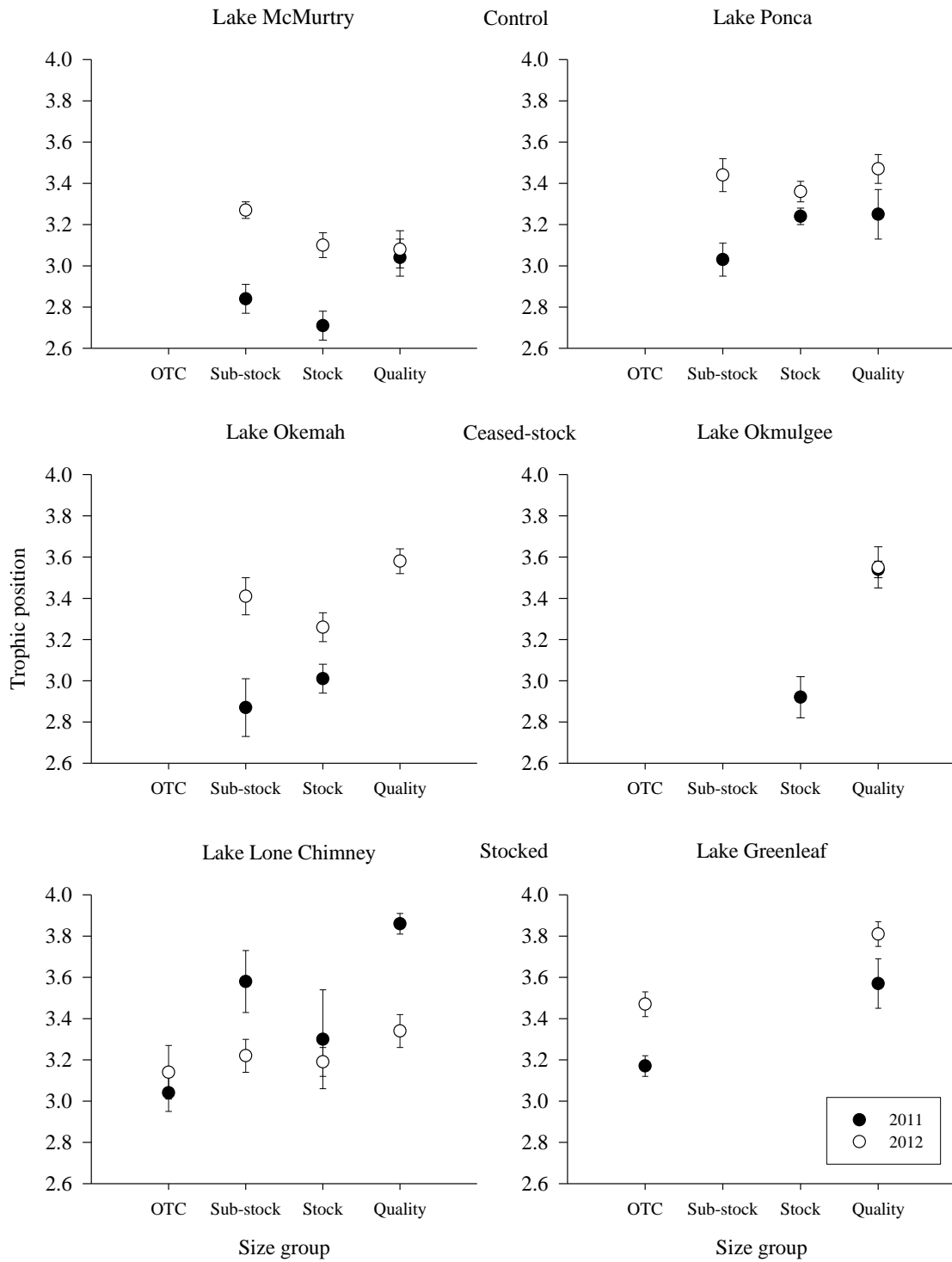
Figure 2. Trophic position estimates of stocked (hatchery (OTC)) and resident channel catfish *Ictalurus punctatus* (sub-stock (< 280 mm), stock-size (≥ 281 to ≤ 410 mm), quality-size (≥ 411 to ≤ 610 mm)) collected from six Oklahoma reservoirs in 2011 and 2012.
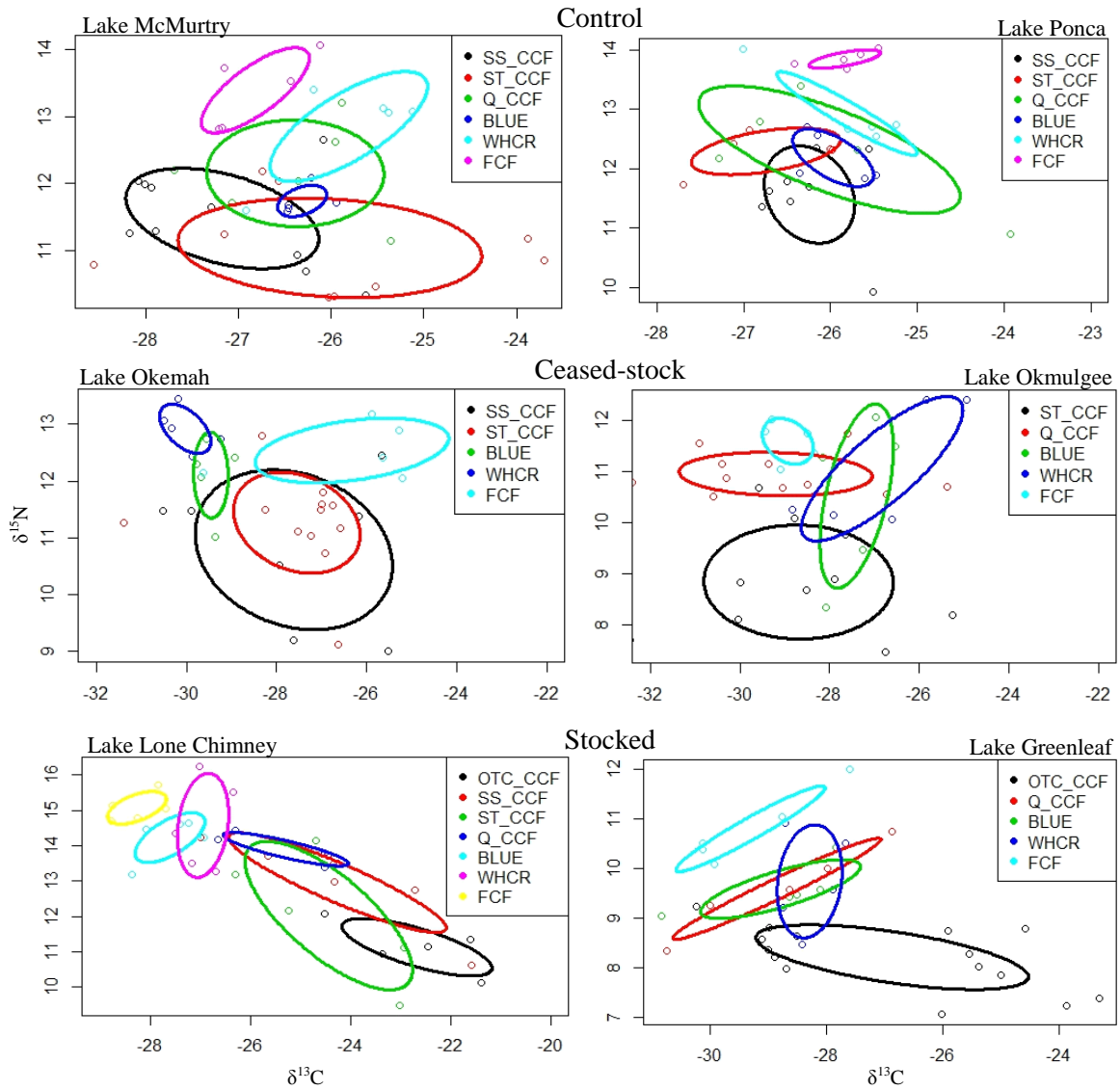
Figure 3. Estimated isotopic niche space ellipses for channel catfish *Ictalurus punctatus* (OTC, stocked fingerlings; SS, sub-stock (≤ 280 mm); ST, stock-size (≥ 281 to ≤ 410 mm); Q, quality-size (≥ 411 to ≤ 610 mm)), bluegill (BLUE, *Lepomis macrochirus*), white crappie (WHCR, *Pomoxis annularis*), and flathead catfish (FCF, *Pylodictis olivaris*) for six Oklahoma reservoirs in 2011.
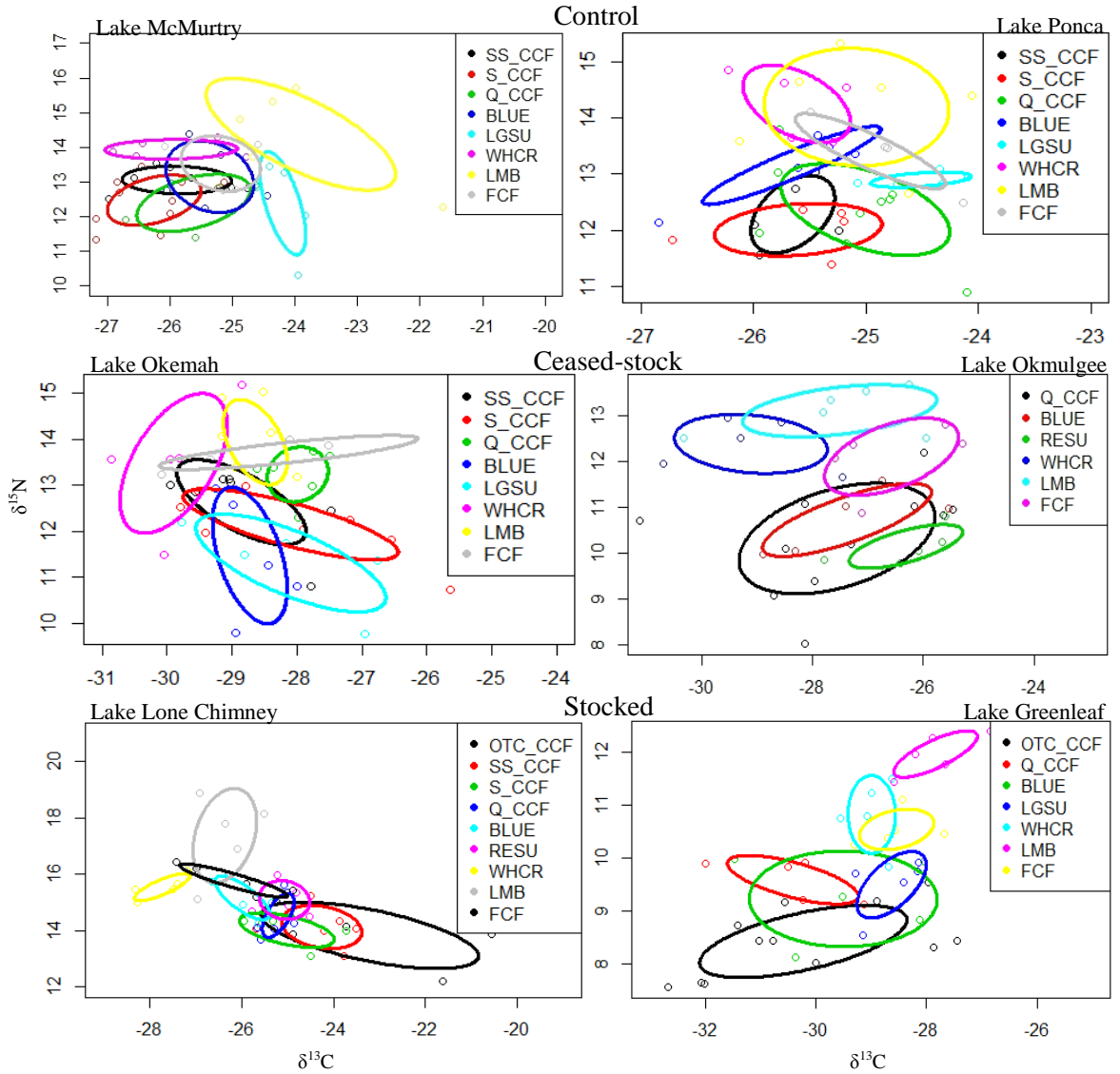
Figure 4. Estimated isotopic niche space ellipses for channel catfish *Ictalurus punctatus* (OTC, stocked fingerlings; SS, sub-stock (≤ 280 mm); ST, stock-size (≥ 281 to ≤ 410 mm); Q, quality-size (≥ 411 to ≤ 610 mm)), bluegill (BLUE, *Lepomis macrochirus*), longear sunfish (LGSU, *Lepomis megalotis*), redear sunfish (RESU, *Lepomis microlophus*), white crappie (WHCR, *Pomoxis annularis*), largemouth bass (LMB, *Micropterus salmoides*) and flathead catfish (FCF, *Pylodictis olivaris*) for six Oklahoma reservoirs in 2012.
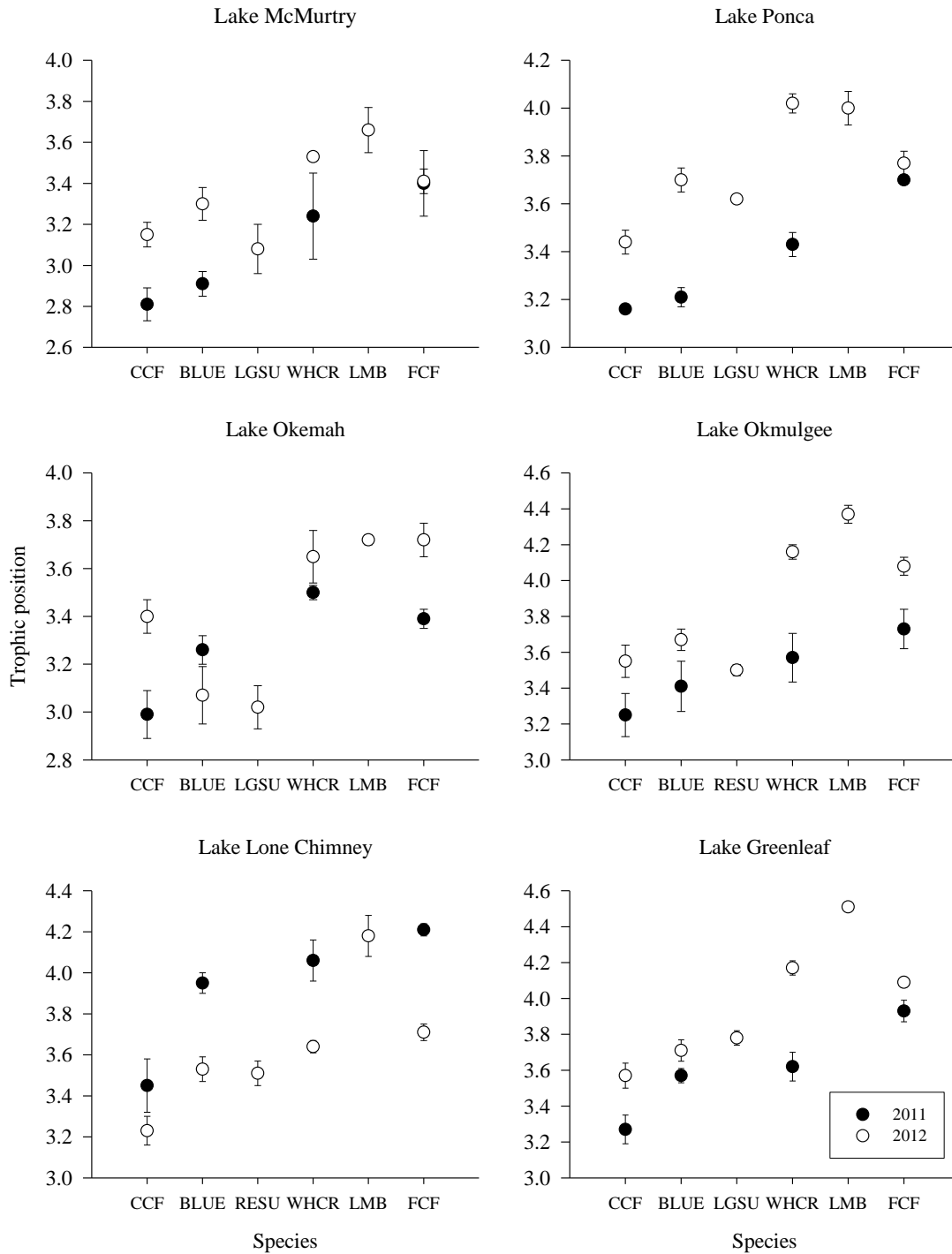
Appendix 1. Trophic position estimates of six species (channel catfish (CCF; *Ictalurus punctatus*), bluegill (BLUE; *Lepomis macrochirus*), longear sunfish (LGSU; *Lepomis megalotis*), redear sunfish (RESU; *Lepomis microlophus*), white crappie (WHCR; *Pomoxis annularis*), largemouth bass (LMB; *Micropterus salmoides*), and flathead catfish (FCF; *Pylodictis olivaris*) of fish collected from six Oklahoma reservoirs in 2011 and 2012.
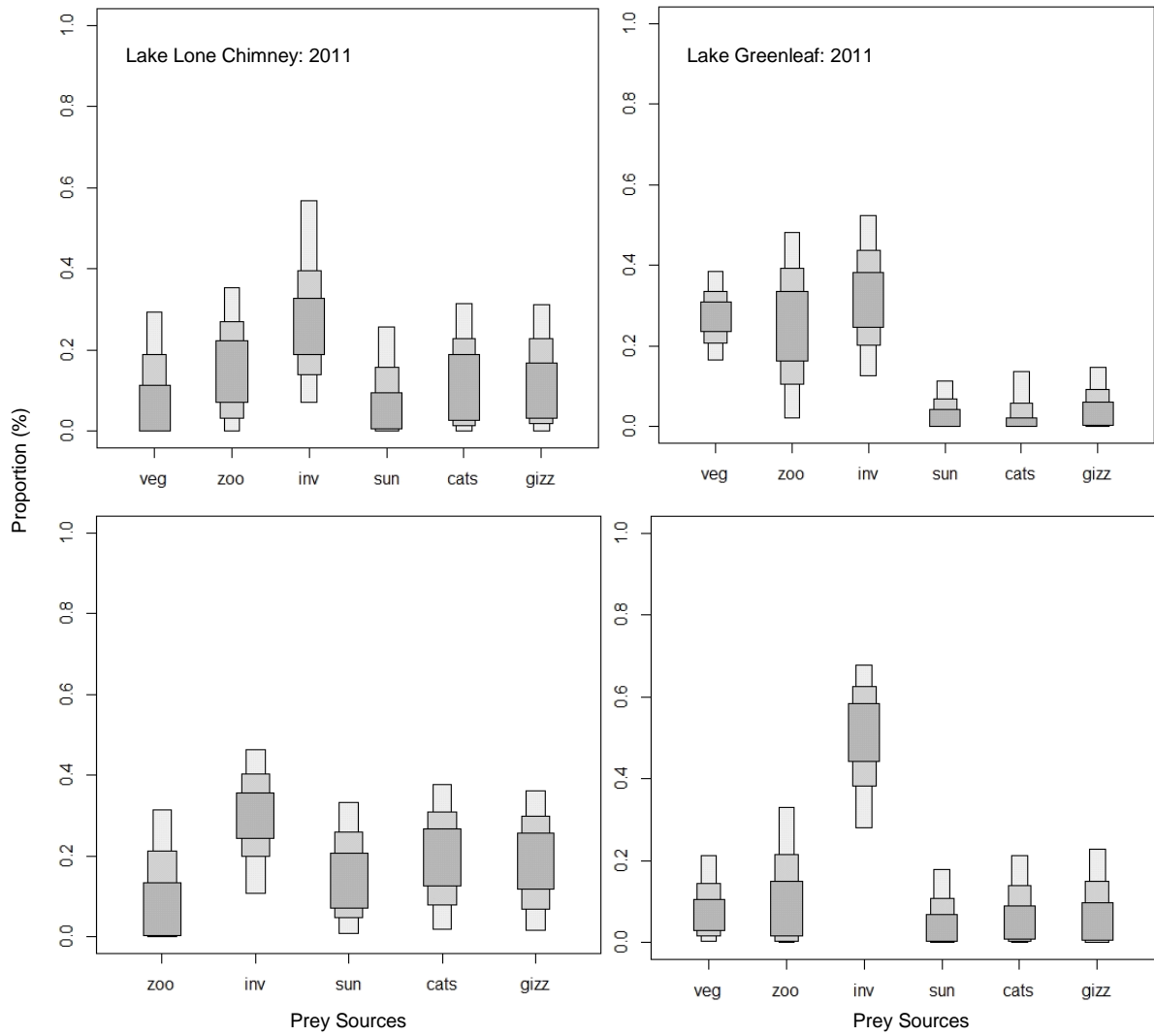
Appendix 2. The estimated diet contributions (95% credibility intervals) of stocked channel catfish *Ictalurus punctatus* in lakes Lone Chimney and Greenleaf based on stable isotope estimates modeled from SIAR Bayesian mixing models.
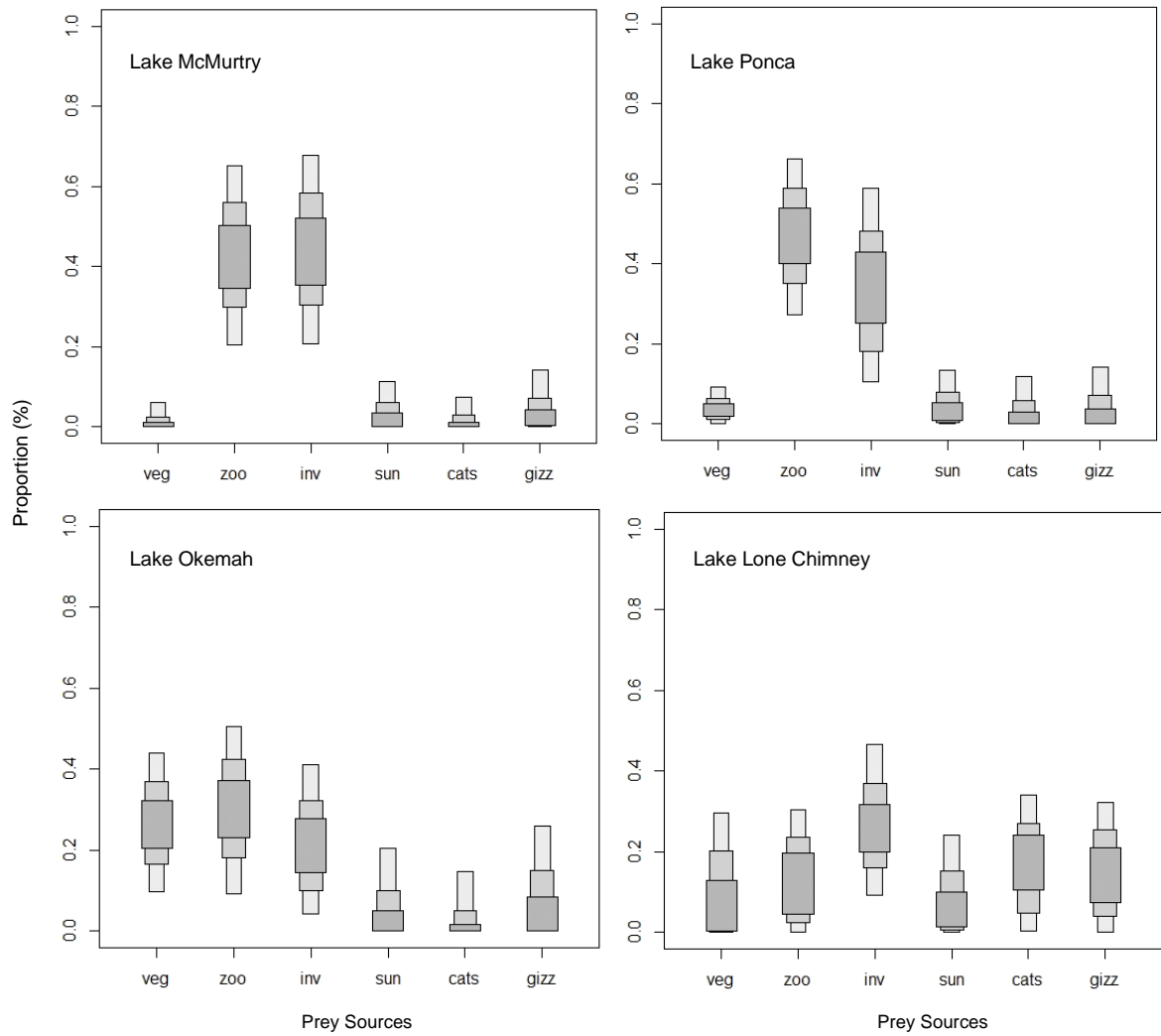
Appendix 3. The estimated diet contributions (95% credibility intervals) of sub-stock (< 280 mm) channel catfish *Ictalurus punctatus* caught in 2011 from four Oklahoma reservoirs based on stable isotope estimates modeled from SIAR Bayesian mixing models.
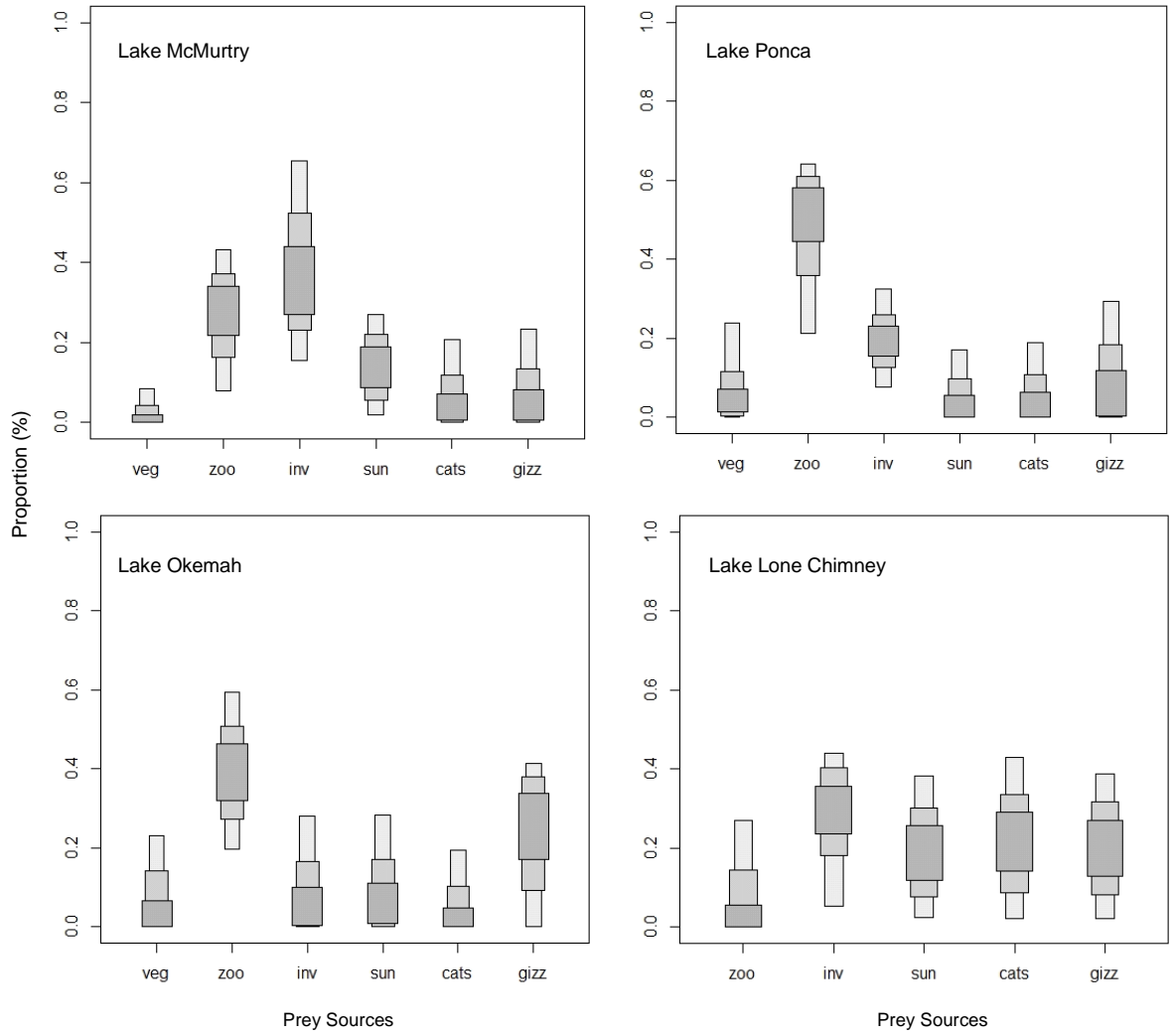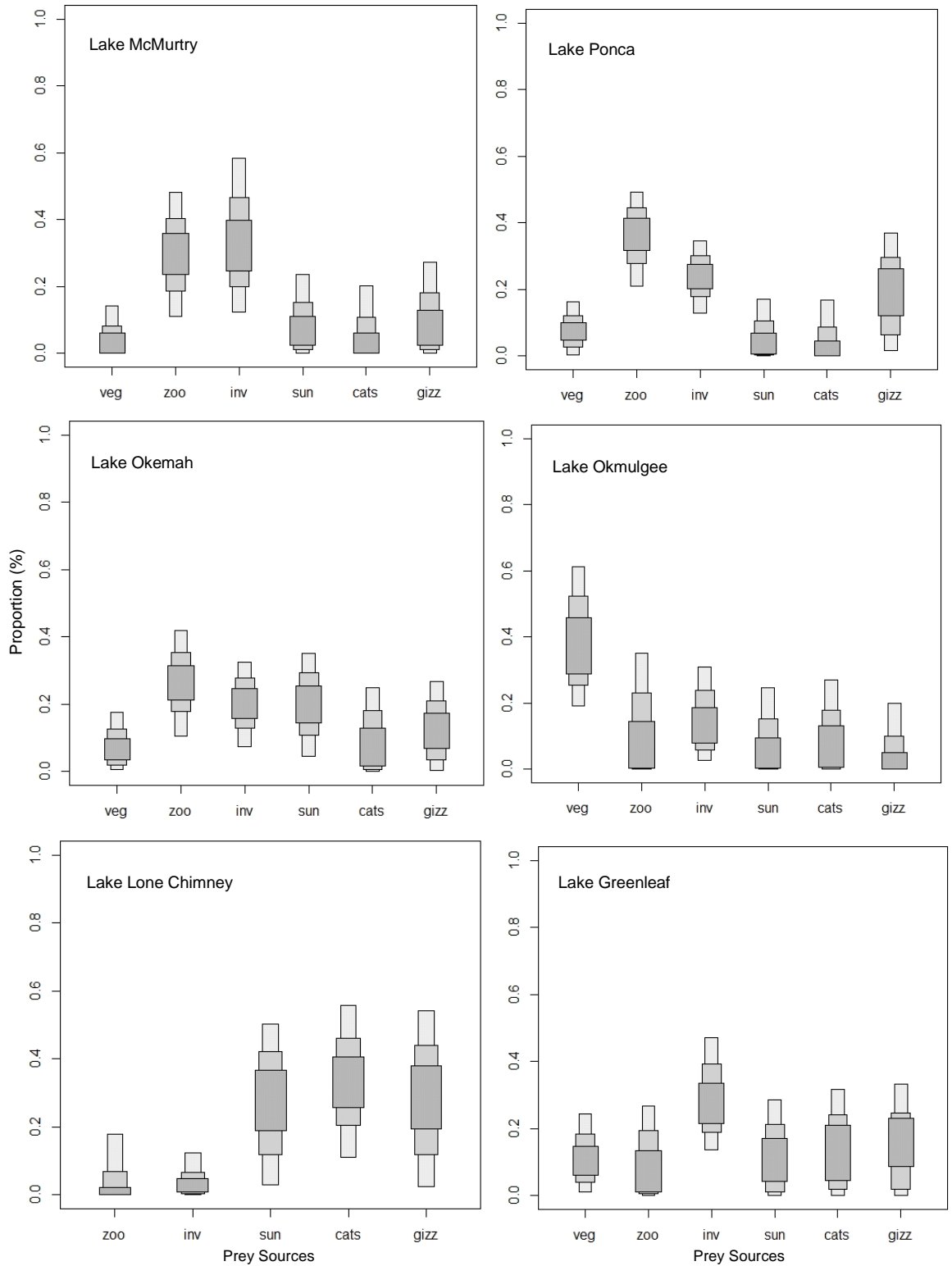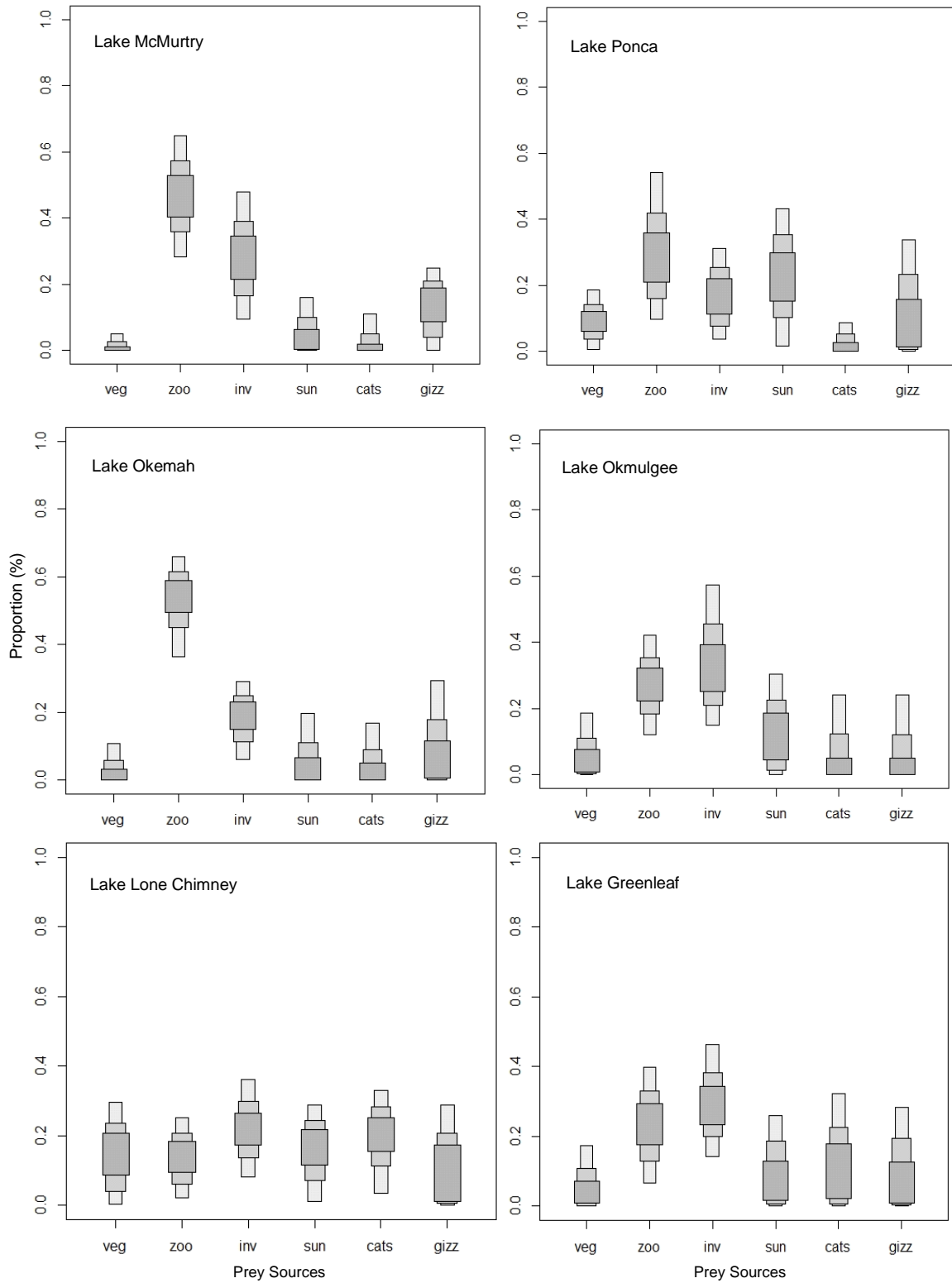
Appendix 4. The estimated diet contributions (95% credibility intervals) of sub-stock (< 280 mm) channel catfish *Ictalurus punctatus* caught in 2012 from four Oklahoma reservoirs based on stable isotope estimates modeled from SIAR Bayesian mixing models.
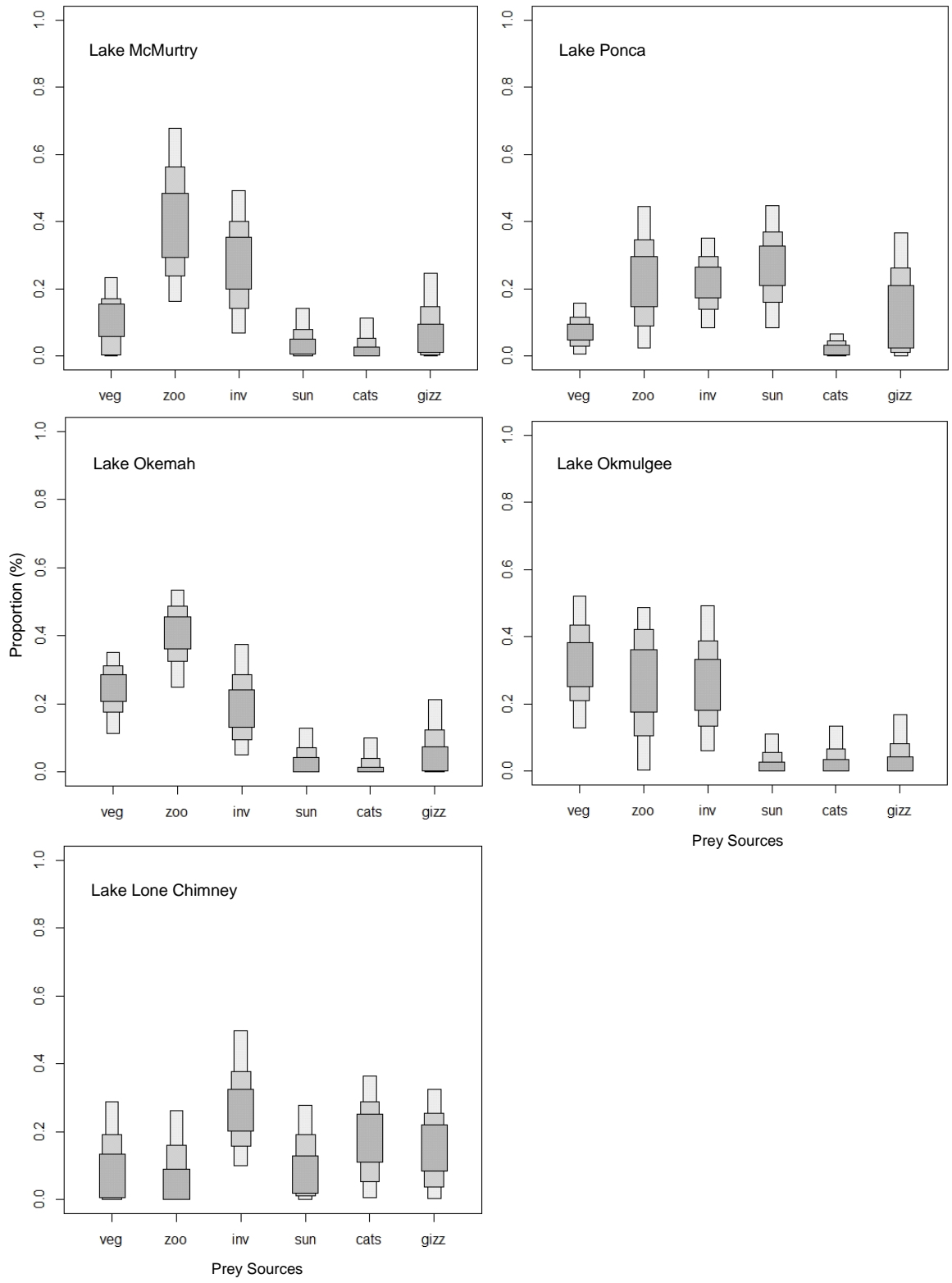
Appendix 5. The estimated diet contributions (95% credibility intervals) of stock-size (≥ 281 to ≤ 410 mm) channel catfish *Ictalurus punctatus* caught in 2011 from five Oklahoma reservoirs based on stable isotope estimates modeled from SIAR Bayesian mixing models.
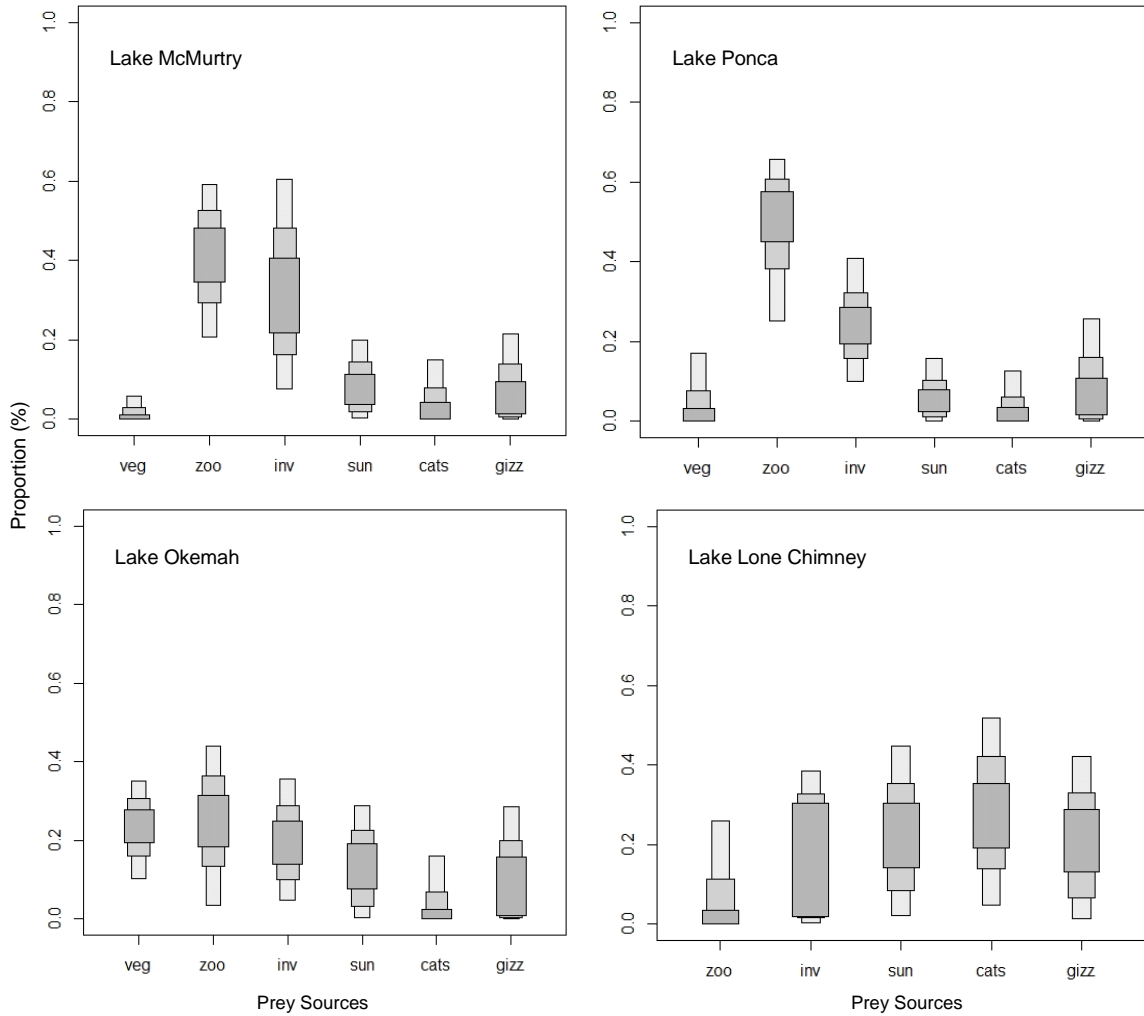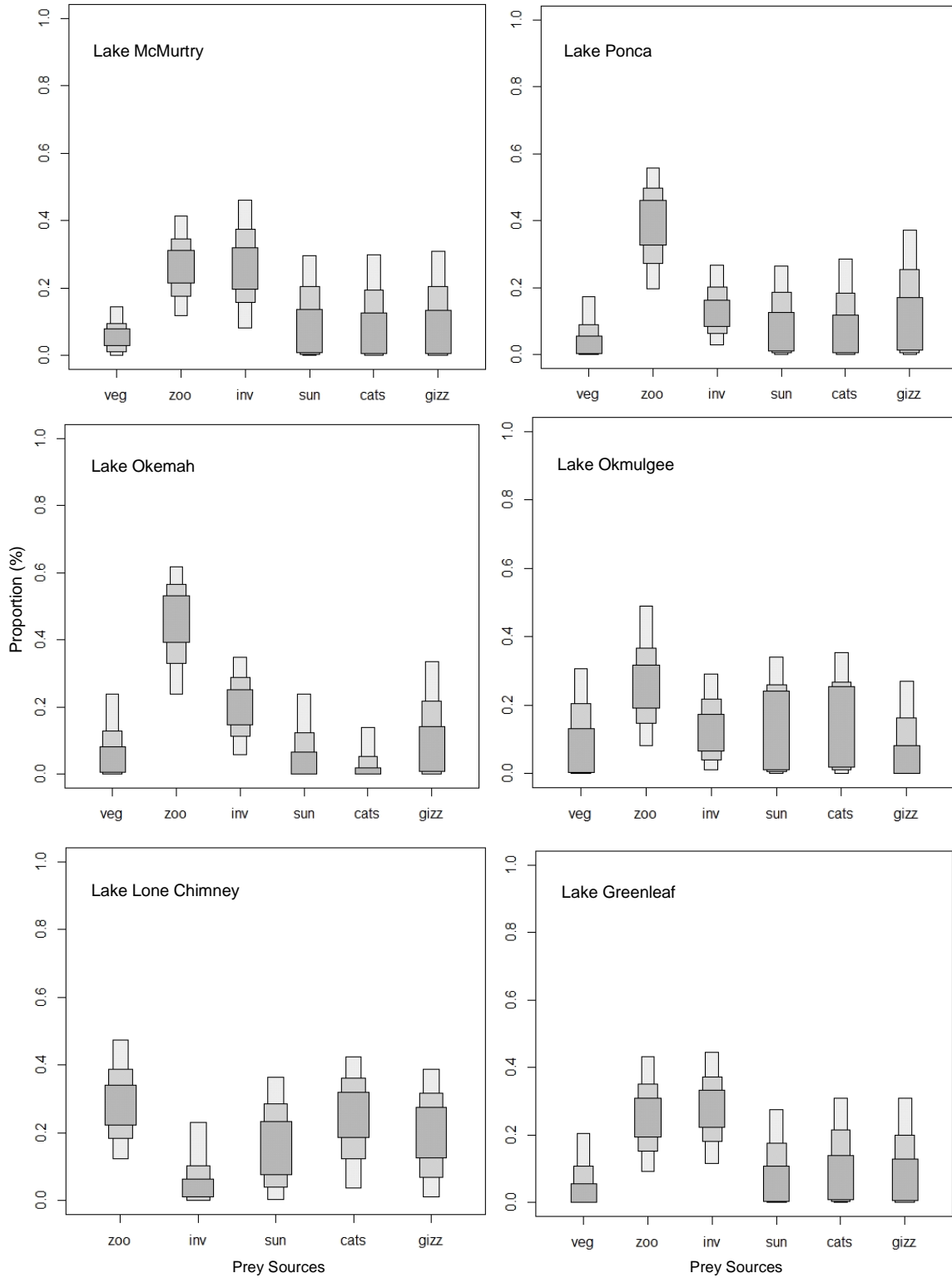
Appendix 6. The estimated diet contributions (95% credibility intervals) of stock-size (≥ 281 to $\leq$ 410 mm) channel catfish *Ictalurus punctatus* caught in 2012 from four Oklahoma reservoirs based on stable isotope estimates modeled from SIAR Bayesian mixing models.
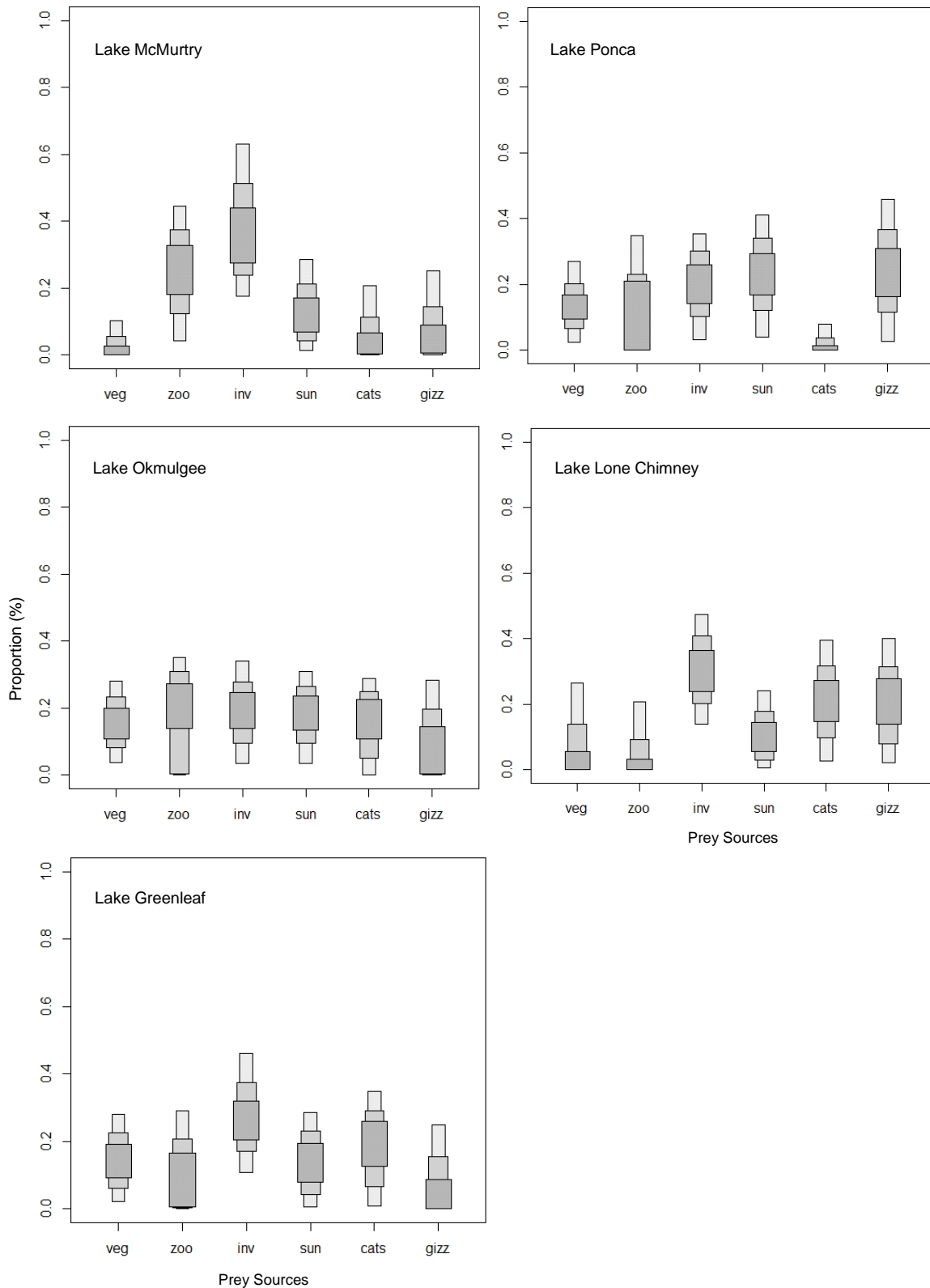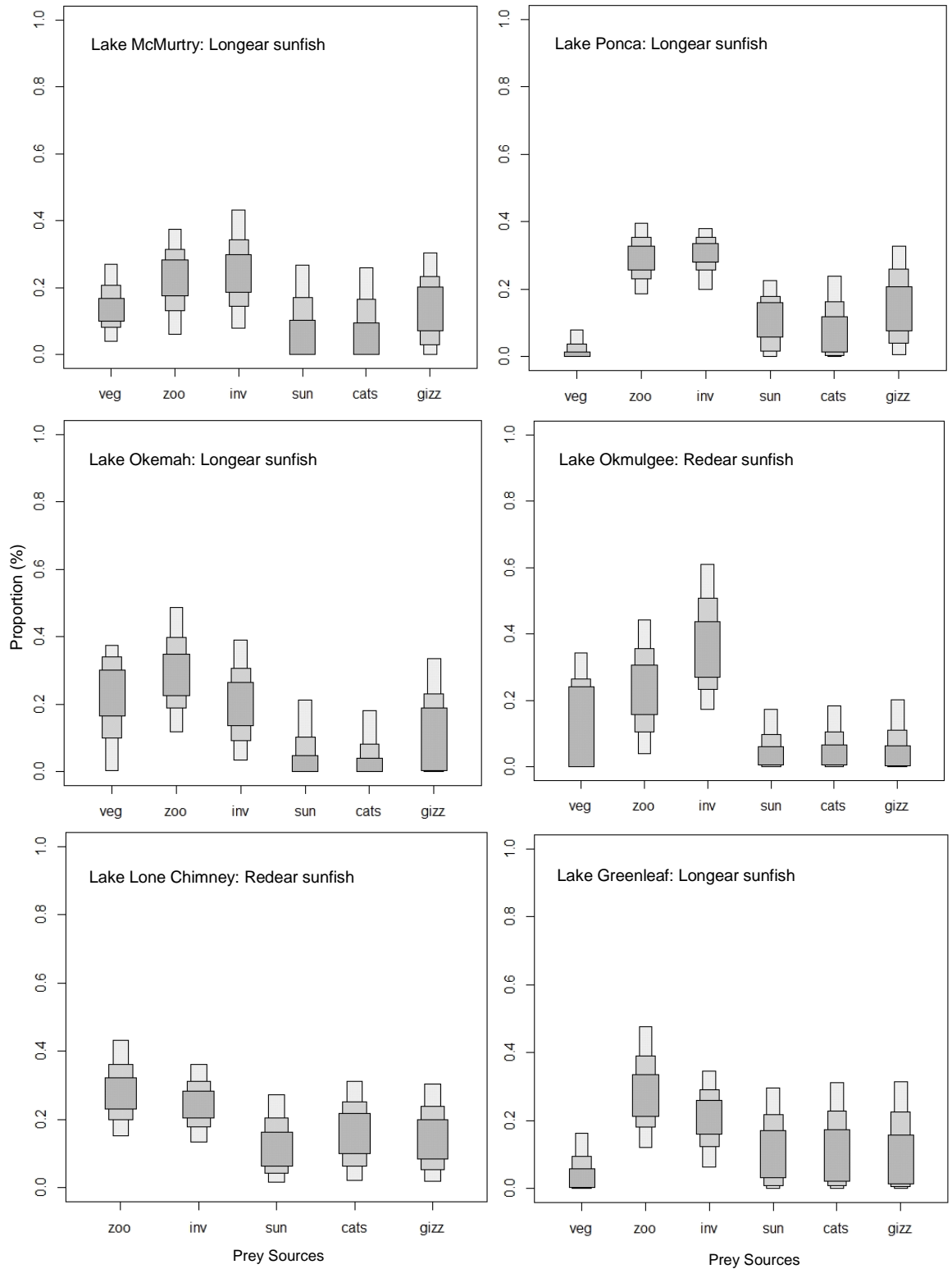
Appendix 7. The estimated diet contributions (95% credibility intervals) of quality-size (≥ 411 to ≤ 610 mm) channel catfish *Ictalurus punctatus* caught in 2011 from five Oklahoma reservoirs based on stable isotope estimates modeled from SIAR Bayesian mixing models.

Appendix 8. The estimated diet contributions (95% credibility intervals) of quality-size (≥ 411 to ≤ 610 mm) channel catfish *Ictalurus punctatus* caught in 2012 from six Oklahoma reservoirs based on stable isotope estimates modeled from SIAR Bayesian mixing models.
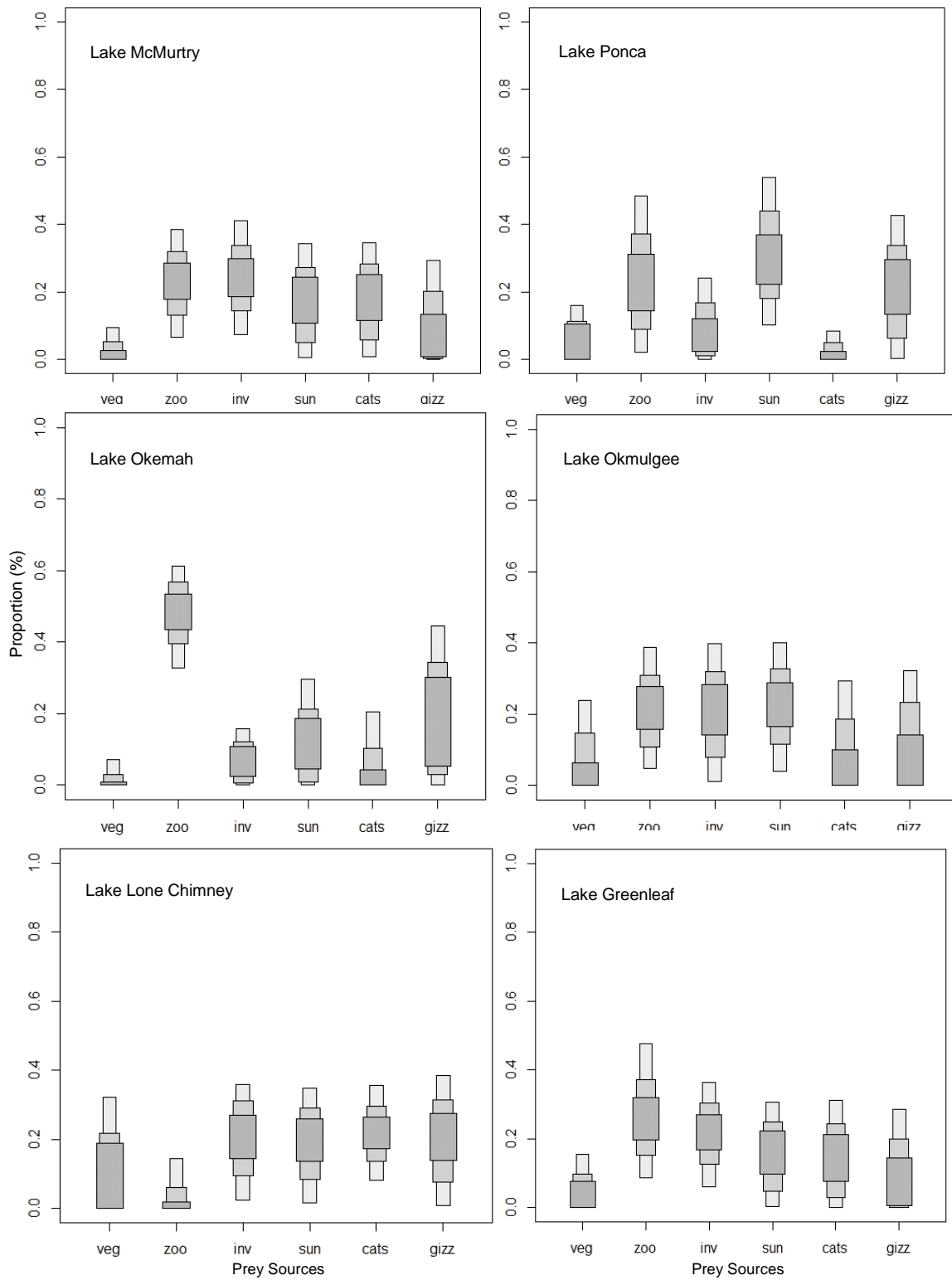
Appendix 9. The estimated diet contributions (95% credibility intervals) of bluegill *Lepomis macrochirus* caught in 2011 from six Oklahoma reservoirs based on stable isotope estimates modeled from SIAR Bayesian mixing models.
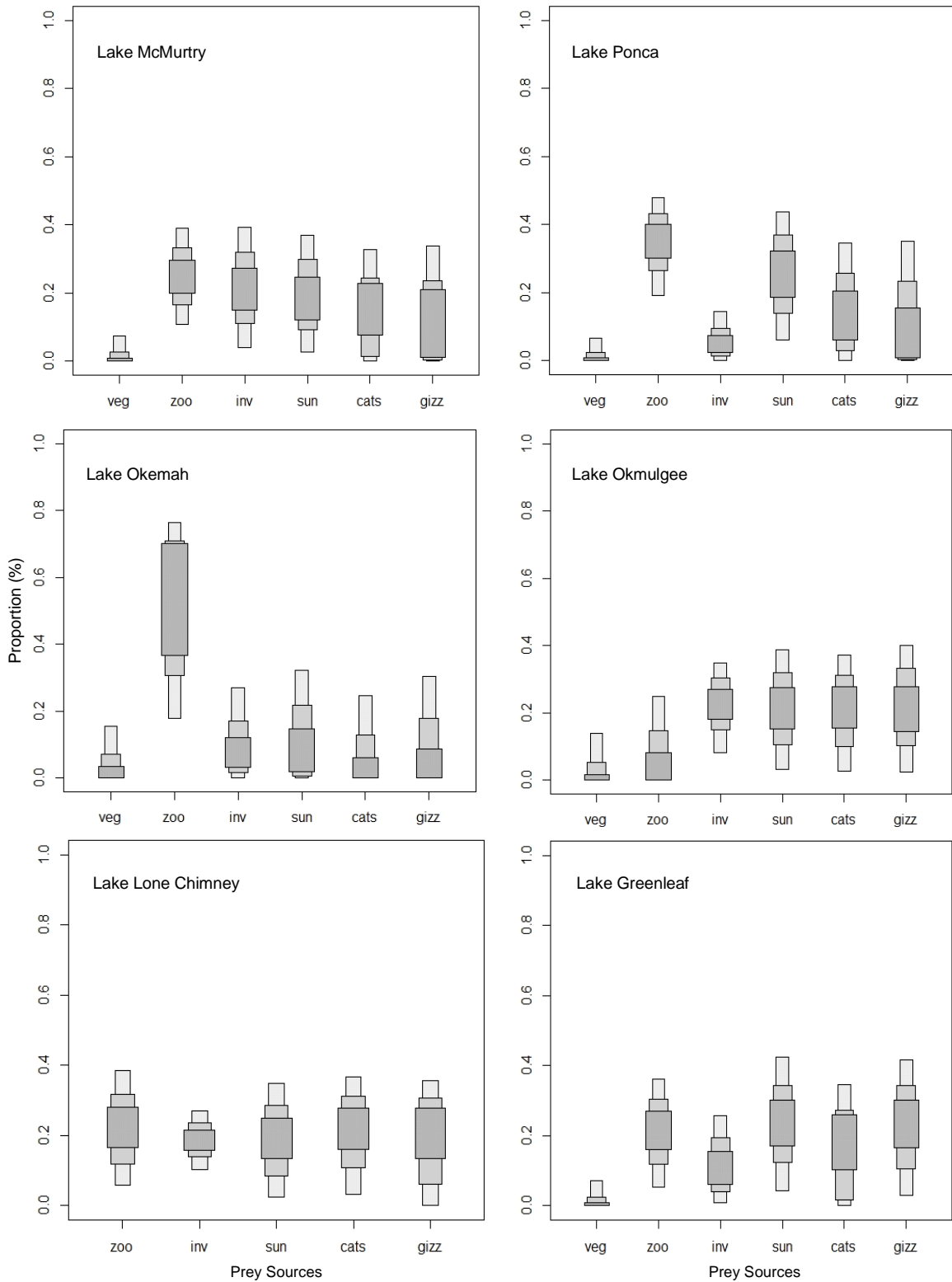
Appendix 10. The estimated diet contributions (95% credibility intervals) of bluegill *Lepomis macrochirus* caught in 2012 from six Oklahoma reservoirs based on stable isotope estimates modeled from SIAR Bayesian mixing models.

147

Appendix 11. The estimated diet contributions (95% credibility intervals) of longear sunfish *Lepomis megalotis* and redear sunfish *Lepomis microlophus* caught in 2012 from six Oklahoma reservoirs based on stable isotope estimates modeled from SIAR Bayesian mixing models
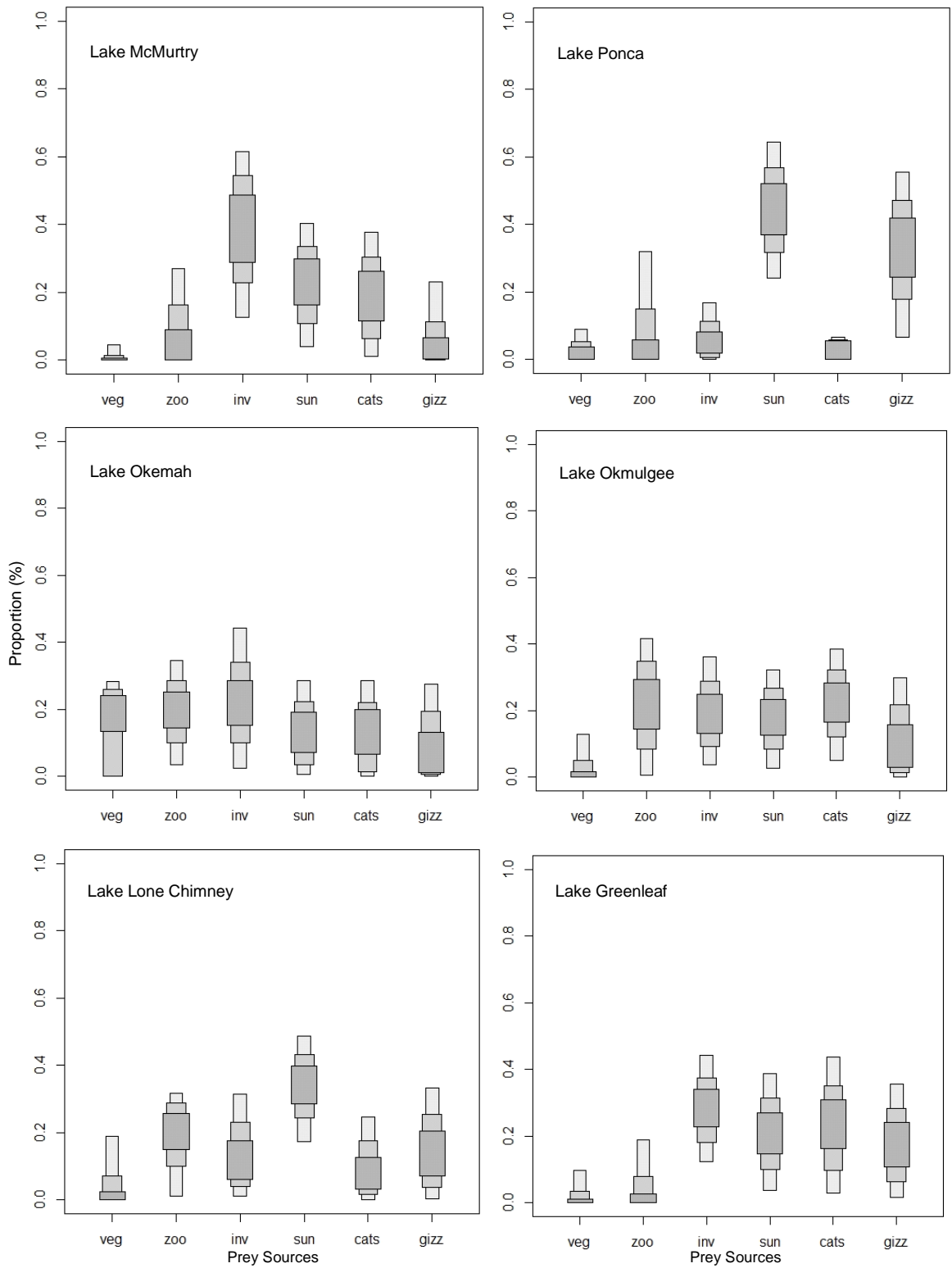
Appendix 12. The estimated diet contributions (95% credibility intervals) of white crappie *Pomoxis annularis* caught in 2011 from six Oklahoma reservoirs based on stable isotope estimates modeled from SIAR Bayesian mixing models
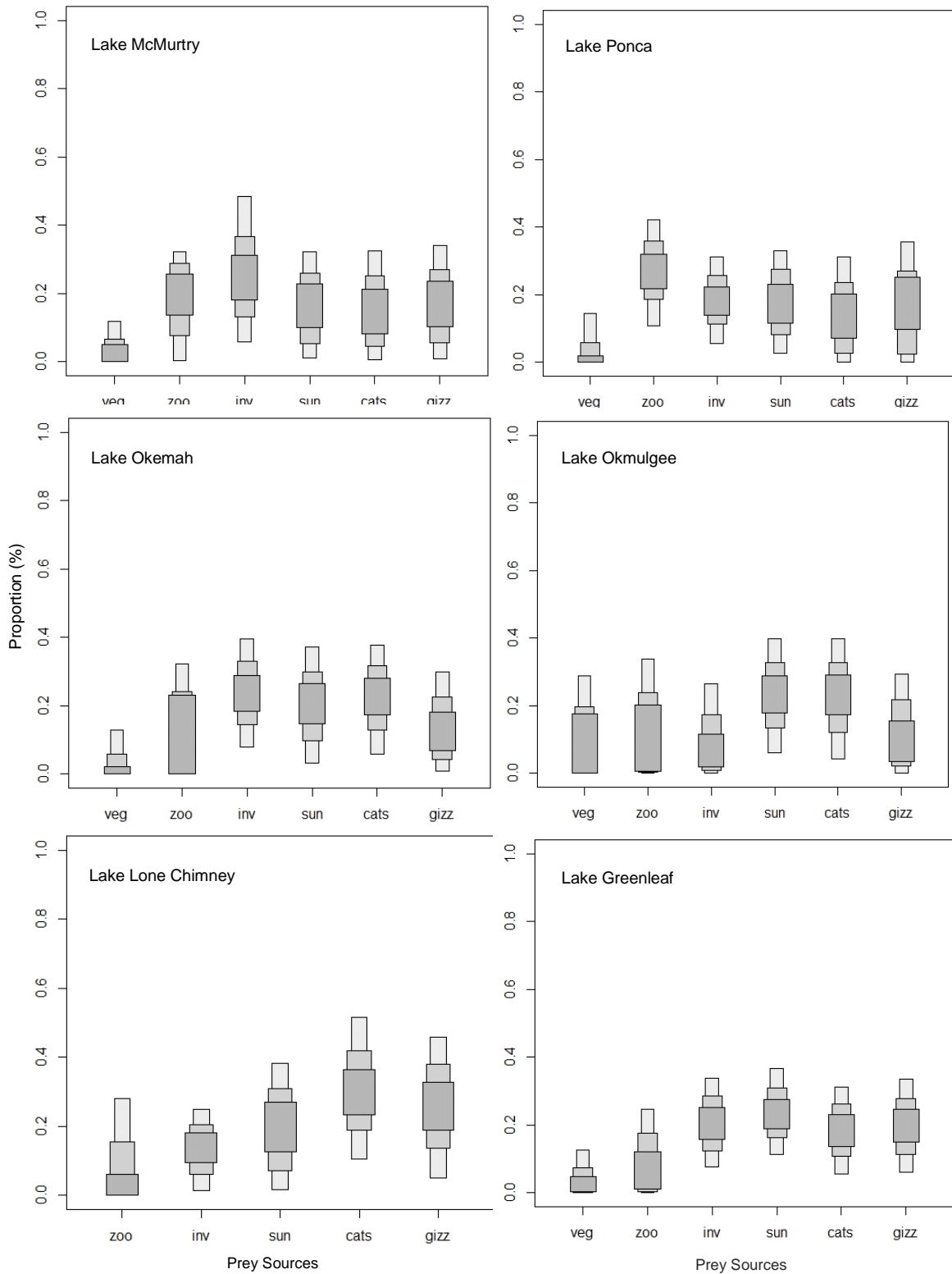
Appendix 13. The estimated diet contributions (95% credibility intervals) of white crappie Pomoxis annularis caught in 2012 from six Oklahoma reservoirs. Estimates based on stable isotope analysis from SIAR Bayesian mixing models.
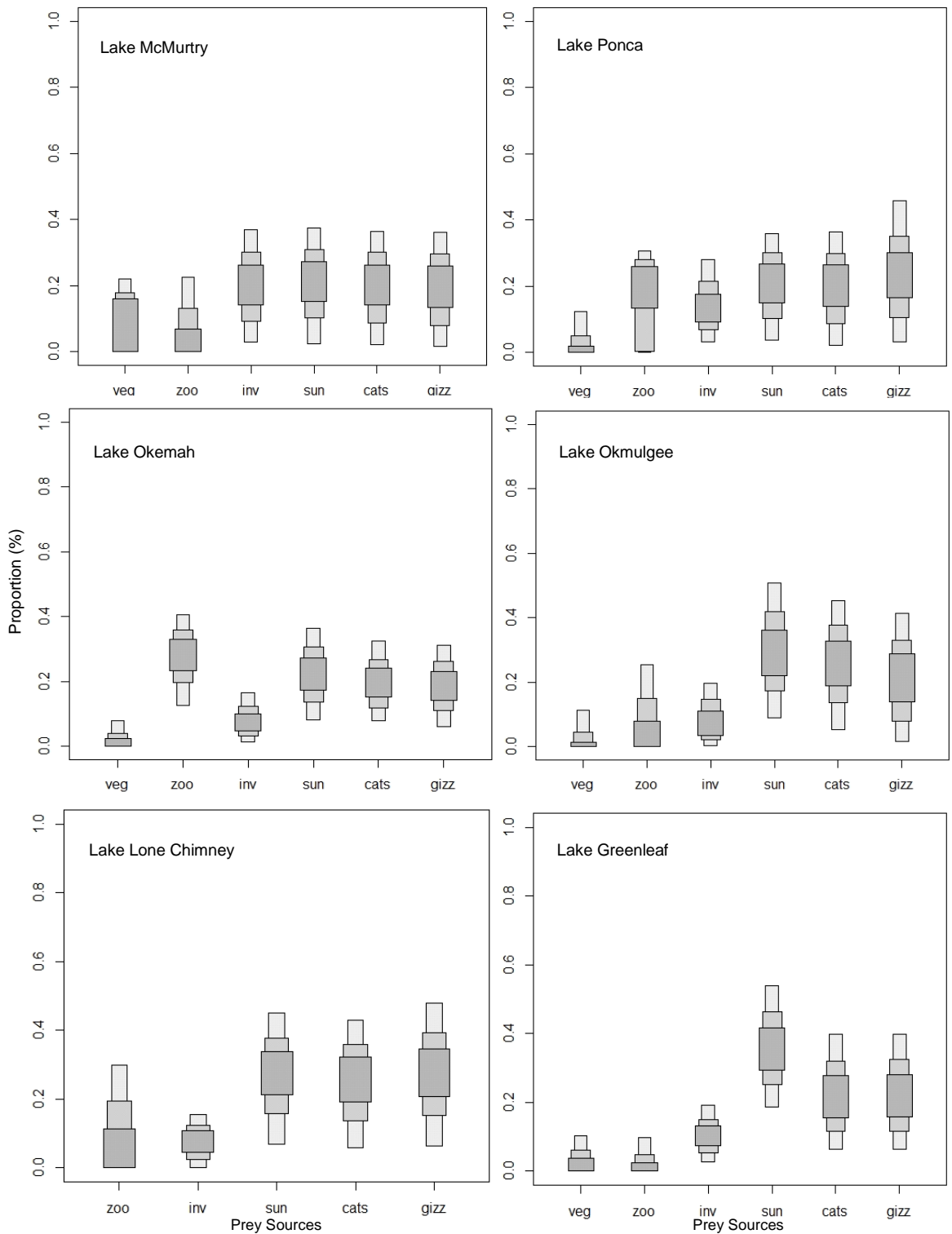
Appendix 14. The estimated diet contributions (95% credibility intervals) of largemouth bass *Micropterus salmoides* caught in 2012 from six Oklahoma reservoirs. Estimates based on stable isotope analysis from SIAR Bayesian mixing models.

Appendix 15. The estimated diet contributions (95% credibility intervals) of flathead catfish *Pylodictis olivaris* caught in 2011 from six Oklahoma reservoirs. Estimates based on stable isotope analysis from SIAR Bayesian mixing model.

Appendix 16. The estimated diet contributions (95% credibility intervals) of flathead catfish *Pylodictis olivaris* caught in 2012 from six Oklahoma reservoirs. Estimates based on stable isotope analysis from SIAR Bayesian mixing model.

VITA

David Randall Stewart Jr

Candidate for the Degree of

Doctor of Philosophy

Thesis: FACTORS RELATED TO STOCKING SUCCESS OF 178 MM CHANNEL
CATFISH IN MEDIUM SIZE OKLAHOMA RESERVOIRS

Major Field: Natural Resource Ecology and Management

Biographical:

Education:

Completed the requirements for the Doctor of Philosophy in Natural Resources
Ecology and Management at Oklahoma State University, Stillwater, Oklahoma
in December, 2013.

Completed the requirements for the Master of Science in Zoology at Middle
Tennessee State University, Murfreesboro, Tennessee in 2009.

Completed the requirements for the Bachelor of Science in Biology at Martin
Methodist College, Pulaski, Tennessee in 2006.

Experience:

Post-doctorate Research Associate, University of Wyoming, 2014

Graduate Research Assistant, Oklahoma State University, 2010-2013

Fisheries Research Biologist II, FL Fish and Wildlife Research Institute, 2009-
2010

Fisheries Research Technician I, TN Wildlife Resources Agency, 2007-2009

Professional Memberships:

American Statistical Association
Oklahoma Chapter of the American Statistical Association
American Fisheries Society
Oklahoma Chapter of the American Fisheries Society
North American Lakes and Reservoir Management