AGE-0 GIZZARD SHAD PREY SUPPLY AND PREDATOR DEMAND: ANALYSIS OF THE TROPHIC SUPPORT CAPACITY OF SOUTHERN U.S. RESERVOIRS

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ABSTRACT

Gizzard shad *Dorosoma cepedianum*, the primary prey in many lakes and reservoirs of the southern U.S., often comprise a majority of the prey biomass in the systems in which they are found. However, they rapidly grow to a size that surpasses the preferred prey sizes of most piscivores. Lakes and reservoirs may, therefore, be prey limited if age-0 gizzard shad abundances are low. Previous studies have not considered the effect of the prey supply of age-0 gizzard shad on the entire piscivore community in a reservoir or the effect of age-0 gizzard shad availability on the growth and condition of piscivores in reservoirs. This study used bioenergetics modeling and Monte Carlo simulations to quantify the abundance of age-0 gizzard shad necessary to sustain seven sport fish species, common to the southern U.S., at diverse growth rates, population sizes, mortality rates, and proportions of gizzard shad in piscivore diets. Annual gizzard shad consumption estimates for individual piscivore species ranged from < 0.01 to 482.5 (kg/ha/year). Annual necessary gizzard shad abundance (accounting for non-predation mortality and reproductive surplus required for prey sustainability) estimates ranged from < 10/ha/piscivore population to > 128,000/ha/piscivore population. Monte Carlo simulations indicated that gizzard shad abundance at the 50th percentile of published age-0 gizzard shad abundances was insufficient to support piscivore communities ≥ 69% of the time. Current findings support the hypothesis that systems must have high prey resource availability to support diverse sport fish communities with high-condition and abundance.

INTRODUCTION

Gizzard shad *Dorosoma cepedianum* are the primary prey in many lakes and reservoirs of the southern and midwestern United States (Noble 1981; Storck 1986; Johnson et al. 1988a). In systems where gizzard shad occur, they often comprise the majority of the prey biomass (Miranda 1983; Stein et al. 1995; Bachmann et al. 1996). However, gizzard shad rapidly grow to a size that surpass the gape-limits of most piscivores (Hambright et al. 1991). Additionally, small piscivores typically consume only gizzard shad < 100 mm TL and large piscivores typically only consume gizzard shad < 200 mm TL (Moore 1988; Dennerline and Van Den Avyle 2000; Vatland and Budy 2007), even when larger prey within the piscivores' gape-limits are abundant (Bonds 2000). As a result, most piscivores consume only age-0 gizzard shad; individuals that have not outgrown their preferred prey sizes (Johnson et al. 1988a; Bonds 2000). Therefore, large gizzard shad individuals contribute to the overall biomass, but not the "available prey" biomass (Ney 1990; Cyterski and Ney 2005). Furthermore, reservoirs with high biomasses of large gizzard shad usually have lower gizzard shad reproduction (Smith 1959; Ostrand et al. 2001). Piscivores, therefore, may be prey-limited (i.e. low age-0 gizzard shad abundance) in spite of high overall gizzard shad biomass. If piscivores in lakes and reservoirs are prey-limited by insufficient age-0 gizzard shad biomass, there are important implications for the management of sport fishes. For example, when sport fish species introductions are made, or when sport fish are stocked as a put-grow-take fishery, poor growth or size structure of piscivores in the system may occur if stocking elevates predator demand in excess of prey biomass. Consequently, the potential for competition among gizzard shad-consuming piscivores has become a recent concern of many fisheries ecologist and management agencies (Cyterski and Ney 2005; Olson et al. 2007; Raborn et al. 2007; Vatland et al. 2008).

The competitive exclusion principle purports that potential competitors will minimize competition by spatially or temporally partitioning resources (Hardin 1960). However, such partitioning is not likely to occur with gizzard shad-consuming piscivores because the gizzard shad prey resource does not exhibit spatial or temporal separation. While piscivores may be spatially separated by habitat preferences, gizzard shad populations likely roam throughout reservoirs as they are commonly found in littoral habitat (Gilwick and Matthews 1990; Bailey and Gerow 2005) as well as throughout the pelagic habitat (Degan and Wilson 1995; Gido 2001). Spatial separation of piscivores, therefore, does not partition the prey resource unless piscivores in separate habitats consume prey other than gizzard shad. Likewise, piscivore taxa may utilize age-0 gizzard shad at dissimilar times of the year due to different prey-size preferences. However, most gizzard shad spawning occurs in the spring (Jester and Jensen 1972; Michaletz 1997a; Sammons et al. 1998) and there is, consequently, little resource renewal between the time when the resource is utilized by smaller and then later, larger piscivores. Gizzard shad consumed by smaller piscivores directly exacerbates resource limitation for larger piscivores. It is, therefore, unlikely that niche partitioning alleviates competition for gizzard shad. An exception may occur if and when prey selection is altered via the partitioning process and alternative prey resources are utilized (Jenkins 1979; Moermond 1979; Venturelli and Tonn 2006).

To date, studies investigating the sufficiency of prey production in reservoirs have not addressed the full scope of this issue, falling short in several key areas. First, they have only considered one to a few of the coexisting piscivores in the system. Even so, most studies have typically found that prey biomass matched or was only slightly above predator demand (Cyterski et al. 2003). However, many reservoirs of the southern and midwestern United States contain six to nine piscivore species, including micropteran and moronid basses, catfishes, crappies, and percids (Bailey 1976; Lee et al. 1980; Johnson et al. 1988b; Graham 1999). Therefore, if the entire piscivore community was considered, it is likely that prey resource limitation often exists and may have decreased piscivore growth, condition, and/or survival (Ploskey and Jenkins 1982; Uphoff 2003). The entire gizzard shad-consuming piscivore community must be considered when evaluating the potential for competition for age-0 gizzard shad prey among piscivores.

Second, prior studies investigating competition for prey likely underestimated predatory demand because they quantified it using actual piscivore consumption rates (piscivores could not, therefore, "demand" more food than was available). Predator demand is more correctly defined as the amount of prey needed for predators to survive and grow optimally, and is predicted to always be greater than actual consumption in prey-limited systems (Ney 1990). Thus, piscivore stocks may exhibit reduced growth and condition even if "estimated predator demand," quantified from actual consumption, is satisfied. Studies demonstrating a positive relationship between availability of age-0 gizzard shad and piscivore growth rates or condition support this definition of predator demand (Morris and Follis 1978; Michaletz 1997b; Porath and Peters 1997; Michaletz 1998a).

Lastly, many previous studies likely over-estimated prey availability by assuming all prey are available to piscivores (i.e., if predator demand was not higher than prey biomass, no prey limitation occurred). It is unlikely that piscivore search and capture efficiencies are 100%. Consequently, a prey biomass that exactly matches the true predator demand will still be insufficient (Ney 1990). Further, a portion of the age-0 gizzard shad will die due to causes unrelated to predation. Some prey biomass must also survive in order to mature and reproduce later in life in order for the prey biomass to be sustainable. The purpose of this study was to investigate prey supply and predator demand of age-0 gizzard shad in southern U.S. reservoirs, and to determine the amount of gizzard shad needed to avoid prey resource limitation and maintain a quality multispecies fishery.

METHODS

Modeling approach

Bioenergetics modeling was used to estimate the biomass of age-0 gizzard shad required by piscivore populations with different growth rates, mortality rates, population sizes, and percentage of gizzard shad in their diets. Modeling scenarios consisted of piscivore communities including largemouth bass *Micropterus salmoides,* white bass *Morone chrysops*, flathead catfish *Pylodictis olivaris*, blue catfish *Ictalurus furcatus*, white crappie *Pomoxis annularis*, large moronids (striped bass *M. saxatilis* or hybrid striped bass *M. saxatilis* X *M. chrysops*; here after referred to as striped bass) and percids (walleye *Sander vitreus* or saugeye *S. vitreus* X *S. canadensis*; here after referred to as walleye). Modeling was accomplished primarily via the “Wisconsin” Fish Bioenergetics 3.0b modeling software (Hanson et al. 1997) using the available bioenergetics models for largemouth bass (Rice et al. 1983), walleye (Kitchell et al. 1977), flathead catfish (Roell and Orth 1993), and striped bass (Hartman and Brandt 1995). Without currently available bioenergetics models for blue catfish or white bass, parameters from Blanc and Margraf (2002) were used to model blue catfish and the striped bass model was used as a surrogate for white bass within the Fish Bioenergetics software. White crappie were modeled with model parameters from Zweifel (2000) in SAS, because the Fish Bioenergetics software is incapable of calculating some of the more complex temperature-mass consumption parameter relationships found in Zweifel's white crappie bioenergetics model.

All modeling scenarios were modeled at both a cool and warm temperature regime. The cool temperature regime was based on temperature logger data from Kentucky Lake, KY for 365 continuous days (1 January 2008 – 30 December 2008) at depths between 1 and 2 m (E. Ganus, Tennessee Wildlife Resource Agency, unpublished data). The warm temperature regime was based on temperature logger data from Possum Kingdom Reservoir, TX for 365 continuous days (1 January 2007 – 30 December 2007) at depths between 1 and 2 m (J. Sullivan, Texas Commission on Environmental Quality, unpublished data). Temperature regimes were modified to allow for a maximum temperature of 28 °C (untransformed maximum cool temperature = 31.3 °C, warm temperature = 31.9 °C), which is the maximum operating temperature of the walleye bioenergetics model. The same modified temperature regimes were used to model all species.

Derivation of model input parameters

Piscivore species were modeled by age cohort at low-, medium-, and high-parameter values for each of four input parameters: growth, mortality, initial population size, and percent of gizzard shad by weight in their diet. Except for diet parameters (see below), low parameter values represented the interpolated 10^{th} percentile of reported values; while medium parameters were the mean of reported values; and high parameters were the interpolated 90^{th} percentile of reported values. All percentiles were interpolated using the percentile function in Microsoft Excel. Literature sources used to derive values for each parameter are listed in Table 1. Only data from lake and reservoir populations were used (i.e., riverine and estuarine population data were not used).

Annual growth increment parameters for each cohort of all species were developed from published mean length-at-age data (Table 1) transformed into mean mass-at-age data using species-specific standard weights (W_s) and published relative weights (W_r). The high growth increment parameter was the interpolated 90th percentile of the mass-at-age values for piscivores with a W_r of 100. Because a W_r of 100 reflects fish at the 75th percentile for the length-mass relationships (Murphy et al. 1991), mass-at-age estimates were modified to reflect fish at the 50th and 25th percentile for mass-at-length (i.e., multiplied the standard weight by the 50th or 25th percentile of W_r published for the species; Table 1) before calculating the medium and low growth increment parameters respectively. The resulting mass-at-age estimates from the 50th percentile of W_r were averaged to produce the medium growth parameter. The 10th percentile of the resulting mass-at-age estimates, were interpolated from the 25th percentile of W_r to produce the low growth parameter.

The interpolated 10th percentile, mean, and interpolated 90th percentile of published mortality rates were used as the low, medium, and high annual mortality rate parameters for each species (Table 1). Because mortality rates are typically determined by catch curves which produce linear mortality rates, separate mortality rates were not derived for each age class, but rather assumed mortality was constant for all ages.

Low, medium, and high initial population size parameters for all species were developed using the 10th percentile, mean, and 90th percentile of published population estimates (Table 1). No published blue catfish population estimates were available for modeling. Instead, a Schnabel mark-recapture population estimate for blue catfish was completed on Lake Arcadia, Oklahoma in June 2009 (Evans and Shoup, unpublished data). This lake has moderate blue catfish electrofishing catch rates (118.5 fish/hr using 2 chase boats; Kuklinski 2008). The resulting population estimate (N = 10,501; 95% confidence interval: 9,234-12,171; based on 12 sample dates with 2,200 marked fish by the end of the study) was used as the medium population size. This value was increased and decreased by 25% to represent the high and low population size parameters, respectively.

The calculated mortality rate parameters were used to distribute the total population estimates among age classes for each species such that the sum of individuals in each age class equaled the total population size and the number of individuals in each age class declined in accordance with the mortality rate. The number of age cohorts modeled for each species was based on the availability of length-at-age data. The maximum age cohort modeled was the oldest age cohort for which a minimum of three published data points (populations) were available. These maximum modeled ages were similar to those reported by mortality studies (Table 1).

Parameters for percent of gizzard shad by weight in the diet were calculated from published diet studies. Data were assigned to age cohorts using mean length-at-age data when necessary because studies frequently presented diet data by piscivore length classes rather than age cohorts. Because diet data were not as common in the literature as the other parameters, the 10^{th} percentile, mean, and 90^{th} percentile of values were not used. Instead, the two lowest and the two highest published percent gizzard shad utilization values for each age cohort were averaged to obtain both the low and high percent gizzard shad diet parameters, respectively. The medium percent gizzard shad diet parameter was calculated by averaging the published values for each age cohort exclusive of the two highest and lowest values. To develop the complete 100% by weight diet for each age cohort needed for modeling, other diet categories were calculated using the same procedure used to calculate gizzard shad percentages. Diet categories and the associated energy densities used included: gizzard shad = 5,105 J/g; other fish = 4,602 J/g; insects = 3,138 J/g; crayfish = 4,393 J/g; zooplankton = 1,987 J/g (Pope et al. 2001); and freshwater mussels = 264 J/g (Eggleton and Schramm 2004). The prey types used for each cohort of each piscivore species depended on reported piscivore diets.

Modeling scenarios

The low, medium, and high values for all input parameters are given by species in Tables 2-8. All combinations of the three levels (low, medium, and high) for each of the four input parameters were modeled for each age cohort of each species ($3^4 = 81$ simulations per cohort). Modeling was completed using a temperature start date corresponding with 15 June for all species, which is the approximate time of year when age-0 gizzard shad are large enough that they begin to appear in piscivore diets (Bodola 1955; Dettmers and Stein 1992; Michaletz 1997b). Consumption estimates for all age cohorts, within a given combination of input parameters, were summed to obtain estimates of annual gizzard shad consumption by each piscivore population.

Conversion of consumed gizzard shad biomass to number of gizzard shad required to sustain piscivore demand

Annual consumption estimates from the bioenergetics model (total biomass consumed) can not be readily compared to gizzard shad population estimates at any specific point in time as gizzard shad biomass is a function of both abundance and mass. Gizzard shad abundance and mass change throughout the year, so there is no time when the standing biomass of gizzard shad represents the total biomass produced for the year. Furthermore, an age-0 gizzard shad biomass that exactly meets piscivore demand will not be sustainable because some gizzard shad will die from causes other than predation, and because a certain number of gizzard shad must survive to reproduce and create the same number of age-0 fish in future years. Therefore, to facilitate comparison of model predictions with measurable gizzard shad population data, the number of shad needed on simulation days 1 (15 June; the time when age-0 fish have grown to a size that they appear in most piscivore diets) and 60 (15 August; a time during the year when gizzard shad are commonly sampled) to support consumption by the piscivore population for the rest of the simulation year were estimated, after adjusting for non-predation mortality and accounting for number of age-0 fish that must survive to sustain age-0 production through reproduction.

To account for non-predation mortality and necessary age-0 survivorship, daily gizzard shad consumption estimates (in grams) from the bioenergetics models were first converted to numbers of gizzard shad using mean daily gizzard shad mass, estimated from the temperature-dependent growth function of the Fish Bioenergetics software with an input start mass of 0.166 g and end mass of 58.2 g. A start mass of 0.166 g was calculated as the equivalent of a 20-mm standard length gizzard shad (the approximate length at which clupeids become heavily utilized by piscivores in mid-June; Hale 1996; Michaletz 1997b; Dennerline and Van Den Avyle 2000), using the length-mass relationships from Bodola (1955). Because data were not available on the average mass of age-1 gizzard shad in June, 425 days of gizzard shad growth were modeled using the start mass of 0.166 g and an end mass of the mean mass-at-age-1 data in August (Bodola 1955; Pierce 1977; Schramm and Pugh 1996; Cyterski et al. 2003). The daily individual mass estimates from the model were then used to estimate number of gizzard shad that would be consumed each day to meet the estimated biomass consumed by piscivores in the piscivore bioenergetic simulations.

Next, to address non-predation mortality, an annualized mortality rate (A) of 0.7 (published range = 0.5-0.9; Tisa 1988; Michaletz 1998b; Clayton and Maceina 2002) derived from catch-curve analysis of age ≥1 individuals (which experience very limited predation mortality; Hale 1996; Michaletz 1997b) was used. This rate of non-predation mortality was assumed constant across all age classes. While total mortality rates for age-0 gizzard shad are typically higher (A = 94.2-99.9%; Jensen et al. 1988; Tisa and Ney 1991; Michaletz 1997a), it is not known how much of this mortality is caused by predation. Therefore, the modeled morality rate is probably conservative for age-0 fish. This annual mortality rate was converted to an instantaneous mortality rate and used to back-calculate number of gizzard shad that would be needed on May 15 (assumed spawn date) to provide the number consumed by piscivores on each day of the simulation. The resulting value (N_c) is the number of offspring needed to exactly meet predator demand by the end of the model year (accounting for non-predation mortality).

Next, N_c was used to determine the number of additional age-0 gizzard shad required to sustain age-0 production each year through reproduction. All gizzard shad were assumed to mature at age-2 (Bodola 1955; Kilambi and Baglin 1969; Jons and Miranda 1997). The mean number of offspring produced per individual over their entire lifetime (R_0) is given as:

$$R_0 = \sum_{x=0}^{k} \left(l_x * m_x \right)$$

where l_x is the probability of surviving from time 0 to time x, m_x is the per-capita birth rate (mean number of offspring produced per individual during year x), and k is the maximum lifespan (years). To calculate the number of age-2 gizzard shad required to produce N_c offspring over their lifetime, age-2 was defined as year-0 in the R_0 calculation (to determine mean number of offspring produced by individuals that have already survived to age-2). Therefore, l_x = 1.0 for these age-2 fish. For subsequent years, l_x was calculated as S^t, where S = annualized survival ($S = 1 - A$ where A = 0.7 as described above) and t is years since age-2. Per-capita birth rate was assumed constant for all reproductive years (m = 233.5; calculated from Cyterski et al. (2003) larval production and adult standing stock estimates). Maximum age was assumed to be 6-years (southern gizzard shad populations typically live 5 – 7 years; (Schramm and Pugh 1996; Clayton and Maceina 2002; Cyterski et al. 2003). This yielded R_0 = 332.8 offspring per individual per lifetime. Therefore, the number of age-2+ individuals that are needed to produce N_c age-0 fish over their lifetime is:

$$N_{age-2} = \frac{N_c}{R_0}$$

Assuming a stable age distribution, N_c offspring would also be produced every year by the age-2+ population (static life tables are analogous to the total production over the lifetime of a single cohort). To determine number of age-0 fish required to leave N_{age-2} fish two years later, the above equation must be adjusted for two years of mortality as:

$$N_{rs1} = \frac{N_c}{R_0 * S^2}$$

This is the number of additional age-0 fish (N_{rs1} for “reproductive surplus” production, first iteration) required to produce the original number of offspring (N_c) each year. However, the required age-0 production must now be adjusted the same way to produce these additional N_{rs1} fish (N_{rs2}, reproductive surplus second iteration). These added N_{rs2} individuals will also require additional surviving age-0 fish to produce them (N_{rs3}), and so on in a convergent infinite series such that:

$$N_{rs} = \frac{N_c}{R_0 * S^2} * \frac{1}{R_0 * S^2} * \frac{1}{R_0 * S^2} * \frac{1}{R_0 * S^2} \ \ldots \text{ or } \ N_{rs} = N_c * \sum_{x=1}^{\infty} \left(\frac{1}{R_0 * S^2} \right)^x$$

which has the finite solution:

$$N_{rs} = N_c * \left[\left(1 - \frac{1}{R_0 * S^2} \right)^{-1} - 1 \right]$$

Where N_{rs} is the total reproductive surplus required for no net change in population size over time when N_c age-0 individuals are consumed by piscivores every year. Therefore, the population must have $N_c + N_{rs} = N_0$ age-0 gizzard shad produced on May 15th to sustainably meet the predator demand (N_c).

Finally, the above calculated N_0 fish were adjusted for non-predation and predation mortality to calculate the number of age-0 gizzard shad needed on simulation days 1 (15 June) and 60 (15 August) to sustainably support consumption by the piscivore population for the rest of the simulation year.

Modeling piscivore community consumption

Model output from the 81 simulations for each species (converted to number of gizzard shad adjusted for non-predation mortality and the required reproductive surplus) were then combined to evaluate the gizzard shad consumption by the entire piscivore community. No published studies provide actual growth, mortality, population size, and diet data for all piscivores in the system, so it was not possible to model actual scenarios. Similarly, it was not feasible to calculate all possible combinations of bioenergetic simulations for the seven species because they were too numerous (81^7 = 22.9 trillion combinations). Therefore, 50,000 randomly selected Monte Carlo simulations (randomly selecting one of the 81 simulations for each of the seven species) were used. The total number of age-0 gizzard shad required by the seven piscivores from model day 60 (15 August) to the end of the simulation year for each simulation was then calculated. These values were compared with published age-0 gizzard shad abundances from late summer

(July-August; Olmstead 1974; Johnson et al. 1988a; Aumen et al. 1992; Michaletz 1998a; Cyterski et al. 2003; Hale et al. 2008).

Sensitivity analysis

Two types of sensitivity analysis were performed to determine which factors most strongly influenced the predicted gizzard shad consumption for each species. First the effects of the three levels (low, medium, high) for each of the four input parameters were visually evaluated by plotting gizzard shad consumption for each piscivore species against the parameter levels at both cool and warm temperatures. Because the low, medium, and high levels of each parameter were derived from the literature, they differed among species. To consider the effects of species, a second sensitivity analysis was performed by modeling each species using standardized parameters for growth, mortality, population size and percent by weight of gizzard shad in piscivore diets. Intervals of 100-g were used as cohorts, a growth increment of 30% the starting mass, no mortality, and 100% of the diet from gizzard shad. A population size of 1 fish in each cohort (maximum weight class was based on the maximum mean mass-at-age for the oldest age cohort in the simulations for each species) was then modeled. Models were run using both the cool and warm temperature regimes. Resulting consumption estimates were plotted against piscivore size class to compare energetic efficiency for each species under these standardized conditions.

RESULTS

Sensitivity analysis testing the effects of the individual input parameters (growth rate, mortality rate, population size, and percent of gizzard shad in the diet; using literature-derived values that differed among species) on gizzard shad consumption indicated that all parameters had a similar magnitude of effect on consumption estimates for all species (largemouth bass Figure 1; white bass Figure 2; striped bass Figure 3; white crappie Figure 4; flathead catfish Figure 5; blue catfish Figure 6; and walleye Figure 7). The effects of the two temperature regimes that were modeled were comparatively minor.

Sensitivity analysis testing effects of the different species models on gizzard shad consumption (using the same input parameters for all species; Figure 8) illustrated that the striped bass model was the least energetically efficient (i.e., highest gizzard shad consumption [g/g/d]). The flathead catfish model was the most energetically efficient model (i.e., lowest gizzard shad consumption [g/g/d]). The largemouth bass, blue catfish, white crappie, and walleye models were similar and had intermediate energetic efficiency. Effects of temperature on consumption were minor for all piscivore species (Figure 8).

The relative ranking (lowest to highest total consumed shad biomass) of the 81 combinations of input parameters varied among species to some extent in both the cool (Table 9) and warm (Table 10) temperature regimes, but these differences were generally small. For all species at both temperatures, consumption was always highest with the combination of high growth, low mortality, high initial population size, and high percent of gizzard shad in diet (3-1-3-3) and lowest with the combination of low growth, high mortality, low initial population size, and low percent of gizzard shad in diet (1-3-1-1). Gizzard shad consumption estimates ranged from < 0.01 to 482.5 (kg/ha/year). While the sensitivity analysis indicated flathead catfish were most energetically efficient and striped bass were least efficient, the differences in population parameters among species frequently were large enough to overcome these differences in bioenergetics inefficiency. Therefore, the species that had the highest or lowest gizzard shad consumption for a given simulation was highly variable (Tables 9-10).

The estimated abundance of gizzard shad required to sustainably meet predator demand (accounting for non-predation mortality and required reproductive surplus) for the remainder of the simulated year on simulation day 1 (Tables 11-12) and day 60 (Tables 13-14) ranged from inconsequentially small (e.g., < 10/ha/piscivore population) to values large enough to suggest prey resource limitation could occur even with a single predator population in systems with low gizzard shad biomass or with a few predators in a system with a more typical gizzard shad biomass (e.g., > 128,000/ha/piscivore population). Tables 11-14 can be used to calculate the abundance of gizzard shad required for any given combination of species with different population parameters by looking up the desired combination of population parameters for each piscivore and summing the gizzard shad abundance required for each species. Monte Carlo simulations indicated that predator demand could frequently exceed sustainable gizzard shad abundance. The required gizzard shad abundance exceeded the 50th percentile of published age-0 gizzard shad abundances 69% of the time at the cool temperature regime and 72% of the time at the warm temperature regime (Figure 9). At least some proportion of the Monte Carlo simulations continued to exceed published age-0 gizzard shad abundances up to the 95^{th} percentile of gizzard shad abundance for both the cool and warm temperature regimes.

DISCUSSION

Monte Carlo simulations indicate that in systems with seven piscivores and below average age-0 gizzard shad abundances, age-0 gizzard shad abundance often limits piscivore populations. Furthermore, it is not until age-0 gizzard shad abundance was above the 75th percentile that all seven piscivores have a greater than 50% probability of not being prey-resource limited, suggesting that managers should not introduce this number of piscivores in most systems. These findings indicate that age-0 gizzard shad limit piscivore populations in many systems where multiple piscivores are present. Moreover these findings, coupled with the results from studies showing positive relationships between age-0 gizzard shad availability and piscivore growth rates and condition (Morris and Follis 1978; Michaletz 1997b; Porath and Peters 1997; Michaletz 1998a), support the hypothesis that systems must have high prey resource availability if they are to support communities of multiple high-condition and abundant piscivores.

Estimated annual consumption for largemouth bass, striped bass, and walleye were similar to those estimated for Norris Reservoir, Tennessee (Table 15) when the studied populations were characterized using the current study's input parameter categories. Estimated annual consumption for largemouth bass and striped bass were also similar to those estimated for Smith Mountain Lake, Virginia (Table 15) when the studied populations were characterized using the current study's input parameter categories. This illustrates that the simplified three-category (low, medium, high) method of characterizing input parameters can produce annual consumption estimates comparable to those with specific input parameters.

Responses to Insufficient Prey and Management Implications

Piscivores likely respond dynamically to insufficient prey resources in lakes and reservoirs, depending on the extent and duration of prey resource limitation. Piscivores can, theoretically, respond via short-term or long-term processes (Moermond 1979). However, long-term responses such as niche partitioning occur over evolutionary time intervals that exceed the duration of most sport fish management regulations and frequently the service lifetimes of reservoirs (Moermond 1979; Raborn et al. 2007). Niche partitioning of prey resources may not occur in reservoirs because piscivore assemblages frequently consist of species that do not coexist natively and, therefore, did not coevolve (Raborn et al. 2007). Resource partitioning of gizzard shad prey is further doubtful due to the lack spatial and temporal separation between gizzard shad and piscivores. Therefore, short-term piscivore responses to insufficient prey are more likely than evolutionary long-term responses in reservoir systems. Short-term responses include reduced consumption (Rice and Cochran 1984) and diet shift (Jenkins 1979; Venturelli and Tonn 2006), typically leading to decreased growth (Muth and Wolfert 1986; Weatherley 1990) and/or population abundance and biomass (Ploskey and Jenkins 1982). These short-term responses influence sport fish condition or population size in ways that are typically counterproductive to management objectives. Prey resource limitation is thought to frequently limit adult sport fish production (Jenkins 1979; Noble 1981; Ploskey and Jenkins 1982; Ney and Orth 1986; Ney 1990). Therefore, managers must set realistic management objectives that are consistent with the available prey biomass of the systems they manage. The simulation output provides tools that can be used to estimate the number and quality of piscivore populations that can be supported by a given prey biomass.

Tables 11-14 can be used by managers to help determine the carrying capacity of any given reservoir. If a manager can rank their piscivore populations with respect to the four population parameters used, then these tables can be used to estimate the abundance of gizzard shad required by this piscivore community. These estimates will be most useful when age-0 gizzard shad abundance is sampled directly (e.g., hydroacoustic or trawl data) in the lake or reservoir of interest. However, the estimates could instead be compared with published gizzard shad abundances (e.g., Figure 9) if only a relative knowledge of the population is known (e.g., catch per unit effort from gill net samples). Estimating the carrying capacity should be especially useful in situations where the introduction of an additional sport piscivore is being considered, as it can be used to check if sufficient prey resources exist.

It must, however, be recognized that the estimates provided are conservative in nature. Age-0 piscivore consumption was not included in the simulations, due to inadequate data availability and, while available literature does not indicate extensive amount of gizzard shad predation by any of the age-0 piscivores modeled (Table 1; % gizzard shad in diet citations), some predation is possible that would further increase the estimated piscivore demand. Further, there could be other resources that constrain piscivore populations that need to be considered. It is not advisable for managers to attempt to "maximize" piscivore demand as annual fluctuations in prey production are common and thus the maximum piscivore biomass that is sustainable will also fluctuate (Ney 1981; Noble 1981; Raborn et al. 2007). The complexity of ecosystems makes them inherently difficult to predict and, therefore, manage. The exact response of piscivorous sport fishes to decreased prey supply is, consequently, unpredictable. Existing piscivore communities may respond with any combination of the previously mentioned short-term responses to the addition of new piscivores to a system, but which piscivores will be most strongly affected is difficult to predict. Alternatively, the piscivore community may, through their prey demand, prevent the success of a newly introduced piscivore. Adaptive management practices should be utilized when stocking piscivores and the pros and cons of piscivore additions and their effect on prey supply should be considered.

Population Input Parameters

Input parameters were interpolated from 10^{th} and 90^{th} percentile estimates because they are applicable to a wide range of systems without being unrealistically extreme. For example, input parameters could have been derived using the 25^{th} and 75^{th} percentile estimates, but these would only cover 50% of systems. Similarly, the modeled parameters are more conservative than they would be if they had been derived them using 1^{st} and 99^{th} percentiles, which would be unrealistically low or "world record" populations. Population scenarios corresponding with "high growth, low mortality, high population, and high % gizzard shad diet (3-1-3-3)" and, likewise, "low growth, high mortality, low population, and low % gizzard shad diet (1-3-1-1)" function as the upper and lower bounds of gizzard shad consumption in the simulations. While it is rare that any population would be as poor (3-1-3-3) or exceptional (1-3-1-1) as these extremes, these parameters only occurred in the Monte Carlo simulations with a 1 in 81 probability (given 81 modeled sets of parameters), a probably that is likely reflective of the proportion of extremely poor or exceptional piscivore populations in southern lakes and reservoirs. Further, the way in which parameters were assigned to populations was "balanced" in that it produced an equal number of poor and exceptional populations. Therefore, random selection of the individual species populations for the Monte Carlo simulations would not result in biased estimates.

Alternative Prey Utilization

Simulations were performed in accordance with the premise that clupeids, particularly gizzard shad, often account for the majority of the prey base in southern U.S. lakes and reservoirs (Noble 1981; Storck 1986; Johnson et al. 1988a). Despite alternative prey availability, many pelagic piscivore species have been shown to feed almost exclusively on gizzard shad or similar clupeids, as few alternative prey fishes occur in the pelagic habitat (Cyterski et al. 2003; Raborn et al. 2007). The increased energy density of clupeids (Pope et al. 2001) also likely makes them a more efficient prey for both littoral and pelagic piscivores based on optimal foraging theory (MacArthur and Pianka 1966). The current study's bioenergetics approach reduced reliance on the premise of primarily gizzard shad prey usage by accounting for alternative prey utilization via the use of low, medium, and high percent gizzard shad in piscivore diet input parameters.

Quality of Model Estimates

The accuracy of the piscivore consumption estimates are dependent on the quality of the physiological parameters of the models and/or the selected input parameters (Raborn et al. 2002). Sensitivity analyses of bioenergetic models have primarily illustrated that the precision of physiological parameters has relatively little influence on model output (Kitchell et al. 1977; Rice et al. 1983; Bartell et al. 1986). Because model input parameters were derived from actual observed populations, the potential for error is constrained by what are believe to be reasonably unbiased inputs (Bartell et al. 1986; Stewart and Binkowski 1986). The models should, therefore, provide estimates that are generally unbiased. Additionally, it is unlikely that the bioenergetic models of all species used in the simulations were systematically biased in the same way, limiting the likelihood of a biased community-level consumption estimate. The application of bioenergetic parameters from species other than the modeled species can also decrease the accuracy of consumption estimates (Ney 1990; Ney 1993). Inaccuracy can, however, be minimized when the utilized parameters are from closely related species of comparable phylogeny, morphology, and behavior (Roell and Orth 1993; Hanson et al. 1997; Raborn et al. 2007). Thus, the use of bioenergetics parameters from similar species for white bass and blue catfish is not expected to have a large effect on model accuracy at the community level.

Temperature Effects

While warm simulations had slightly higher consumption estimates, as expected, the effects of temperature on consumption were smaller than expected. The temperature regimes were chosen because of their relatively northern and southern origins within the southern U.S., and are believe to be representative of typical southern lakes and reservoirs. However, these two temperature regimes were still very similar (mean daily temperature difference was 1.5 °C), which likely is the cause of the small temperature effects in the model output. The degree of temperature-dependency in the equations of the bioenergetics models may not strongly affect consumption estimates at these small differences in temperature. Subtle differences in temperatures, especially at moderate temperatures, are not expected to influence bioenergetics estimates as much as more extreme temperature differences (Bajer et al. 2004; Petersen and Paukert 2005; Schoenebeck et al. 2008). Furthermore, bioenergetic estimates of consumption based on growth increments are largely insensitive to temperature effects (Rice and Cochran 1984). Therefore, it is logical that the relatively small temperature differences among typical southern U.S. lakes and reservoirs are less important than piscivore population characteristics in determining gizzard shad consumption by piscivores.

Future Research Needs

This study used bioenergetics modeling to illustrate potential for prey resources to limit piscivore condition and abundance in southern U.S. lakes and reservoirs. These predicted outcomes need to be substantiated with subsequent field research. Specifically, condition and abundance of piscivore communities needs to be compared in systems with differing levels of gizzard shad consumption and correlated with predictions of this study's models. Such investigations would be labor intensive, but likely not overly expensive and are logically the next step in gaining a greater understanding of gizzard shad supply-predator demand in southern U.S. lakes and reservoirs. Additionally, further research on basic gizzard shad life history is needed to enable age-0 prey production and management strategies to be developed.

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APPENDECES

TABLE 1.—Literature sources used to derive bioenergetics input parameters.

Species	Input parameter	Number of Populations	Data sources
Largemouth bass	Growth	87	W_s Equation: Wege and Anderson 1978 (Mraz et al. 1961; Bryant and Houser 1971; Zweiacker 1972; Olmstead 1974; Carlander 1977; Nieman and Clady 1979; Zdinak et al. 1980; Miller 1984; Jacobs et al. 1986; Whitworth 1989; Willis et al. 1990; Neumann et al. 1994; Johnson and Davis 1997; Schramm et al. 1999; Weathers et al. 2000; Leitner and Bulak 2008)
	Mortality	45	(Carlander 1977; Forbes 1989; Raborn et al. 2003; Allen et al. 2008)
	Initial population size	11	(Jenkins 1957; Zweiacker 1972; Olmstead 1974; Woodrum 1978; Harris et al. 1979; Orth 1980; Zdinak et al. 1980; Bettoli et al. 1993; Kerley 1993; Neumann et al. 1994; Maceina et al. 1995)

	% Gizzard shad in diet	10	(Jester 1971; Aggus 1972; Storck 1986; Wanjala et al. 1986; Horton and Gilliland 1990; Pope et al. 2001; Sammons and Maceina 2006)
White bass	Growth	38	W_s Equation: Brown and Murphy 1991 (Yellayi and Kilambi 1976; Moen and Dewey 1980; Colvin 1993; Carlander 1997; Willis et al. 1997; Colvin 2002; Guy et al. 2002; Lovell and Maceina 2002)
	Mortality	23	(Yellayi and Kilambi 1976; Colvin 1993; Muoneke 1994; Colvin 2002; Lovell and Maceina 2002; Schultz and Robinson 2002; Willis et al. 2002)
	Initial population size	2	(Orth 1980; Kerley 1993)
	% Gizzard shad in diet	6	(Moser 1968; Jester 1971; Olmstead and Kilambi 1971; Germann and Bunch 1985; Hartman 1998; Olson et al. 2007)
Striped bass	Growth	22	W_s Equation: Brown and Murphy 1991 (Scruggs 1957; Ware 1971; Crandall 1978; Axon 1979; Van Den Avyle and Higginbotham 1979; Kilambi and Zdinak

			1981; Germann and Bunch 1983; Ebert et al. 1987; Carlander 1997; Schramm et al. 1999; Van Horn et al. 1999; Thompson 2006; Thompson et al. 2007)
	Mortality	5	(Moore et al. 1991; Hightower et al. 2001; Young and Isely 2004; Thompson et al. 2007)
	Initial population size	2	(Axon 1979; Moore et al. 1991)
	% Gizzard shad in diet	9	(Combs 1978; Ott and Malvestuto 1981; Borkowski and Snyder 1982; Germann 1982; Germann and Bunch 1985; Matthews et al. 1988; Slipke et al. 2000; Olson et al. 2007)
White crappie	Growth	64	W_s Equation: Neumann and Murphy 1991 (Marcy 1954; Jenkins 1957; Carlander 1977; Sewell 1979; Cichra 1983; Mosher 1984; Parrish et al. 1986; Angyal et al. 1987; Colvin 1991; Muoneke et al. 1992; Guy and Willis 1995; Boxrucker 1999; Schramm et al. 1999; Sammons et al. 2002; Doyle et al. 2003; Parks and Driscoll 2003;

			Pope et al. 2004; Miller et al. 2008)
	Mortality	8	(Angyal et al. 1987; Colvin 1991; Hammers and Miranda 1991; Boxrucker 1999)
	Initial population size	8	(Jenkins 1957; Olmstead 1974; Angyal et al. 1987; Miranda et al. 1990; Kerley 1993)
	% Gizzard shad in diet	3	(Bolton 1985; Muoneke et al. 1992) Additional ≥ age-2 diet data collected by the authors from Lake Carl Blackwell, Oklahoma (33.3% gizzard shad, n=19)
Flathead catfish	Growth	9	W_s Equation: Bister et al. 2000[a] (Carroll and Hall 1964; Edmundon 1974; Jenkins 1952; Layher and Boles 1979; McCoy 1953; Turner 1980)
	Mortality	4	(Summerfelt and Turner 1972; Winkelman 2002)

	Initial population size	4	(Kerley 1993; Orth 1980; Winkelman 2002) An additional Schnabel mark-recapture population size estimate was completed (2008) by the authors for Lake Carl Blackwell, Oklahoma; N=2,545 (2,116-3,129)
	% Gizzard shad in diet	8	(Jolley and Irwin 2003; Layher and Boles 1980; Turner and Summerfelt 1970)
Blue catfish	Growth	17	W_s Equation: Muoneke and Pope 1999 (Boxrucker and Kuklinski 2006; Graham 1999; Jenkins 1956; Mauck and Boxrucker 2004)
	Mortality	6	(Boxrucker and Kuklinski 2006; Graham 1999; Mauck and Boxrucker 2004)
	Initial population size	1	Schnabel mark-recapture population size estimate was completed (2009) by the authors for Arcadia Lake, Oklahoma; N=10,501 (9,234-12,171)

	% Gizzard shad in diet	4	(Edds et al. 2002; Grist 2002; Jolley and Irwin 2003) Additional ≥ age-3 diet data collected by the authors from Arcadia Lake, Oklahoma (96.1% gizzard shad, n=99)
Walleye	Growth	54	W_s Equation: Murphy et al. 1990 (Carlander 1997; Colby et al. 1979; Kempinger and Carline 1977; Marwitz and Hubert 1995; Moss et al. 1985; Quist et al. 2003; Rabern 1998)
	Mortality	25	(Carlander 1997; Colby et al. 1979; Kocovsky and Carline 2001; Quist et al. 2004)
	Initial population size	9	(Carlander 1997; Colby et al. 1979; Kempinger and Carline 1977; Kocovsky and Carline 2001)
	% Gizzard shad in diet	9	(Besler and Taylor 2002; Denlinger et al. 2006; Horton and Gilliland 1990; Humphreys et al. 1984; Jester 1971; Leeds 1988; Olson et al. 2007)

[a] Distribution of W_r not included in reference; a W_r of 93 was used for the 50th percentile and a W_r of 88 for the 25th percentile. A W_r of 93 was chosen for the 50th percentile because 93 was the mode of all species (W_r = 93-95). A W_r of 88 was chosen for the 25th percentile because 88 was the median of all species (W_r = 86-90).

TABLE 2.—Largemouth bass input parameters used in bioenergetics simulations. Low, medium, and high parameters corresponded with the 10th percentile, mean, and 90th percentile of published values. Initial population size estimates were paired with low, medium, and high annual mortality (A). Age-0 fish were not included in the model but are shown here to illustrate the interaction between total population size and mortality rates.

	Annual growth increment (g)						Gizzard shad consumed (percent by weight)			Initial population size (#/ha)								
	Low		Medium		High					Low			Medium			High		
Age	Start	End	Start	End	Start	End	Low	Medium	High	A 37.4%	A 59.1%	A 82.0%	A 37.4%	A 59.1%	A 82.0%	A 37.4%	A 59.1%	A 82.0%
0	-	-	-	-	-	-	-	-	-	2.44	3.82	5.30	70.02	109.61	152.11	170.81	267.36	371.04
1	38.9	47.6	57.4	164.2	76.5	340.4	2.6%	13.5%	63.9%	1.53	1.56	0.95	43.84	44.85	27.38	106.93	109.40	66.79
2	47.6	107.5	164.2	381.2	340.4	750.6	0.4%	33.7%	71.2%	0.96	0.64	0.17	27.44	18.35	4.93	66.94	44.77	12.02
3	107.5	227.1	381.2	628.6	750.6	1,188.8	2.3%	18.9%	69.9%	0.60	0.26	0.03	17.18	7.51	0.89	41.90	18.32	2.16
4	227.1	348.5	628.6	876.1	1,188.8	1,535.6	2.3%	28.4%	73.6%	0.37	0.11	0.01	10.75	3.07	0.16	26.23	7.50	0.39
5	348.5	490.8	876.1	1,203.6	1,535.6	1,918.9	2.4%	32.8%	73.6%	0.23	0.04	0.00	6.73	1.26	0.03	16.42	3.07	0.07
6	490.8	628.9	1,203.6	1,474.6	1,918.9	2,354.6	2.4%	32.8%	73.6%	0.15	0.02	0.00	4.21	0.51	0.01	10.28	1.26	0.01
7	628.9	715.2	1,474.6	1,595.4	2,354.6	2,417.9	2.4%	32.8%	73.6%	0.09	0.01	0.00	2.64	0.21	0.00	6.43	0.51	0.00
8	715.2	1,147.0	1,595.4	1,859.0	2,417.9	3,040.1	2.4%	32.8%	73.6%	0.06	0.00	0.00	1.65	0.09	0.00	4.03	0.21	0.00
9	1,147.0	1,578.9	1,859.0	2,122.6	3,040.1	3,662.3	2.4%	32.8%	73.6%	0.04	0.00	0.00	1.03	0.04	0.00	2.52	0.09	0.00
									∑(#/ha)	6.47	6.47	6.47	185.50	185.50	185.50	452.48	452.48	452.48

TABLE 3.—White bass input parameters used in bioenergetics simulations. Low, medium, and high parameters corresponded with the 10th percentile, mean, and 90th percentile of published values. Initial population size estimates were paired with low, medium, and high annual mortality (A). Age-0 fish were not included in the model but are shown here to illustrate the interaction between total population size and mortality rates.

	Annual growth increment (g)						Gizzard shad consumed (percent by weight)			Initial population size (#/ha)								
	Low		Medium		High					Low			Medium			High		
Age	Start	End	Start	End	Start	End	Low	Medium	High	A 38.2%	A 62.4%	A 79.4%	A 38.2%	A 62.4%	A 79.4%	A 38.2%	A 62.4%	A 79.4%
0	-	-	-	-	-	-	-	-	-	12.63	20.19	25.69	22.55	36.06	45.87	32.47	51.92	66.06
1	22.1	105.8	83.0	290.0	183.4	503.6	68.1%	76.1%	82.7%	7.80	7.60	5.29	13.94	13.56	9.45	20.07	19.53	13.61
2	105.8	227.6	290.0	491.2	503.6	833.6	65.5%	73.4%	81.5%	4.82	2.86	1.09	8.61	5.10	1.95	12.40	7.35	2.80
3	227.6	369.0	491.2	652.2	833.6	1,013.4	65.5%	73.4%	80.4%	2.98	1.07	0.22	5.32	1.92	0.40	7.66	2.76	0.58
4	369.0	450.0	652.2	722.7	1,013.4	1,067.6	65.5%	73.4%	80.8%	1.84	0.40	0.05	3.29	0.72	0.08	4.74	1.04	0.12
5	450.0	508.4	722.7	811.1	1,067.6	1,142.7	65.5%	75.4%	96.7%	1.14	0.15	0.01	2.03	0.27	0.02	2.93	0.39	0.02
6	508.4	579.0	811.1	918.4	1,142.7	1,369.5	65.5%	75.4%	96.7%	0.70	0.06	0.00	1.26	0.10	0.00	1.81	0.15	0.01
7	579.0	649.7	918.4	1,025.6	1,369.5	1,596.3	65.5%	75.4%	96.7%	0.43	0.02	0.00	0.78	0.04	0.00	1.12	0.06	0.00
									∑(#/ha)	32.36	32.36	32.36	57.78	57.78	57.78	83.20	83.20	83.20

TABLE 4.—Striped bass input parameters used in bioenergetics simulations. Low, medium, and high parameters corresponded with the 10th percentile, mean, and 90th percentile of published values. Initial population size estimates were paired with low, medium, and high annual mortality (A). Age-0 fish were not included in the model but are shown here to illustrate the interaction between total population size and mortality rates.

										Initial population size (#/ha)								
	Annual growth increment (g)									Low			Medium			High		
	Low		Medium		High		Gizzard shad consumed (percent by weight)											
Age	Start	End	Start	End	Start	End	Low	Medium	High	A 43.2%	A 54.7%	A 61.3%	A 43.2%	A 54.7%	A 61.3%	A 43.2%	A 54.7%	A 61.3%
0	-	-	-	-	-	-	-	-	-	2.41	3.03	3.38	9.22	11.58	12.94	16.04	20.13	22.50
1	53.8	335.7	195.8	872.8	375.2	1,244.3	44.5%	69.8%	93.7%	1.37	1.37	1.31	5.24	5.24	5.01	9.11	9.11	8.72
2	335.7	816.8	872.8	1,628.1	1,244.3	2,387.3	64.5%	70.2%	91.5%	0.78	0.62	0.51	2.97	2.37	1.94	5.17	4.12	3.38
3	816.8	1,629.3	1,628.1	2,358.6	2,387.3	3,648.4	64.5%	74.6%	91.5%	0.44	0.28	0.20	1.69	1.07	0.75	2.94	1.87	1.31
4	1,629.3	1,797.9	2,358.6	3,265.6	3,648.4	5,257.0	64.6%	77.4%	91.5%	0.25	0.13	0.08	0.96	0.49	0.29	1.67	0.85	0.51
5	1,797.9	2,493.2	3,265.6	4,257.1	5,257.0	6,783.3	64.6%	77.4%	91.5%	0.14	0.06	0.03	0.54	0.22	0.11	0.95	0.38	0.20
6	2,493.2	2,678.2	4,257.1	5,721.8	6,783.3	10,023.0	64.6%	77.4%	91.5%	0.08	0.03	0.01	0.31	0.10	0.04	0.54	0.17	0.08
7	2,678.2	2,863.3	5,721.8	7,186.5	10,023.0	13,262.8	64.6%	77.4%	91.5%	0.05	0.01	0.00	0.18	0.05	0.02	0.31	0.08	0.03
									∑(#/ha)	5.52	5.52	5.52	21.11	21.11	21.11	36.71	36.71	36.71

TABLE 5.—White crappie input parameters used in bioenergetics simulations. Low, medium, and high parameters corresponded with the 10th percentile, mean, and 90th percentile of published values. Initial population size estimates were paired with low, medium, and high annual mortality (A). Age-0 fish were not included in the model but are shown here to illustrate the interaction between total population size and mortality rates.

	Annual growth increment (g)						Gizzard shad consumed (percent by weight)			Initial population size (#/ha)								
	Low		Medium		High					Low			Medium			High		
Age	Start	End	Start	End	Start	End	Low	Medium	High	A 34.9%	A 69.%	A 89.1%	A 34.9%	A 69.%	A 89.1%	A 34.9%	A 69.%	A 89.1%
0	-	-	-	-	-	-	-	-	-	55.92	107.58	138.05	306.22	589.08	755.90	638.93	1,229.13	1,577.21
1	15.1	23.4	42.6	73.8	87.1	140.3	8.5%	17.0%	34.0%	36.39	32.89	15.05	199.24	180.08	82.39	415.72	375.73	171.92
2	23.4	44.8	73.8	159.8	140.3	296.6	33.3%	57.9%	72.9%	23.68	10.05	1.64	129.63	55.05	8.98	270.49	114.86	18.74
3	44.8	91.5	159.8	279.0	296.6	464.5	33.3%	57.9%	72.9%	15.40	3.07	0.18	84.35	16.83	0.98	175.99	35.11	2.04
4	91.5	145.1	279.0	360.8	464.5	637.3	33.3%	57.9%	72.9%	10.02	0.94	0.02	54.88	5.14	0.11	114.51	10.73	0.22
5	145.1	223.2	360.8	436.6	637.3	763.5	33.3%	57.9%	72.9%	6.52	0.29	0.00	35.71	1.57	0.01	74.51	3.28	0.02
6	223.2	300.7	436.6	547.4	763.5	864.6	33.3%	57.9%	72.9%	4.24	0.09	0.00	23.23	0.48	0.00	48.48	1.00	0.00
7	300.7	378.2	547.4	658.2	864.6	965.7	33.3%	57.9%	72.9%	2.76	0.03	0.00	15.12	0.15	0.00	31.54	0.31	0.00
									∑(#/ha)	154.94	154.94	154.94	848.38	848.38	848.38	1,770.15	1,770.15	1,770.15

TABLE 6.—Flathead catfish input parameters used in bioenergetics simulations. Low, medium, and high parameters corresponded with the 10th percentile, mean, and 90th percentile of published values. Initial population size estimates were paired with low, medium, and high annual mortality (A). Age-0 fish were not included in the model but are shown here to illustrate the interaction between total population size and mortality rates.

	Annual growth increment (g)						Gizzard shad consumed (percent by weight)			Initial population size (#/ha)								
	Low		Medium		High					Low			Medium			High		
Age	Start	End	Start	End	Start	End	Low	Medium	High	A 10.7%	A 26.3%	A 43.6%	A 10.7%	A 26.3%	A 43.6%	A 10.7%	A 26.3%	A 43.6%
0	-	-	-	-	-	-	-	-	-	0.05	0.09	0.15	0.25	0.49	0.81	0.45	0.90	1.47
1	17.6	53.0	60.2	205.7	122.7	480.6	0.0%	0.0%	0.0%	0.04	0.07	0.09	0.22	0.36	0.46	0.41	0.66	0.83
2	53.0	102.8	205.7	595.3	480.6	1,275.0	0.0%	0.0%	0.0%	0.04	0.05	0.05	0.20	0.27	0.26	0.36	0.49	0.47
3	102.8	284.5	595.3	1,355.7	1,275.0	2,584.1	0.0%	28.1%	56.1%	0.03	0.04	0.03	0.18	0.20	0.15	0.32	0.36	0.26
4	284.5	765.2	1,355.7	2,258.3	2,584.1	3,774.1	0.0%	28.8%	57.7%	0.03	0.03	0.02	0.16	0.15	0.08	0.29	0.27	0.15
5	765.2	1,371.3	2,258.3	3,600.7	3,774.1	6,686.2	50.3%	69.0%	95.3%	0.03	0.02	0.01	0.14	0.11	0.05	0.26	0.20	0.08
6	1,371.3	2,033.5	3,600.7	5,083.5	6,686.2	9,686.5	50.3%	69.0%	95.3%	0.02	0.01	0.00	0.13	0.08	0.03	0.23	0.14	0.05
7	2,033.5	2,647.4	5,083.5	6,419.7	9,686.5	11,722.0	50.3%	69.0%	95.3%	0.02	0.01	0.00	0.11	0.06	0.01	0.21	0.11	0.03
8	2,647.4	4,320.8	6,419.7	8,436.0	11,722.0	13,609.7	50.3%	69.0%	95.3%	0.02	0.01	0.00	0.10	0.04	0.01	0.18	0.08	0.02
9	4,320.8	4,787.1	8,436.0	9,771.7	13,609.7	15,601.1	50.3%	69.0%	95.3%	0.02	0.01	0.00	0.09	0.03	0.00	0.16	0.06	0.01
10	4,787.1	5,118.4	9,771.7	11,092.6	15,601.1	16,962.3	50.3%	69.0%	95.3%	0.02	0.00	0.00	0.08	0.02	0.00	0.15	0.04	0.00
11	5,118.4	6,394.0	11,092.6	12,225.4	16,962.3	17,664.4	50.3%	69.0%	95.3%	0.01	0.00	0.00	0.07	0.02	0.00	0.13	0.03	0.00
12	6,394.0	7,669.6	12,225.4	13,358.2	17,664.4	18,366.6	50.3%	69.0%	95.3%	0.01	0.00	0.00	0.06	0.01	0.00	0.12	0.02	0.00
13	7,669.6	8,945.3	13,358.2	14,491.0	18,366.6	19,068.7	50.3%	69.0%	95.3%	0.01	0.00	0.00	0.06	0.01	0.00	0.10	0.02	0.00
									∑(#/ha)	0.35	0.35	0.35	1.85	1.85	1.85	3.38	3.38	3.38

TABLE 7.—Blue catfish input parameters used in bioenergetics simulations. Low, medium, and high parameters corresponded with the 10th percentile, mean, and 90th percentile of published values. Initial population size estimates were paired with low, medium, and high annual mortality (A). Age-0 fish were not included in the model but are shown here to illustrate the interaction between total population size and mortality rates.

Age	Annual growth increment (g)						Gizzard shad consumed (percent by weight)			Initial population size (#/ha)								
	Low		Medium		High					Low			Medium			High		
	Start	End	Start	End	Start	End	Low	Medium	High	A 15.4%	A 31.3%	A 49.5%	A 15.4%	A 31.3%	A 49.5%	A 15.4%	A 31.3%	A 49.5%
0	-	-	-	-	-	-	-	-	-	1.77	3.35	5.29	2.36	4.47	7.06	2.95	5.59	8.82
1	27.2	36.9	34.3	88.0	46.8	154.5	2.5%	9.8%	19.5%	1.50	2.30	2.67	1.99	3.07	3.56	2.49	3.84	4.46
2	36.9	95.3	88.0	222.7	154.5	394.3	2.5%	8.5%	15.8%	1.27	1.58	1.35	1.69	2.11	1.80	2.11	2.64	2.25
3	95.3	185.9	222.7	439.4	394.3	772.2	7.2%	55.5%	96.0%	1.07	1.09	0.68	1.43	1.45	0.91	1.78	1.81	1.14
4	185.9	192.7	439.4	762.5	772.2	1,311.6	7.2%	56.9%	100.0%	0.91	0.75	0.34	1.21	1.00	0.46	1.51	1.25	0.57
5	192.7	381.7	762.5	1,365.7	1,311.6	2,598.1	22.0%	91.0%	97.9%	0.77	0.51	0.17	1.02	0.68	0.23	1.28	0.86	0.29
6	381.7	493.9	1,365.7	2,068.2	2,598.1	4,198.1	22.0%	91.0%	97.9%	0.65	0.35	0.09	0.86	0.47	0.12	1.08	0.59	0.15
7	493.9	511.3	2,068.2	2,386.3	4,198.1	6,206.9	22.0%	91.0%	97.9%	0.55	0.24	0.04	0.73	0.32	0.06	0.91	0.40	0.07
8	511.3	667.7	2,386.3	2,762.3	6,206.9	8,215.8	22.0%	91.0%	97.9%	0.46	0.17	0.02	0.62	0.22	0.03	0.77	0.28	0.04
9	667.7	824.1	2,762.3	3,138.2	8,215.8	10,224.6	22.0%	91.0%	97.9%	0.39	0.11	0.01	0.52	0.15	0.02	0.65	0.19	0.02
10	824.1	980.4	3,138.2	3,514.2	10,224.6	12,233.4	22.0%	91.0%	97.9%	0.33	0.08	0.01	0.44	0.10	0.01	0.55	0.13	0.01
11	980.4	1,136.8	3,514.2	3,890.1	12,233.4	14,242.2	22.0%	91.0%	97.9%	0.28	0.05	0.00	0.37	0.07	0.00	0.47	0.09	0.00
12	1,136.8	1,293.2	3,890.1	4,266.0	14,242.2	16,251.0	22.0%	91.0%	97.9%	0.24	0.04	0.00	0.32	0.05	0.00	0.40	0.06	0.00
13	1,293.2	1,449.6	4,266.0	4,642.0	16,251.0	18,259.8	22.0%	91.0%	97.9%	0.20	0.03	0.00	0.27	0.03	0.00	0.34	0.04	0.00
14	1,449.6	1,606.0	4,642.0	5,017.9	18,259.8	20,268.7	22.0%	91.0%	97.9%	0.17	0.02	0.00	0.23	0.02	0.00	0.28	0.03	0.00
15	1,606.0	1,762.4	5,017.9	5,393.9	20,268.7	22,277.5	22.0%	91.0%	97.9%	0.14	0.01	0.00	0.19	0.02	0.00	0.24	0.02	0.00
									∑(#/ha)	10.69	10.69	10.69	14.26	14.26	14.26	17.82	17.82	17.82

TABLE 8.—Walleye input parameters used in bioenergetics simulations. Low, medium, and high parameters corresponded with the 10th percentile, mean, and 90th percentile of published values. Initial population size estimates were paired with low, medium, and high annual mortality (A). Age-0 fish were not included in the model but are shown here to illustrate the interaction between total population size and mortality rates.

	Annual growth increment (g)						Gizzard shad consumed (percent by weight)			Initial population size (#/ha)								
	Low		Medium		High					Low			Medium			High		
Age	Start	End	Start	End	Start	End	Low	Medium	High	A 32.8%	A 50.9%	A 69.7%	A 32.8%	A 50.9%	A 69.7%	A 32.8%	A 50.9%	A 69.7%
0	-	-	-	-	-	-	-	-	-	8.47	12.98	17.77	44.52	68.20	93.41	93.48	143.20	196.13
1	32.5	98.1	99.3	314.6	182.0	601.8	29.6%	80.5%	94.3%	5.69	6.37	5.38	29.92	33.51	28.30	62.82	70.36	59.43
2	98.1	224.8	314.6	645.2	601.8	1,135.0	52.9%	80.5%	94.3%	3.82	3.13	1.63	20.10	16.46	8.58	42.21	34.57	18.01
3	224.8	403.5	645.2	1,014.1	1,135.0	1,800.5	57.7%	80.1%	94.3%	2.57	1.54	0.49	13.51	8.09	2.60	28.37	16.98	5.46
4	403.5	562.9	1,014.1	1,361.8	1,800.5	2,326.6	57.7%	80.1%	94.3%	1.73	0.76	0.15	9.08	3.97	0.79	19.06	8.34	1.65
5	562.9	715.0	1,361.8	1,691.1	2,326.6	2,927.9	57.7%	80.1%	94.3%	1.16	0.37	0.05	6.10	1.95	0.24	12.81	4.10	0.50
6	715.0	933.6	1,691.1	2,104.8	2,927.9	3,464.6	57.7%	80.1%	94.3%	0.78	0.18	0.01	4.10	0.96	0.07	8.61	2.01	0.15
7	933.6	1,040.7	2,104.8	2,288.4	3,464.6	4,026.6	57.7%	80.1%	94.3%	0.52	0.09	0.00	2.76	0.47	0.02	5.78	0.99	0.05
8	1,040.7	1,151.0	2,288.4	2,472.1	4,026.6	4,211.1	57.7%	80.1%	94.3%	0.35	0.04	0.00	1.85	0.23	0.01	3.89	0.49	0.01
9	1,151.0	1,256.7	2,472.1	2,655.7	4,211.1	4,293.7	57.7%	80.1%	94.3%	0.24	0.02	0.00	1.24	0.11	0.00	2.61	0.24	0.00
10	1,256.7	1,362.3	2,655.7	2,839.4	4,293.7	4,376.4	57.7%	80.1%	94.3%	0.16	0.01	0.00	0.84	0.06	0.00	1.76	0.12	0.00
									∑(#/ha)	25.50	25.50	25.50	134.02	134.02	134.02	281.39	281.39	281.39

TABLE 9.—Annual total prey (total) and gizzard shad (GZD) consumption estimates (kg/ha) from cool temperature regime bioenergetics simulations. Population parameters numerically coded in order as growth-mortality-initial population size-percent by weight gizzard shad; low (1), medium (2), and high (3) parameters corresponded with the, 10^{th} percentile, mean, and 90^{th} percentile of published values for each piscivore species.

Population parameters	Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total
1-3-1-1	0.02	0.08	1.79	2.67	2.82	4.85	0.65	1.48	0.00	0.20	0.13	1.56	0.27	2.10
1-3-1-2	0.03	0.08	2.05	2.73	3.30	4.56	1.16	1.44	0.04	0.23	0.58	1.44	0.46	2.04
1-3-1-3	0.04	0.07	2.14	2.61	4.03	4.37	1.32	1.40	0.13	0.19	0.80	1.36	0.76	1.94
1-3-2-1	0.09	0.41	3.19	4.76	10.78	18.55	3.39	7.75	0.13	5.88	0.17	2.08	1.30	11.22
1-3-2-2	0.16	0.41	3.66	4.88	12.61	17.43	6.09	7.58	1.18	6.67	0.77	1.92	2.37	10.87
1-3-2-3	0.23	0.40	3.83	4.66	15.41	16.72	6.94	7.36	3.69	5.59	1.07	1.81	3.98	10.31
1-3-3-1	0.16	0.75	4.59	6.85	18.74	32.26	7.12	16.28	0.31	14.34	0.21	2.61	2.67	23.33
1-3-3-2	0.29	0.74	5.27	7.03	21.93	30.31	12.79	15.91	2.88	16.26	0.97	2.39	4.90	22.61
1-3-3-3	0.42	0.72	5.52	6.71	26.79	29.07	14.58	15.46	8.99	13.63	1.33	2.26	8.27	21.45
1-2-1-1	0.08	0.23	5.57	8.38	4.09	6.89	2.36	4.71	0.02	0.82	0.51	3.74	1.34	8.00
1-2-1-2	0.12	0.23	6.47	8.68	4.75	6.51	3.71	4.63	0.19	0.87	2.11	3.38	2.35	7.72
1-2-1-3	0.17	0.22	6.82	8.26	5.75	6.25	4.24	4.50	0.52	0.76	2.57	3.26	3.48	7.38
1-2-2-1	0.44	1.23	9.94	14.97	15.66	26.37	12.40	24.74	0.45	23.44	0.68	4.99	7.36	43.83
1-2-2-2	0.66	1.21	11.55	15.51	18.18	24.92	19.53	24.32	5.53	24.89	2.81	4.51	12.89	42.29
1-2-2-3	0.93	1.18	12.18	14.76	22.01	23.92	22.30	23.65	14.96	21.78	3.43	4.34	19.05	40.42
1-2-3-1	0.80	2.25	14.32	21.55	27.23	45.85	26.03	51.95	1.11	57.18	0.86	6.24	15.34	91.37
1-2-3-2	1.21	2.20	16.63	22.33	31.61	43.33	41.00	51.07	13.50	60.72	3.51	5.63	26.86	88.18
1-2-3-3	1.70	2.15	17.54	21.25	38.27	41.58	46.82	49.65	36.48	53.13	4.29	5.43	39.71	84.26
1-1-1-1	0.24	0.54	16.79	25.47	7.26	11.87	6.41	11.83	0.05	2.22	1.49	8.14	18.48	160.18
1-1-1-2	0.33	0.52	19.75	26.58	8.35	11.29	9.36	11.67	0.60	2.27	5.72	7.26	12.07	26.18
1-1-1-3	0.45	0.51	21.35	25.13	9.97	10.85	10.71	11.36	1.45	2.04	6.49	7.13	15.72	25.35
1-1-2-1	1.26	2.86	29.98	45.49	27.77	45.42	33.67	62.19	1.31	63.66	1.99	10.85	39.31	149.59
1-1-2-2	1.77	2.81	35.39	47.63	31.96	43.22	49.21	61.35	17.18	65.05	7.63	9.68	66.08	143.34
1-1-2-3	2.43	2.73	38.13	44.87	38.14	41.52	56.28	59.69	41.65	58.66	8.65	9.51	86.06	138.79
1-1-3-1	2.29	5.22	43.33	65.73	48.29	78.98	70.70	130.58	3.20	155.28	2.48	13.57	82.02	312.13
1-1-3-2	3.23	5.11	50.78	68.34	55.57	75.14	103.32	128.81	41.91	158.67	9.54	12.11	137.89	299.09
1-1-3-3	4.43	4.99	54.91	64.61	66.31	72.19	118.18	125.32	101.60	143.08	10.81	11.89	179.56	289.59
2-3-1-1	0.03	0.19	4.25	6.32	5.32	9.45	1.67	3.93	0.01	0.44	0.37	3.94	0.38	3.01
2-3-1-2	0.06	0.19	4.86	6.47	6.32	8.79	3.09	3.84	0.09	0.49	1.67	3.60	0.66	2.91

Population parameters	Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total
2-3-1-3	0.09	0.18	5.08	6.18	7.79	8.43	3.52	3.73	0.27	0.42	2.23	3.41	1.08	2.76
2-3-2-1	0.17	1.02	7.59	11.29	20.36	36.15	8.79	20.67	0.26	12.56	0.50	5.25	1.90	16.18
2-3-2-2	0.32	1.00	8.68	11.55	24.18	33.64	16.23	20.19	2.59	14.14	2.22	4.80	3.46	15.64
2-3-2-3	0.49	0.98	9.07	11.03	29.79	32.26	18.48	19.60	7.89	11.91	2.97	4.55	5.77	14.81
2-3-3-1	0.30	1.87	10.93	16.26	35.40	62.85	18.46	43.40	0.63	30.63	0.62	6.56	3.93	33.70
2-3-3-2	0.59	1.83	12.50	16.63	42.05	58.49	34.07	42.38	6.32	34.50	2.78	6.00	7.18	32.57
2-3-3-3	0.90	1.80	13.06	15.89	51.79	56.09	38.81	41.16	19.23	29.06	3.71	5.69	12.01	30.84
2-2-1-1	0.14	0.47	11.78	17.68	7.50	12.98	5.63	11.52	0.03	1.76	1.65	10.87	2.16	12.12
2-2-1-2	0.23	0.46	13.62	18.25	8.82	12.16	9.09	11.32	0.42	1.86	6.67	9.77	3.72	11.66
2-2-1-3	0.32	0.45	14.32	17.38	10.76	11.67	10.37	11.00	1.12	1.63	7.98	9.47	5.40	11.14
2-2-2-1	0.76	2.53	21.04	31.56	28.70	49.67	29.58	60.57	0.94	50.45	2.20	14.50	11.64	66.06
2-2-2-2	1.21	2.47	24.33	32.59	33.73	46.54	47.78	59.49	11.99	53.47	8.89	13.03	20.21	63.58
2-2-2-3	1.73	2.42	25.58	31.04	41.16	44.65	54.52	57.82	32.18	46.86	10.64	12.62	29.39	60.71
2-2-3-1	1.39	4.61	30.30	45.45	49.90	86.36	62.11	127.17	2.28	123.05	2.75	18.12	24.24	137.78
2-2-3-2	2.20	4.51	35.03	46.92	58.65	80.92	100.32	124.91	29.36	130.42	11.11	16.29	42.13	132.60
2-2-3-3	3.15	4.40	36.83	44.69	71.57	77.62	114.48	121.40	78.49	114.30	13.30	15.78	61.27	126.60
2-1-1-1	0.38	0.94	30.65	46.39	12.84	21.43	14.17	26.62	0.09	4.40	4.89	25.64	11.00	41.27
2-1-1-2	0.55	0.93	35.91	48.28	14.91	20.26	21.06	26.25	1.17	4.50	18.67	22.84	18.43	39.51
2-1-1-3	0.76	0.90	38.58	45.72	17.90	19.46	24.08	25.53	2.87	4.05	20.99	22.50	23.91	38.24
2-1-2-1	2.04	5.05	54.74	82.83	49.14	82.00	74.50	139.95	2.50	126.31	6.53	34.19	60.05	225.71
2-1-2-2	2.95	4.95	64.13	86.21	57.03	77.53	110.70	137.98	33.69	129.22	24.89	30.46	100.77	216.03
2-1-2-3	4.08	4.83	68.90	81.63	68.48	74.45	126.56	134.21	82.30	116.33	27.99	30.00	130.74	209.08
2-1-3-1	3.73	9.21	78.82	119.27	85.44	142.58	156.43	293.84	6.09	308.12	8.16	42.74	125.26	470.89
2-1-3-2	5.37	9.03	92.34	124.15	99.16	134.79	232.42	289.70	82.18	315.20	31.11	38.07	210.22	450.69
2-1-3-3	7.44	8.80	99.21	117.55	119.06	129.45	265.72	281.79	200.75	283.75	34.99	37.50	272.75	436.19
3-3-1-1	0.05	0.32	7.11	10.56	7.62	13.54	2.87	6.83	0.01	0.71	0.64	6.58	0.52	3.77
3-3-1-2	0.09	0.31	8.12	10.79	9.06	12.60	5.35	6.66	0.15	0.80	2.83	6.01	0.90	3.64
3-3-1-3	0.14	0.31	8.48	10.31	11.16	12.09	6.10	6.47	0.45	0.68	3.75	5.71	1.43	3.45
3-3-2-1	0.26	1.70	12.69	18.87	29.15	51.79	15.07	35.90	0.42	20.43	0.86	8.77	2.65	20.35

Population parameters	Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total
3-3-2-2	0.50	1.67	14.50	19.27	34.67	48.20	28.13	34.99	4.22	23.00	3.78	8.01	4.77	19.65
3-3-2-3	0.77	1.64	15.15	18.41	42.71	46.25	32.06	34.00	12.83	19.38	5.00	7.62	7.61	18.53
3-3-3-1	0.47	3.10	18.28	27.17	50.68	90.05	31.65	75.38	1.02	49.82	1.07	10.97	5.46	42.32
3-3-3-2	0.92	3.05	20.87	27.75	60.28	83.80	59.07	73.47	10.31	56.11	4.72	10.02	9.87	40.86
3-3-3-3	1.40	2.99	21.81	26.52	74.26	80.41	67.32	71.38	31.30	47.27	6.26	9.52	15.87	38.67
3-2-1-1	0.21	0.73	18.89	28.30	10.79	18.67	9.37	19.41	0.05	2.82	2.73	17.90	3.25	16.33
3-2-1-2	0.33	0.71	21.80	29.17	12.69	17.49	15.28	19.03	0.67	2.99	11.00	16.09	5.57	15.70
3-2-1-3	0.48	0.70	22.90	27.80	15.48	16.79	17.45	18.50	1.80	2.62	13.14	15.60	7.81	15.02
3-2-2-1	1.12	3.89	33.73	50.53	41.27	71.43	49.25	102.00	1.49	80.85	3.64	23.87	17.65	89.15
3-2-2-2	1.78	3.81	38.93	52.09	48.57	66.93	80.34	100.03	19.20	85.87	14.67	21.46	30.35	85.70
3-2-2-3	2.55	3.72	40.90	49.65	59.23	64.25	91.71	97.25	51.51	75.15	17.52	20.80	42.57	81.98
3-2-3-1	2.05	7.09	48.57	72.77	71.76	124.19	103.41	214.17	3.63	197.21	4.55	29.83	36.79	185.94
3-2-3-2	3.25	6.95	56.05	75.01	84.44	116.37	168.68	210.02	46.83	209.45	18.33	26.82	63.29	178.74
3-2-3-3	4.65	6.79	58.89	71.49	102.98	111.70	192.56	204.20	125.65	183.32	21.90	26.00	88.78	170.98
3-1-1-1	0.52	1.34	46.49	70.28	18.70	31.17	22.99	43.51	0.13	6.75	7.76	40.82	18.18	64.04
3-1-1-2	0.76	1.31	54.38	73.07	21.72	29.48	34.38	42.85	1.78	6.92	29.64	36.37	30.44	61.37
3-1-1-3	1.05	1.28	58.29	69.26	26.05	28.33	39.31	41.69	4.39	6.22	33.37	35.83	38.90	59.56
3-1-2-1	2.80	7.16	83.03	125.50	71.57	119.27	120.84	228.70	3.77	193.74	10.35	54.43	99.37	350.37
3-1-2-2	4.07	7.02	97.10	130.48	83.12	112.80	180.72	225.24	51.10	198.67	39.53	48.50	166.50	335.73
3-1-2-3	5.64	6.84	104.09	123.67	99.68	108.39	206.63	219.12	125.89	178.46	44.50	47.78	212.81	325.84
3-1-3-1	5.11	13.06	119.56	180.72	124.44	207.38	253.73	480.18	9.21	472.57	12.94	68.03	207.30	730.98
3-1-3-2	7.41	12.79	139.82	187.90	144.53	196.12	379.45	472.93	124.65	484.60	49.41	60.63	347.36	700.44
3-1-3-3	10.29	12.48	149.89	178.08	173.32	188.46	433.84	460.06	307.09	435.32	55.62	59.72	443.99	679.80

TABLE 10.— Annual total prey (total) and gizzard shad (GZD) consumption estimates (kg/ha) from warm temperature regime bioenergetics simulations. Population parameters are numerically coded in order as growth-mortality-initial population size-percent by weight gizzard shad; low (1), medium (2), and high (3) parameters corresponded with the 10^{th} percentile, mean, and 90^{th} percentile of published values for each piscivore species.

Population parameters	Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total
1-3-1-1	0.02	0.08	1.96	2.93	3.07	5.30	0.74	1.69	0.00	0.20	0.13	1.59	0.23	2.08
1-3-1-2	0.03	0.08	2.19	2.93	3.60	4.98	1.33	1.65	0.04	0.20	0.60	1.46	0.43	2.01
1-3-1-3	0.04	0.07	2.32	2.82	4.40	4.77	1.51	1.60	0.13	0.19	0.82	1.38	0.73	1.91
1-3-2-1	0.09	0.41	3.50	5.23	11.76	20.27	3.87	8.88	0.13	5.88	0.18	2.13	1.28	11.36
1-3-2-2	0.16	0.41	3.92	5.22	13.77	19.04	6.98	8.68	1.04	5.76	0.79	1.95	2.37	11.02
1-3-2-3	0.23	0.40	4.14	5.03	16.83	18.26	7.95	8.43	3.60	5.45	1.09	1.85	4.02	10.45
1-3-3-1	0.16	0.75	4.59	6.83	20.44	35.25	8.12	18.64	0.31	14.34	0.22	2.66	2.68	23.71
1-3-3-2	0.29	0.74	5.05	7.53	23.94	33.10	14.65	18.22	2.54	14.05	0.99	2.44	4.95	23.00
1-3-3-3	0.42	0.72	5.12	6.81	29.26	31.75	16.69	17.69	8.77	13.29	1.36	2.31	8.39	21.81
1-2-1-1	0.08	0.23	5.40	6.56	4.48	7.55	2.68	5.36	0.02	0.82	0.56	3.98	1.40	8.36
1-2-1-2	0.12	0.23	5.64	7.52	5.20	7.14	4.23	5.27	0.18	0.80	2.27	3.59	2.46	8.08
1-2-1-3	0.17	0.22	5.96	7.25	6.30	6.85	4.83	5.12	0.53	0.76	2.76	3.46	3.64	7.72
1-2-2-1	0.44	1.23	6.22	9.36	17.14	28.91	14.08	28.19	0.46	23.40	0.74	5.30	7.68	45.80
1-2-2-2	0.66	1.21	7.03	9.44	19.91	27.30	22.25	27.71	5.20	22.92	3.03	4.78	13.47	44.23
1-2-2-3	0.93	1.18	7.48	9.07	24.11	26.20	25.40	26.93	15.08	21.94	3.68	4.62	19.91	42.25
1-2-3-1	0.80	2.25	7.61	11.31	29.80	50.26	29.56	59.19	1.12	57.08	0.93	6.63	16.03	95.55
1-2-3-2	1.21	2.20	8.20	12.20	34.62	47.47	46.71	58.18	12.67	55.91	3.79	5.98	28.11	92.29
1-2-3-3	1.70	2.15	8.48	11.27	41.93	45.55	53.33	56.55	36.78	53.53	4.60	5.77	41.55	88.16
1-1-1-1	0.24	0.54	8.94	10.87	7.98	13.06	7.24	13.40	0.05	2.23	1.69	9.11	7.72	29.37
1-1-1-2	0.33	0.52	9.14	12.16	9.19	12.43	10.60	13.22	0.59	2.19	6.48	8.13	12.99	28.15
1-1-1-3	0.45	0.51	9.64	11.72	10.97	11.94	12.13	12.86	1.49	2.09	7.32	7.99	16.91	27.26
1-1-2-1	1.26	2.86	11.11	16.72	30.53	49.99	38.07	70.43	1.32	64.00	2.26	12.15	42.30	160.79
1-1-2-2	1.77	2.81	11.82	17.57	35.16	47.55	55.73	69.48	16.80	62.84	8.65	10.84	71.13	154.16
1-1-2-3	2.43	2.73	12.55	16.85	41.96	45.68	63.74	67.59	42.63	60.02	9.76	10.66	92.60	149.24
1-1-3-1	2.29	5.22	12.99	19.48	53.08	86.92	79.94	147.89	3.23	156.12	2.82	15.19	88.25	335.50
1-1-3-2	3.23	5.11	13.16	17.51	61.12	82.68	117.02	145.88	40.98	153.29	10.81	13.56	148.42	321.67
1-1-3-3	4.43	4.99	13.36	16.19	72.95	79.42	133.83	141.91	103.98	146.42	12.20	13.33	193.21	311.40
2-3-1-1	0.03	0.19	13.60	20.20	5.75	10.22	1.88	4.42	0.01	0.43	0.38	3.97	0.35	2.99
2-3-1-2	0.06	0.19	13.88	16.87	6.84	9.51	3.47	4.31	0.08	0.42	1.68	3.63	0.63	2.89

Population parameters	Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total
2-3-1-3	0.09	0.18	14.60	19.56	8.43	9.12	3.95	4.19	0.27	0.40	2.25	3.44	1.06	2.73
2-3-2-1	0.17	1.02	15.14	20.12	22.02	39.12	9.86	23.24	0.26	12.38	0.50	5.29	1.89	16.35
2-3-2-2	0.32	1.00	15.50	18.81	26.16	36.40	18.22	22.67	2.27	12.12	2.24	4.83	3.47	15.80
2-3-2-3	0.49	0.98	15.96	19.41	32.24	34.91	20.77	22.02	7.62	11.49	3.00	4.59	5.82	14.96
2-3-3-1	0.30	1.87	16.00	24.07	38.28	68.02	20.70	48.79	0.63	30.19	0.63	6.61	3.95	34.11
2-3-3-2	0.59	1.83	18.07	24.26	45.48	63.28	38.26	47.59	5.54	29.55	2.80	6.04	7.24	32.96
2-3-3-3	0.90	1.80	18.93	28.72	56.06	60.70	43.60	46.24	18.58	28.04	3.75	5.74	12.14	31.21
2-2-1-1	0.14	0.47	19.24	23.32	8.14	14.10	6.30	12.94	0.03	1.75	1.68	11.06	2.23	12.61
2-2-1-2	0.23	0.46	19.58	29.09	9.57	13.21	10.20	12.70	0.39	1.71	6.78	9.94	3.87	12.13
2-2-1-3	0.32	0.45	20.64	30.92	11.69	12.68	11.64	12.34	1.13	1.64	8.12	9.63	5.62	11.58
2-2-2-1	0.76	2.53	21.62	29.09	31.15	53.96	33.14	68.00	0.94	50.10	2.24	14.75	12.19	69.02
2-2-2-2	1.21	2.47	21.80	28.98	36.63	50.55	53.59	66.73	11.27	49.04	9.04	13.25	21.19	66.42
2-2-2-3	1.73	2.42	22.99	27.94	44.72	48.51	61.19	64.89	32.35	47.07	10.82	12.84	30.77	63.42
2-2-3-1	1.39	4.61	23.19	34.78	54.16	93.82	69.58	142.77	2.29	122.21	2.80	18.43	25.43	144.02
2-2-3-2	2.20	4.51	23.20	31.04	63.69	87.89	112.53	140.11	27.50	119.62	11.30	16.57	44.21	138.58
2-2-3-3	3.15	4.40	23.69	27.88	77.76	84.33	128.48	136.24	78.90	114.80	13.53	16.05	64.21	132.32
2-1-1-1	0.38	0.94	24.60	29.86	14.01	23.40	15.85	29.81	0.09	4.42	4.94	25.93	12.59	46.64
2-1-1-2	0.55	0.93	26.08	34.93	16.27	22.12	23.57	29.37	1.15	4.34	18.85	23.10	21.12	44.64
2-1-1-3	0.76	0.90	27.68	33.58	19.54	21.25	26.95	28.58	2.94	4.15	21.21	22.75	27.30	43.23
2-1-2-1	2.04	5.05	33.40	50.09	53.61	89.52	83.31	156.67	2.52	126.80	6.58	34.58	68.94	255.38
2-1-2-2	2.95	4.95	33.81	51.29	62.25	84.64	123.87	154.40	32.87	124.40	25.14	30.81	115.64	244.43
2-1-2-3	4.08	4.83	34.23	51.79	74.78	81.30	141.67	150.23	84.32	119.15	28.28	30.33	149.50	236.71
2-1-3-1	3.73	9.21	36.85	55.22	93.21	155.65	174.91	328.95	6.15	309.31	8.23	43.22	143.84	532.85
2-1-3-2	5.37	9.03	37.55	50.29	108.24	147.15	260.09	324.18	80.18	303.44	31.42	38.51	241.29	510.01
2-1-3-3	7.44	8.80	38.60	51.95	130.01	141.35	297.45	315.43	205.69	290.63	35.35	37.91	311.93	493.90
3-3-1-1	0.05	0.32	38.92	52.32	8.20	14.58	3.18	7.60	0.01	0.70	0.74	7.01	0.49	3.76
3-3-1-2	0.09	0.31	39.86	48.36	9.76	13.57	5.96	7.41	0.13	0.68	3.18	6.40	0.88	3.63
3-3-1-3	0.14	0.31	41.42	55.43	12.02	13.01	6.79	7.20	0.43	0.65	4.13	6.10	1.42	3.44
3-3-2-1	0.26	1.70	42.31	49.78	31.38	55.80	16.74	39.96	0.41	20.00	0.98	9.35	2.68	20.59

Population parameters	Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total	GZD	Total
3-3-2-2	0.50	1.67	42.35	50.17	37.34	51.91	31.33	38.96	3.69	19.58	4.24	8.53	4.83	19.88
3-3-2-3	0.77	1.64	43.92	53.32	45.99	49.79	35.67	37.83	12.32	18.58	5.51	8.13	7.75	18.81
3-3-3-1	0.47	3.10	48.69	73.85	54.55	97.01	35.15	83.89	1.01	48.79	1.23	11.69	5.58	42.97
3-3-3-2	0.92	3.05	51.54	77.91	64.92	90.26	65.77	81.81	9.00	47.76	5.30	10.67	10.08	41.48
3-3-3-3	1.40	2.99	53.07	79.51	79.95	86.57	74.90	79.43	30.05	45.32	6.88	10.17	16.17	39.25
3-2-1-1	0.21	0.73	55.59	74.81	11.66	20.19	10.41	21.60	0.05	2.79	3.85	23.07	3.35	17.02
3-2-1-2	0.33	0.71	58.59	78.73	13.72	18.91	17.02	21.19	0.62	2.73	15.12	20.68	5.77	16.36
3-2-1-3	0.48	0.70	59.65	79.82	16.73	18.15	19.42	20.60	1.80	2.62	17.59	20.17	8.10	15.65
3-2-2-1	1.12	3.89	60.93	71.68	44.60	77.24	54.74	113.54	1.49	80.10	5.13	30.77	18.34	93.18
3-2-2-2	1.78	3.81	61.12	92.48	52.50	72.36	89.48	111.41	17.93	78.39	20.16	27.58	31.58	89.57
3-2-2-3	2.55	3.72	63.25	76.78	64.02	69.44	102.09	108.27	51.65	75.27	23.45	26.89	44.36	85.67
3-2-3-1	2.05	7.09	63.57	75.50	77.54	134.29	114.93	238.40	3.63	195.39	6.42	38.46	38.26	194.41
3-2-3-2	3.25	6.95	69.50	93.43	91.28	125.82	187.87	233.92	43.73	191.20	25.20	34.48	65.89	186.89
3-2-3-3	4.65	6.79	75.63	89.58	111.31	120.73	214.36	227.32	125.99	183.60	29.31	33.62	92.56	178.75
3-1-1-1	0.52	1.34	88.01	133.16	20.31	33.87	25.54	48.38	0.13	6.77	13.00	64.73	19.55	69.15
3-1-1-2	0.76	1.31	92.04	139.12	23.60	32.03	38.24	47.66	1.73	6.64	48.86	57.58	32.75	66.23
3-1-1-3	1.05	1.28	100.09	134.54	28.30	30.77	43.72	46.36	4.49	6.37	53.99	56.93	41.89	64.26
3-1-2-1	2.80	7.16	104.62	140.59	77.72	129.61	134.26	254.29	3.80	194.23	17.33	86.31	107.06	378.63
3-1-2-2	4.07	7.02	108.91	129.00	90.30	122.56	201.02	250.55	49.73	190.48	65.15	76.78	179.34	362.63
3-1-2-3	5.64	6.84	113.52	134.82	108.28	117.74	229.80	243.69	128.90	182.63	72.00	75.92	229.35	351.86
3-1-3-1	5.11	13.06	132.53	200.33	135.13	225.35	281.89	533.91	9.28	473.78	21.66	107.88	223.39	790.01
3-1-3-2	7.41	12.79	150.66	202.45	157.01	213.10	422.08	526.05	121.30	464.62	81.43	95.98	374.20	756.64
3-1-3-3	10.29	12.48	163.46	194.14	188.27	204.70	482.50	511.67	314.42	445.49	90.00	94.90	478.55	734.17

TABLE 11.—Gizzard shad (GZD) abundance (#/ha) needed on simulation day 1 (15 June) from cool temperature regime bioenergetics simulations to meet sustainable predator consumption (accounting for non-predation gizzard shad annual mortality rate of 0.7 and the biomass required to sustain population through reproduction with a 233 offspring/individual annual reproductive rate). Population parameters are numerically coded in order as growth-mortality-initial population size-percent by weight gizzard shad; low (1), medium (2), and high (3) parameters corresponded with the 10^{th} percentile, mean, and 90^{th} percentile of published values for each piscivore species. Values are sorted from lowest to highest consumption for each piscivore.

Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD
1-3-1-1	4.0	1-3-1-1	664.6	1-3-1-1	877.1	1-3-1-1	96.0	1-3-1-1	2.1	1-3-1-1	48.0	1-3-1-1	132.6
1-3-1-2	6.9	1-3-1-2	764.6	1-3-1-2	1,016.2	1-3-1-2	170.6	2-3-1-1	3.8	1-3-2-1	64.0	2-3-1-1	187.2
2-3-1-1	7.6	1-3-1-3	800.4	1-3-1-3	1,234.1	1-3-1-3	194.4	1-2-1-1	6.4	1-3-3-1	80.0	3-3-1-1	266.6
1-3-1-3	10.1	1-3-2-1	1,186.9	1-2-1-1	1,241.4	2-3-1-1	246.7	3-3-1-1	5.7	2-3-1-1	139.6	1-3-1-2	232.8
3-3-1-1	11.8	1-3-2-2	1,365.3	1-2-1-2	1,429.4	1-2-1-1	316.2	2-2-1-1	12.1	1-2-1-1	183.9	2-3-1-2	331.5
2-3-1-2	14.4	1-3-2-3	1,429.2	2-3-1-1	1,693.2	3-3-1-1	420.0	1-1-1-1	16.5	2-3-2-1	186.1	3-3-1-2	470.5
1-2-1-1	18.7	2-3-1-1	1,626.0	1-2-1-3	1,720.1	2-3-1-2	448.2	1-3-1-2	19.5	1-3-1-2	218.4	1-3-1-3	385.0
1-3-2-1	21.5	1-3-3-1	1,709.1	2-3-1-2	1,989.7	1-2-1-2	493.1	3-2-1-1	18.4	2-3-3-1	232.6	2-3-1-3	544.6
2-3-1-3	21.9	1-2-1-1	1,816.1	1-1-1-1	2,121.2	1-3-2-1	504.8	2-1-1-1	30.7	3-3-1-1	235.5	3-3-1-3	747.4
3-3-1-2	22.6	2-3-1-2	1,862.9	2-2-1-1	2,313.8	2-3-1-3	510.6	2-3-1-2	39.1	1-2-2-1	245.3	1-2-1-1	552.5
1-2-1-2	27.6	2-3-1-3	1,947.7	1-1-1-2	2,428.7	1-2-1-3	563.3	3-1-1-1	45.5	1-3-2-2	291.2	1-3-2-1	660.4
2-2-1-1	32.9	1-3-3-2	1,966.0	2-3-1-3	2,439.8	2-2-1-1	751.7	3-3-1-2	61.1	1-3-1-3	300.3	2-3-2-1	959.8
3-3-1-3	34.3	1-3-3-3	2,058.1	3-3-1-1	2,447.8	1-1-1-1	813.6	1-3-1-3	61.8	1-2-3-1	306.6	2-2-1-1	895.0
1-3-2-2	36.7	1-2-1-2	2,114.9	2-2-1-2	2,694.5	3-3-1-2	770.0	1-3-2-1	61.5	3-3-2-1	314.1	3-3-2-1	1,394.6
1-2-1-3	38.6	1-2-1-3	2,234.5	1-1-1-3	2,881.9	3-3-1-3	877.6	1-2-1-2	75.3	1-3-3-2	364.0	1-2-1-2	969.8
1-3-3-1	39.2	3-3-1-1	2,783.0	3-3-1-2	2,892.2	1-3-2-2	896.5	2-3-1-3	118.3	3-3-3-1	392.6	3-2-1-1	1,331.4
2-3-2-1	40.6	2-3-2-1	2,903.5	2-2-1-3	3,272.5	1-3-2-3	1,022.0	2-3-2-1	110.3	1-3-2-3	400.4	1-3-2-2	1,209.0
3-2-1-1	48.1	1-2-2-1	3,243.0	3-2-1-1	3,344.3	1-3-3-1	1,059.9	1-3-3-1	150.0	1-3-3-3	500.5	1-3-3-1	1,362.0
1-1-1-1	51.0	3-3-1-2	3,182.3	1-3-2-1	3,356.3	1-1-1-2	1,181.9	3-3-1-3	181.9	1-1-1-1	515.0	2-3-2-2	1,749.5
2-2-1-2	51.3	2-3-2-2	3,326.5	3-3-1-3	3,550.9	2-2-1-2	1,198.3	1-2-2-1	182.9	2-2-1-1	588.2	1-2-1-3	1,437.1
1-3-2-3	53.9	3-3-1-3	3,326.1	2-1-1-1	3,784.2	3-2-1-1	1,246.7	3-3-2-1	164.9	2-3-1-2	619.2	2-2-1-2	1,546.3
3-3-2-1	63.3	2-3-2-3	3,478.0	1-3-2-2	3,888.4	1-1-1-3	1,352.0	1-2-1-3	205.6	1-1-2-1	686.8	2-3-3-1	1,986.8
1-3-3-2	66.9	1-2-2-2	3,776.7	3-2-1-2	3,912.1	2-2-1-3	1,358.6	1-1-1-2	213.0	1-2-1-2	753.2	3-3-2-2	2,510.5
1-1-1-2	71.3	2-2-1-1	3,922.8	2-1-1-2	4,363.3	2-3-2-1	1,296.9	3-2-1-2	246.0	2-2-2-1	784.4	3-2-1-2	2,287.1
2-2-1-3	73.0	1-2-2-3	3,990.1	1-3-2-3	4,722.5	1-2-2-1	1,662.0	2-2-1-2	293.2	2-3-1-3	821.7	1-3-2-3	2,042.5
2-3-3-1	74.1	2-3-3-1	4,181.0	1-2-2-1	4,750.4	2-1-1-1	1,795.7	2-3-3-1	268.9	2-3-2-2	825.7	3-3-3-1	2,879.4
3-2-1-2	75.6	2-2-1-2	4,546.7	3-2-1-3	4,754.9	1-3-3-2	1,882.4	2-2-2-1	348.8	1-1-3-1	858.5	2-2-1-3	2,235.1
2-3-2-2	77.2	1-2-3-1	4,669.9	2-1-1-3	5,216.3	3-2-1-2	2,004.5	2-2-1-3	417.3	1-2-1-3	917.1	1-3-3-2	2,506.8
2-1-1-1	84.1	2-2-1-3	4,786.5	1-2-2-2	5,469.5	1-3-3-3	2,145.9	2-1-1-2	413.5	3-2-1-1	944.0	2-3-2-3	2,916.6

Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD
1-1-1-3	97.5	2-3-3-2	4,790.2	3-1-1-1	5,501.6	3-2-1-3	2,288.5	1-2-3-1	446.1	2-2-3-1	980.5	3-2-1-3	3,221.8
1-3-3-3	98.3	1-1-1-1	5,001.6	1-3-3-1	5,835.5	3-3-2-1	2,207.5	1-1-2-1	472.9	1-2-2-2	1,004.3	3-3-2-3	4,012.6
1-2-2-1	100.0	3-3-2-1	4,969.6	3-1-1-2	6,363.0	2-3-2-2	2,356.1	3-3-3-1	402.2	2-3-3-2	1,032.1	2-3-3-2	3,634.5
3-2-1-3	108.0	2-3-3-3	5,008.4	2-3-2-1	6,479.2	2-1-1-2	2,646.7	1-1-1-3	516.9	3-3-1-2	1,037.7	1-2-2-1	3,025.3
3-1-1-1	115.3	1-2-3-2	5,438.4	1-2-2-3	6,582.1	1-2-2-2	2,592.1	1-3-2-2	559.9	2-3-2-3	1,095.6	3-3-3-2	5,207.8
3-3-3-1	115.5	1-2-3-3	5,745.8	1-3-3-2	6,760.6	2-3-2-3	2,684.2	3-1-1-2	622.9	1-2-2-3	1,222.9	1-3-3-3	4,245.8
2-3-2-3	117.1	1-1-1-2	5,895.5	3-1-1-3	7,606.6	2-3-3-1	2,723.0	3-2-1-3	648.5	3-2-2-1	1,258.8	2-1-1-1	3,666.3
2-1-1-2	120.4	3-3-2-2	5,682.6	2-3-2-2	7,613.6	3-1-1-1	2,904.8	3-2-2-1	527.5	1-2-3-2	1,255.4	1-1-1-2	4,212.5
3-3-2-2	120.8	3-3-2-3	5,939.3	1-1-2-1	8,116.9	1-2-2-3	2,960.7	2-2-3-1	850.3	3-3-1-3	1,367.9	2-2-2-1	4,835.2
2-3-3-2	140.8	1-1-1-3	6,397.1	1-3-3-3	8,210.9	2-1-1-3	3,026.5	2-1-2-1	881.5	2-3-3-3	1,369.5	2-3-3-3	6,069.6
1-2-2-2	147.7	3-2-1-1	6,388.1	1-2-3-1	8,259.3	1-2-3-1	3,489.7	2-1-1-3	1,003.3	3-3-2-2	1,383.7	3-1-1-1	5,035.1
2-1-1-3	166.3	2-2-2-1	7,005.0	2-2-2-1	8,853.8	2-2-2-1	3,951.3	2-3-2-2	1,121.4	1-2-3-3	1,528.6	3-3-3-3	8,372.3
3-1-1-2	166.5	3-3-3-1	7,156.2	1-1-2-2	9,293.3	1-1-2-1	4,276.7	1-1-3-1	1,153.6	3-2-3-1	1,573.5	1-2-2-2	5,310.0
2-2-2-1	176.1	3-2-1-2	7,386.6	2-3-2-3	9,335.9	3-3-2-2	4,047.7	1-3-3-2	1,365.8	2-1-1-1	1,679.6	3-2-2-1	7,224.9
1-2-3-1	182.2	3-2-1-3	7,766.9	3-3-2-1	9,366.4	3-1-1-2	4,305.8	3-1-1-3	1,515.2	3-3-3-2	1,729.6	1-1-1-3	5,484.7
3-3-2-3	183.3	3-3-3-2	8,182.9	1-2-3-2	9,509.6	3-3-2-3	4,612.9	3-1-2-1	1,305.1	3-3-2-3	1,824.1	1-1-1-1	5,994.5
1-2-2-3	206.5	2-2-2-3	8,547.3	2-2-2-2	10,310.5	3-1-1-3	4,923.5	3-3-2-2	1,753.5	1-1-1-2	1,974.0	1-2-3-1	6,308.6
2-3-3-3	213.5	3-3-3-3	8,552.6	1-1-2-3	11,027.9	3-3-3-1	4,635.0	1-3-2-3	1,774.2	1-1-1-3	2,234.1	2-1-1-2	6,152.0
3-3-3-2	220.2	2-1-1-1	9,219.2	3-3-2-2	11,067.1	2-3-3-2	4,947.0	3-2-3-1	1,286.7	2-1-2-1	2,239.7	1-2-2-3	7,865.6
3-1-1-3	230.5	2-2-3-1	10,087.2	2-3-3-1	11,265.2	1-2-3-2	5,442.4	1-2-2-2	2,161.0	3-3-3-3	2,280.1	2-2-2-2	8,401.5
3-2-2-1	257.3	1-1-2-2	10,527.5	1-2-3-3	11,444.1	2-3-3-3	5,635.8	2-1-3-1	2,150.1	2-2-1-2	2,363.7	3-1-1-2	8,440.0
1-2-3-2	269.4	2-1-1-2	10,823.8	2-2-2-3	12,522.1	1-1-2-2	6,212.5	2-3-3-2	2,735.5	3-1-1-1	2,579.4	2-1-1-3	7,980.7
1-1-2-1	272.8	1-1-2-3	11,423.2	3-2-2-1	12,797.0	1-2-3-3	6,216.5	2-3-2-3	3,395.4	1-1-2-2	2,632.3	3-2-2-2	12,457.7
2-2-2-2	274.2	3-2-2-1	11,407.2	2-3-3-2	13,237.6	2-2-2-2	6,299.0	3-1-3-1	3,183.4	2-1-3-1	2,799.5	2-2-3-1	10,072.8
2-2-3-1	321.1	2-1-1-3	11,657.8	3-3-2-3	13,587.7	3-2-2-1	6,553.3	3-3-3-2	4,277.2	2-2-1-3	2,811.8	3-1-1-3	10,886.2
3-3-3-3	334.3	2-2-3-2	11,691.4	1-1-3-1	14,112.6	1-1-2-3	7,106.9	1-3-3-3	4,327.7	1-1-2-3	2,979.1	1-2-3-2	11,063.5
1-2-3-3	376.5	2-2-3-3	12,308.0	2-1-2-1	14,480.2	2-2-2-3	7,190.2	2-2-2-2	4,483.9	2-2-2-2	3,151.9	3-2-3-1	15,059.0
1-1-2-2	381.4	1-1-3-1	12,861.0	3-2-2-2	14,970.0	2-2-3-1	8,296.3	3-3-2-3	5,218.3	1-1-3-2	3,290.3	2-2-2-3	12,173.2
2-2-2-3	390.7	3-2-2-2	13,190.2	2-2-3-1	15,393.8	1-1-3-1	8,979.5	1-2-3-2	5,271.3	3-1-2-1	3,439.6	3-2-2-3	17,575.7

Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD
3-2-2-2	404.3	3-1-1-1	14,064.0	1-1-3-2	16,158.0	3-3-3-2	8,498.7	1-2-2-3	5,898.1	1-1-3-3	3,723.8	1-1-2-1	13,700.7
2-1-2-1	449.8	3-2-2-3	13,869.3	2-3-3-3	16,232.0	2-1-2-1	9,438.9	1-1-2-2	6,112.4	2-2-2-3	3,749.4	1-2-3-3	16,395.7
3-2-3-1	469.1	1-1-3-2	15,159.6	3-3-3-1	16,285.0	3-3-3-3	9,685.5	3-2-2-2	7,057.8	3-2-1-2	3,796.8	2-2-3-2	17,514.1
1-1-3-1	497.5	1-1-3-3	16,449.4	2-1-2-2	16,696.3	3-2-2-2	10,536.4	2-3-3-3	8,282.2	2-2-3-2	3,878.3	3-2-3-2	25,977.3
2-2-3-2	500.0	2-1-2-1	16,462.6	2-2-3-2	17,926.6	3-2-2-3	12,029.2	3-3-3-3	12,728.9	3-1-3-1	4,299.4	2-1-2-1	20,009.7
1-1-2-3	521.5	3-1-1-2	16,477.7	3-2-2-3	18,194.9	1-1-3-2	13,043.9	2-2-3-2	10,993.6	3-2-1-3	4,520.3	2-2-3-3	25,383.7
3-2-2-3	577.9	3-2-3-1	16,426.3	1-1-3-3	19,173.8	2-2-3-2	13,225.6	2-2-2-3	11,972.7	2-2-3-3	4,686.6	1-1-2-2	23,065.7
3-1-2-1	617.0	3-1-1-3	17,695.0	3-3-3-2	19,242.0	2-1-2-2	13,912.4	2-1-2-2	11,863.6	3-2-2-2	5,062.9	3-1-2-1	27,504.3
2-1-2-2	644.3	2-2-2-2	8,119.1	2-1-2-3	19,960.4	3-2-3-1	13,759.6	1-2-3-3	14,386.9	3-2-2-3	6,027.6	3-2-3-3	36,656.3
1-1-3-2	695.4	2-1-2-2	19,328.1	3-1-2-1	21,052.2	1-1-3-3	14,922.0	1-1-2-3	14,829.9	3-2-3-2	6,328.6	1-1-3-1	28,586.7
2-2-3-3	712.4	3-2-3-2	18,993.8	2-2-3-3	21,771.8	3-1-2-1	15,268.8	1-1-3-2	14,909.7	2-1-1-2	6,388.8	1-1-2-3	30,031.8
3-2-3-2	737.1	3-2-3-3	19,971.7	3-2-3-1	22,249.8	2-2-3-3	15,096.8	3-2-3-2	17,215.8	2-1-1-3	7,160.9	2-1-2-2	33,620.2
2-1-3-1	820.1	1-1-2-1	8,931.3	3-3-3-3	23,624.5	2-1-2-3	15,908.4	3-2-2-3	18,606.0	3-2-3-3	7,534.3	3-1-2-2	46,148.3
2-1-2-3	889.7	2-1-2-3	20,817.3	3-1-2-2	24,348.3	2-1-3-1	19,818.2	3-1-2-2	17,873.9	2-1-2-2	8,519.2	2-1-3-1	41,734.8
3-1-2-2	890.5	2-1-3-1	23,706.1	2-1-3-1	25,176.3	3-2-3-2	22,122.7	2-2-3-3	29,204.6	2-1-2-3	9,548.7	2-1-2-3	43,633.2
1-1-3-3	950.9	3-1-2-1	25,114.0	3-2-3-2	26,027.8	3-1-2-2	22,633.0	2-1-2-3	28,787.8	3-1-1-2	9,833.9	1-1-3-2	48,127.1
3-2-3-3	1,053.6	2-1-3-2	27,832.3	2-1-3-2	29,029.3	3-2-3-3	25,257.0	2-1-3-2	28,938.3	2-1-3-2	10,648.8	3-1-3-1	57,372.5
3-1-3-1	1,125.0	3-1-2-2	29,424.1	3-1-2-3	29,106.9	3-1-2-3	25,880.2	1-1-3-3	36,174.0	3-1-1-3	11,046.0	3-1-2-3	59,542.5
2-1-3-2	1,174.8	2-1-3-3	29,976.8	3-2-3-3	31,634.9	2-1-3-2	29,210.9	3-1-2-3	43,476.1	2-1-3-3	11,935.7	1-1-3-3	62,662.0
3-1-2-3	1,233.4	3-1-2-3	31,597.9	2-1-3-3	34,704.5	2-1-3-3	32,164.1	3-2-3-3	45,385.0	3-1-2-2	13,113.1	2-1-3-2	70,133.4
2-1-3-3	1,622.3	3-1-3-1	36,164.0	3-1-3-1	36,602.7	3-1-3-1	32,059.0	3-1-3-2	43,599.1	3-1-2-3	14,729.3	3-1-3-2	96,273.4
3-1-3-2	1,623.8	3-1-3-2	42,370.5	3-1-3-2	42,333.6	3-1-3-2	47,521.1	2-1-3-3	70,220.8	3-1-3-2	16,391.1	2-1-3-3	91,025.6
3-1-3-3	2,249.0	3-1-3-3	45,500.8	3-1-3-3	50,607.1	3-1-3-3	54,339.1	3-1-3-3	106,049.5	3-1-3-3	18,411.3	3-1-3-3	124,220.9

TABLE 12.— Gizzard shad (GZD) abundance (#/ha) needed on simulation day 1 (15 June) from warm temperature regime bioenergetics simulations to meet sustainable predator consumption (accounting for non-predation gizzard shad annual mortality rate of 0.7 and the biomass required to sustain population through reproduction with a 233 offspring/individual annual reproductive rate). Population parameters are numerically coded in order as growth-mortality-initial population size-percent by weight gizzard shad; low (1), medium (2), and high (3) parameters corresponded with the 10^{th} percentile, mean, and 90^{th} percentile of published values for each piscivore species. Values are sorted from lowest to highest consumption for each piscivore.

Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD
1-3-1-1	4.0	1-3-1-1	646.2	1-3-1-1	851.4	1-3-1-1	99.5	1-3-1-1	2.1	1-3-1-1	47.1	1-3-1-1	116.8
1-3-1-2	6.8	1-3-1-2	724.0	1-3-1-2	986.7	1-3-1-2	177.1	2-3-1-1	3.7	1-3-2-1	62.8	2-3-1-1	169.9
2-3-1-1	7.6	1-3-1-3	764.6	1-3-1-3	1,198.5	1-3-1-3	201.9	3-3-1-1	5.5	1-3-3-1	78.5	1-3-1-2	216.1
1-3-1-3	10.0	1-3-2-1	1,153.9	1-2-1-1	1,207.5	2-3-1-1	253.0	1-2-1-1	6.1	2-3-1-1	134.1	3-3-1-1	249.0
3-3-1-1	11.8	1-3-2-2	1,292.8	1-2-1-2	1,390.6	1-2-1-1	328.4	2-2-1-1	11.6	1-2-1-1	188.5	2-3-1-2	311.8
2-3-1-2	14.3	1-3-2-3	1,365.3	2-3-1-1	1,642.5	3-3-1-1	428.1	1-1-1-1	15.7	1-3-1-2	213.7	1-3-1-3	367.0
1-2-1-1	18.6	2-3-1-1	1,579.3	1-2-1-3	1,673.6	2-3-1-2	460.0	1-3-1-2	16.7	2-3-3-1	223.5	3-3-1-2	450.1
1-3-2-1	21.4	1-3-3-1	1,661.6	2-3-1-2	1,930.3	1-2-1-2	513.3	3-2-1-1	17.4	1-2-2-1	251.4	2-3-1-3	521.8
2-3-1-3	21.8	1-2-1-1	1,778.7	1-1-1-1	2,069.4	2-3-1-3	524.3	2-1-1-1	29.1	3-3-1-1	259.0	1-2-1-1	548.7
3-3-1-2	22.4	2-3-1-2	1,762.8	2-2-1-1	2,248.4	1-3-2-1	522.8	2-3-1-2	33.5	2-3-2-1	273.0	1-3-2-1	639.3
1-2-1-2	27.4	1-3-3-2	1,861.6	1-1-1-2	2,369.8	1-2-1-3	586.2	3-1-1-1	42.9	1-3-2-2	285.0	3-3-1-3	722.4
2-2-1-1	32.7	2-3-1-3	1,859.2	2-3-1-3	2,367.5	2-2-1-1	774.3	3-3-1-2	52.2	1-3-1-3	293.1	2-2-1-1	875.1
3-3-1-3	34.1	1-3-3-3	1,929.9	3-3-1-1	2,371.9	3-3-1-2	786.4	1-3-1-3	58.9	1-2-3-1	314.2	2-3-2-1	930.2
1-3-2-2	36.5	1-2-1-2	2,014.1	2-2-1-2	2,618.8	1-1-1-1	845.9	1-3-2-1	60.9	3-3-2-1	345.4	1-2-1-2	963.7
1-2-1-3	38.3	1-2-1-3	2,148.9	1-1-1-3	2,812.2	3-3-1-3	895.7	1-2-1-2	67.3	1-3-3-2	356.2	1-3-2-2	1,183.4
1-3-3-1	39.0	3-3-1-1	2,700.8	3-3-1-2	2,803.0	1-3-2-2	931.1	2-3-2-1	107.2	1-3-2-3	390.8	3-2-1-1	1,312.3
2-3-2-1	40.4	2-3-2-1	2,820.2	2-2-1-3	3,181.3	1-3-2-3	1,061.2	2-3-1-3	111.5	3-3-3-1	431.7	1-3-3-1	1,334.0
3-2-1-1	47.8	3-3-1-2	3,010.8	3-2-1-1	3,245.7	1-3-3-1	1,097.6	2-2-1-2	140.3	1-3-3-3	488.5	3-3-2-1	1,363.2
1-1-1-1	50.6	1-2-2-1	3,176.2	1-3-2-1	3,258.0	1-1-1-2	1,230.2	1-3-3-1	148.6	1-1-1-1	551.4	1-2-1-3	1,428.6
2-2-1-2	50.9	2-3-2-2	3,147.7	3-3-1-3	3,441.0	2-2-1-2	1,235.4	3-3-2-1	158.7	2-2-1-1	566.4	2-2-1-2	1,522.3
1-3-2-3	53.6	3-3-1-3	3,174.7	2-1-1-1	3,686.6	3-2-1-1	1,277.8	3-3-1-3	170.4	2-3-1-2	594.6	2-3-2-2	1,707.4
3-3-2-1	63.0	2-3-2-3	3,320.0	1-3-2-2	3,775.6	1-1-1-3	1,407.2	1-2-2-1	176.3	1-1-2-1	735.3	2-3-3-1	1,940.8
1-3-3-2	66.5	1-2-2-2	3,596.6	3-2-1-2	3,797.5	2-3-2-1	1,329.7	1-1-1-2	195.7	2-2-2-1	755.3	1-3-2-3	2,009.6
1-1-1-2	70.7	1-2-2-3	3,837.3	2-1-1-2	4,252.0	2-2-1-3	1,410.8	1-2-1-3	197.5	1-2-1-2	768.2	2-2-1-3	2,205.6
2-2-1-3	72.5	2-2-1-1	3,838.6	1-3-2-3	4,586.0	1-2-2-1	1,726.4	3-2-1-2	219.3	2-3-1-3	789.2	3-2-1-2	2,264.7
2-3-3-1	73.7	2-3-3-1	4,061.1	1-2-2-1	4,620.4	2-1-1-1	1,854.1	2-3-3-1	261.5	2-3-2-2	792.9	1-1-1-1	2,509.4
3-2-1-2	75.0	2-2-1-2	4,327.2	3-2-1-3	4,615.3	1-3-3-2	1,955.1	2-2-2-1	331.9	1-1-3-1	919.1	3-3-2-2	2,464.7
2-3-2-2	76.8	1-2-3-1	4,573.7	2-1-1-3	5,084.3	3-2-1-2	2,057.6	2-1-1-2	379.3	1-2-1-3	929.9	1-3-3-2	2,469.2
2-1-1-1	83.4	2-2-1-3	4,598.6	1-2-2-2	5,321.2	1-3-3-3	2,228.0	3-3-3-1	387.1	2-2-3-1	944.2	3-3-3-1	2,844.4

Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD
1-1-1-3	96.7	2-3-3-2	4,532.7	3-1-1-1	5,352.0	3-2-1-3	2,348.3	2-2-1-3	399.3	2-3-3-2	991.1	2-3-2-3	2,857.3
1-3-3-3	97.6	1-1-1-1	4,927.0	1-3-3-1	5,664.6	3-3-2-1	2,250.2	1-2-3-1	430.1	1-2-2-2	1,024.3	1-2-2-1	3,004.7
1-2-2-1	99.3	2-3-3-3	4,780.8	3-1-1-2	6,191.0	2-3-2-2	2,418.0	1-1-2-1	449.6	2-3-2-3	1,052.3	3-2-1-3	3,192.1
3-2-1-3	107.3	3-3-2-1	4,822.8	2-3-2-1	6,285.1	2-1-1-2	2,734.3	1-1-1-3	496.8	3-3-1-2	1,116.8	2-3-3-2	3,562.5
3-1-1-1	114.5	1-2-3-2	5,179.1	1-2-2-3	6,404.1	1-2-2-2	2,698.3	1-3-2-2	480.5	1-2-2-3	1,240.0	2-1-1-1	3,870.5
3-3-3-1	114.8	1-2-3-3	5,525.7	1-3-3-2	6,564.5	2-3-2-3	2,755.8	3-2-2-1	499.1	1-2-3-2	1,280.4	3-3-2-3	3,955.6
2-3-2-3	116.4	3-3-2-2	5,376.5	3-1-1-3	7,400.7	2-3-3-1	2,791.8	3-1-1-2	570.3	3-2-1-1	1,287.5	1-1-1-2	4,226.6
2-1-1-2	119.5	1-1-1-2	5,636.0	2-3-2-2	7,386.2	3-1-1-1	2,987.3	3-2-1-3	619.0	2-3-3-3	1,315.4	1-3-3-3	4,193.1
3-3-2-2	120.0	3-3-2-3	5,669.0	1-1-2-1	7,918.8	2-1-1-3	3,127.4	2-2-3-1	809.5	3-3-1-3	1,442.0	2-2-2-1	4,791.8
2-3-3-2	140.0	1-1-1-3	6,203.2	1-3-3-3	7,973.5	1-2-2-3	3,081.5	2-1-2-1	833.6	3-3-2-2	1,489.2	3-1-1-1	5,208.3
1-2-2-2	146.7	3-2-1-1	6,243.2	1-2-3-1	8,033.4	1-2-3-1	3,624.8	2-1-1-3	964.6	1-2-3-3	1,549.9	3-3-3-2	5,142.6
2-1-1-3	165.0	2-2-2-1	6,854.6	2-2-2-1	8,603.7	2-2-2-1	4,070.0	2-3-2-2	960.3	2-1-1-1	1,609.0	1-2-2-2	5,276.7
3-1-1-2	165.2	3-2-1-2	7,027.8	1-1-2-2	9,068.2	3-3-2-2	4,133.4	1-1-3-1	1,096.6	3-2-2-1	1,716.8	1-1-1-3	5,502.1
2-2-2-1	174.9	3-3-3-1	6,944.8	2-3-2-3	9,059.2	3-1-1-2	4,431.9	1-3-3-2	1,172.1	3-3-3-2	1,861.5	2-3-3-3	5,961.7
1-2-3-1	181.0	3-2-1-3	7,457.9	3-3-2-1	9,076.1	1-1-2-1	4,446.3	3-2-3-1	1,217.5	3-3-2-3	1,922.8	1-2-3-1	6,269.3
3-3-2-3	182.2	2-2-2-2	7,727.1	1-2-3-2	9,251.7	3-3-2-3	4,708.2	3-1-2-1	1,230.4	1-1-1-2	2,106.7	2-1-1-2	6,501.2
1-2-2-3	205.0	3-3-3-2	7,742.1	2-2-2-2	10,021.0	3-3-3-1	4,724.6	3-1-1-3	1,455.6	2-1-2-1	2,145.6	3-2-2-1	7,185.5
2-3-3-3	212.2	2-2-2-3	8,211.7	1-1-2-3	10,760.9	3-1-1-3	5,067.3	3-3-2-2	1,498.0	3-2-3-1	2,146.0	1-2-2-3	7,822.2
3-3-3-2	218.9	3-3-3-3	8,163.3	3-3-2-2	10,725.6	2-3-3-2	5,077.0	1-3-2-3	1,689.7	2-2-1-2	2,275.8	2-1-1-3	8,412.5
3-1-1-3	228.8	1-1-2-1	8,798.1	2-3-3-1	10,927.7	1-2-3-2	5,665.5	1-2-2-2	1,931.8	1-1-1-3	2,373.0	3-1-1-2	8,736.5
3-2-2-1	255.5	2-1-1-1	9,076.1	1-2-3-3	11,134.6	2-3-3-3	5,786.3	2-1-3-1	2,033.4	3-3-3-3	2,403.5	2-2-2-2	8,335.5
1-2-3-2	267.4	1-1-2-2	10,064.3	2-2-2-3	12,173.4	1-1-2-2	6,466.4	2-3-3-2	2,342.4	2-1-3-1	2,681.9	3-3-3-3	8,253.4
1-1-2-1	270.7	2-2-3-1	9,870.6	3-2-2-1	12,420.0	1-2-3-3	6,470.0	3-1-3-1	3,001.2	2-2-1-3	2,706.7	2-2-3-1	9,998.1
2-2-2-2	272.3	2-1-1-2	10,343.3	2-3-3-2	12,842.2	2-2-2-2	6,493.9	2-3-2-3	3,199.4	1-1-2-2	2,809.1	3-1-1-3	11,252.6
2-2-3-1	318.9	1-1-2-3	11,077.0	3-3-2-3	13,167.1	3-2-2-1	6,716.8	3-3-3-2	3,654.1	2-2-2-2	3,034.7	1-2-3-2	11,009.9
3-3-3-3	332.2	2-1-1-3	11,286.9	1-1-3-1	13,768.2	1-1-2-3	7,396.7	2-2-2-2	4,024.8	1-1-2-3	3,164.3	2-2-2-3	12,076.7
1-2-3-3	373.8	2-2-3-2	11,127.0	2-1-2-1	14,106.8	2-2-2-3	7,415.5	1-3-3-3	4,121.7	1-1-3-2	3,511.4	3-2-2-2	12,400.3
1-1-2-2	378.5	3-2-2-1	11,148.4	3-2-2-2	14,531.2	2-2-3-1	8,545.5	1-2-3-2	4,712.1	2-2-2-3	3,609.2	1-1-2-1	13,740.4
2-2-2-3	388.0	2-2-3-3	11,824.8	2-2-3-1	14,959.0	3-3-3-2	8,678.7	3-3-2-3	4,888.1	2-2-3-2	3,793.2	3-2-3-1	14,992.7

Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD
3-2-2-2	401.4	1-1-3-1	12,669.3	1-1-3-2	15,766.6	1-1-3-1	9,335.6	1-1-2-2	5,614.8	1-1-3-3	3,955.3	1-2-3-3	16,321.2
2-1-2-1	446.5	3-2-2-2	12,549.4	2-3-3-3	15,750.8	2-1-2-1	9,745.9	1-2-2-3	5,666.8	3-1-1-1	4,197.6	2-2-3-2	17,392.1
3-2-3-1	465.9	3-2-2-3	13,317.5	3-3-3-1	15,780.3	3-3-3-3	9,885.4	3-2-2-2	6,291.5	2-2-3-3	4,511.5	3-2-2-3	17,478.4
1-1-3-1	493.7	3-1-1-1	13,829.7	2-1-2-2	16,270.5	3-2-2-2	10,815.5	2-3-3-3	7,804.2	3-2-1-2	5,042.5	2-1-2-1	21,193.3
2-2-3-2	496.5	1-1-3-2	14,492.5	2-2-3-2	17,423.2	3-2-2-3	12,343.5	2-2-3-2	9,817.6	3-1-2-1	5,597.4	1-1-2-2	23,142.9
1-1-2-3	517.4	3-1-1-2	15,743.1	3-2-2-3	17,660.8	1-1-3-2	13,577.0	2-1-2-2	10,882.0	3-2-1-3	5,838.0	2-2-3-3	25,198.2
3-2-2-3	573.8	1-1-3-3	15,950.7	1-1-3-3	18,709.7	2-2-3-2	13,634.8	2-2-2-3	11,457.3	2-1-1-2	6,122.8	3-2-3-2	25,873.4
3-1-2-1	612.4	2-1-2-1	16,207.1	3-3-3-2	18,648.2	2-1-2-2	14,372.5	3-3-3-3	11,923.2	3-2-2-2	6,723.9	3-1-2-1	28,518.7
2-1-2-2	639.5	3-2-3-1	16,053.7	2-1-2-3	19,455.4	3-2-3-1	14,102.8	1-1-3-2	13,695.9	2-1-1-3	6,861.3	1-1-3-1	28,669.6
1-1-3-2	690.1	3-1-1-3	17,115.6	3-1-2-1	20,479.4	1-1-3-3	15,530.3	1-2-3-3	13,822.8	3-1-3-1	6,996.6	1-1-2-3	30,127.2
2-2-3-3	707.4	3-2-3-2	18,071.1	2-2-3-3	21,165.5	3-1-2-1	15,702.4	1-1-2-3	14,254.3	3-2-2-3	7,784.7	2-1-2-2	35,597.9
3-2-3-2	732.0	2-1-2-2	18,470.0	3-2-3-1	21,594.2	2-2-3-3	15,569.9	3-2-3-2	15,346.7	2-1-2-2	8,164.5	3-2-3-3	36,469.0
2-1-3-1	814.0	3-2-3-3	19,177.1	3-3-3-3	22,893.2	2-1-2-3	16,439.0	3-1-2-2	16,363.2	3-2-3-2	8,404.8	2-1-3-1	44,220.3
2-1-2-3	883.0	2-1-2-3	20,154.9	3-1-2-2	23,690.0	2-1-3-1	20,490.5	3-2-2-3	17,759.6	2-1-2-3	9,149.3	2-1-2-3	46,063.4
3-1-2-2	883.9	2-1-3-1	23,338.1	2-1-3-1	24,527.0	3-2-3-2	22,708.6	2-1-3-2	26,544.0	3-2-3-3	9,730.7	3-1-2-2	47,837.4
1-1-3-3	943.5	3-1-2-1	24,695.7	3-2-3-2	25,264.9	3-1-2-2	23,296.0	2-1-2-3	27,676.4	2-1-3-2	10,205.4	1-1-3-2	48,288.2
3-2-3-3	1,046.3	2-1-3-2	26,596.7	2-1-3-2	28,288.9	3-2-3-3	25,916.9	2-2-3-3	27,947.3	2-1-3-3	11,436.4	3-1-3-1	59,504.8
3-1-3-1	1,116.7	3-1-2-2	28,112.3	3-1-2-3	28,319.1	3-1-2-3	26,635.9	1-1-3-3	34,770.0	3-1-1-2	15,749.9	3-1-2-3	61,614.2
2-1-3-2	1,166.0	2-1-3-3	29,023.0	3-2-3-3	30,706.2	2-1-3-2	30,177.0	3-1-3-2	39,914.1	3-1-1-3	17,366.9	1-1-3-3	62,860.9
3-1-2-3	1,224.2	3-1-2-3	30,563.3	2-1-3-3	33,826.5	3-1-3-1	32,969.4	3-1-2-3	41,765.5	3-1-2-2	21,001.9	2-1-3-2	74,275.7
2-1-3-3	1,610.1	3-1-3-1	35,561.6	3-1-3-1	35,606.9	2-1-3-3	34,515.8	3-2-3-3	43,320.3	3-1-2-3	23,158.1	2-1-3-3	96,112.2
3-1-3-2	1,611.6	3-1-3-2	40,481.6	3-1-3-2	41,189.1	3-1-3-2	48,913.2	2-1-3-3	67,509.9	3-1-3-2	26,251.9	3-1-3-2	99,813.8
3-1-3-3	2,232.1	3-1-3-3	44,011.0	3-1-3-3	49,237.5	3-1-3-3	55,925.6	3-1-3-3	101,877.0	3-1-3-3	28,947.1	3-1-3-3	128,559.4

TABLE 13.— Gizzard shad (GZD) abundance (#/ha) needed on simulation day 60 (15 August) from cool temperature regime bioenergetics simulations to meet sustainable predator consumption (accounting for non-predation gizzard shad annual mortality rate of 0.7 and the biomass required to sustain population through reproduction with a 233 offspring/individual annual reproductive rate). Population parameters are numerically coded in order as growth-mortality-initial population size-percent by weight gizzard shad; low (1), medium (2), and high (3) parameters corresponded with the 10^{th} percentile, mean, and 90^{th} percentile of published values for each piscivore species. Values are sorted from lowest to highest consumption for each piscivore.

Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD
1-3-1-1	1.3	1-3-1-1	129.0	1-3-1-1	207.1	1-3-1-1	50.9	1-3-1-1	0.3	1-3-1-1	9.6	1-3-1-1	19.6
1-3-1-2	2.2	1-3-1-2	148.1	1-3-1-2	242.3	1-3-1-2	91.0	2-3-1-1	0.7	1-3-2-1	12.8	2-3-1-1	27.8
2-3-1-1	2.3	1-3-1-3	154.9	1-3-1-3	296.0	1-3-1-3	103.8	1-2-1-1	1.2	1-3-3-1	16.0	3-3-1-1	36.8
1-3-1-3	3.3	1-3-2-1	230.4	1-2-1-1	301.0	2-3-1-1	133.7	3-3-1-1	1.1	2-3-1-1	28.1	1-3-1-2	34.0
3-3-1-1	3.7	1-3-2-2	264.4	1-2-1-2	349.4	1-2-1-1	185.3	1-3-1-2	3.1	2-3-2-1	37.5	2-3-1-2	48.9
2-3-1-2	4.6	1-3-2-3	276.6	2-3-1-1	392.5	3-3-1-1	230.4	1-1-1-1	3.3	1-2-1-1	38.6	3-3-1-2	64.6
1-2-1-1	6.2	2-3-1-1	309.1	1-2-1-3	422.9	2-3-1-2	245.4	2-3-1-2	6.8	1-3-1-2	43.6	1-3-1-3	55.7
1-3-2-1	6.7	1-3-3-1	331.8	2-3-1-2	466.3	1-3-2-1	267.8	2-2-1-1	2.5	2-3-3-1	46.8	2-3-1-3	80.2
2-3-1-3	7.0	2-3-1-2	353.4	1-1-1-1	514.1	2-3-1-3	279.6	1-3-1-3	9.5	3-3-1-1	48.4	3-3-1-3	103.1
3-3-1-2	7.1	2-3-1-3	369.2	2-2-1-1	553.6	1-2-1-2	290.7	2-1-1-1	6.6	1-2-2-1	51.4	1-3-2-1	95.7
1-2-1-2	9.4	1-3-3-2	380.8	3-3-1-1	563.2	1-2-1-3	332.0	3-2-1-1	4.0	1-3-2-2	58.1	1-2-1-1	101.2
2-2-1-1	10.8	1-3-3-3	398.4	2-3-1-3	574.4	3-3-1-2	427.7	3-3-1-2	11.2	1-3-1-3	60.1	2-3-2-1	140.6
3-3-1-3	10.8	1-2-1-1	404.0	1-1-1-2	614.7	2-2-1-1	446.5	1-3-2-1	9.3	1-2-3-1	64.3	2-2-1-1	159.6
1-3-2-2	11.9	1-2-1-2	469.1	2-2-1-2	650.7	1-3-2-2	478.5	1-2-1-2	14.6	3-3-2-1	64.5	3-3-2-1	189.8
1-3-3-1	12.3	1-2-1-3	494.8	3-3-1-2	670.0	3-3-1-3	487.4	2-3-1-3	20.8	1-3-3-2	72.6	1-3-2-2	174.4
2-3-2-1	12.5	3-3-1-1	518.1	1-1-1-3	733.4	1-1-1-1	458.8	3-3-1-3	34.1	1-3-2-3	80.1	1-2-1-2	177.2
1-2-1-3	13.2	2-3-2-1	551.9	1-3-2-1	792.3	1-3-2-3	545.5	3-1-1-1	10.0	3-3-3-1	80.7	1-3-3-1	196.8
3-2-1-1	15.9	3-3-1-2	591.6	2-2-1-3	794.0	1-3-3-1	562.3	1-3-3-1	22.6	1-3-3-3	100.1	3-2-1-1	234.5
2-2-1-2	17.1	3-3-1-3	618.1	3-2-1-1	798.1	2-3-2-1	702.8	1-2-1-3	39.3	1-1-1-1	107.8	2-3-2-2	256.0
1-3-2-3	17.6	2-3-2-2	631.0	3-3-1-3	825.3	2-2-1-2	718.0	2-3-2-1	19.5	2-2-1-1	123.9	2-2-1-2	275.8
1-1-1-1	17.4	2-3-2-3	659.4	1-3-2-2	927.0	1-1-1-2	733.3	1-2-2-1	34.1	2-3-1-2	125.2	3-3-3-3	1,147.7
3-3-2-1	19.7	1-2-2-1	721.3	3-2-1-2	939.1	3-2-1-1	746.9	1-1-1-2	45.3	1-1-2-1	149.1	1-3-2-3	293.3
1-3-3-2	21.6	2-3-3-1	794.7	2-1-1-1	948.7	2-2-1-3	814.2	2-2-1-2	56.3	1-2-1-2	158.2	2-3-3-1	290.6
2-3-3-1	22.8	1-2-2-2	837.7	2-1-1-2	1,101.0	1-1-1-3	838.8	3-2-1-2	50.9	2-2-2-1	165.2	1-2-1-3	261.8
2-2-1-3	24.5	2-2-1-1	860.1	1-3-2-3	1,132.5	1-2-2-1	974.2	2-2-1-3	85.1	2-3-2-2	167.0	3-3-2-3	550.1
2-3-2-2	24.4	1-2-2-3	883.5	1-2-2-1	1,151.9	1-3-3-2	1,004.8	3-2-1-3	136.7	2-3-1-3	167.6	3-3-2-2	341.9
1-1-1-2	25.0	2-3-3-2	908.7	3-2-1-3	1,145.3	2-1-1-1	1,121.8	2-1-1-2	88.9	1-1-3-1	186.4	2-3-2-3	427.4
3-2-1-2	25.2	3-3-2-1	925.3	2-1-1-3	1,321.9	1-3-3-3	1,145.3	1-3-2-2	87.6	1-2-1-3	193.4	3-2-1-2	402.0
2-1-1-1	28.9	2-3-3-3	949.5	1-2-2-2	1,336.9	3-2-1-2	1,212.7	3-3-2-1	31.9	3-2-1-1	205.4	1-3-3-2	361.1

Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Require d GZD	Population parameters	Required GZD
1-2-2-1	33.4	1-2-3-1	1,038.7	3-1-1-1	1,385.4	2-3-2-2	1,290.1	2-3-3-1	47.6	2-3-3-2	208.8	2-2-1-3	401.3
1-1-1-3	34.3	2-2-1-3	1,045.5	2-3-2-1	1,502.0	3-2-1-3	1,384.4	1-1-1-3	109.8	1-2-2-2	211.0	2-3-3-2	531.3
3-2-1-3	36.1	3-3-2-2	1,056.5	1-3-3-2	1,611.7	2-3-2-3	1,469.5	1-2-3-1	83.3	3-3-1-2	213.3	1-3-3-3	609.2
3-3-3-1	35.9	3-3-2-3	1,103.8	1-2-2-3	1,618.3	1-2-2-2	1,528.1	3-1-1-2	134.8	2-3-2-3	223.5	1-2-2-1	554.0
2-3-2-3	37.2	1-2-3-2	1,206.3	3-1-1-2	1,609.0	2-3-3-1	1,475.7	2-2-2-1	71.1	1-2-2-3	257.8	3-2-1-3	566.3
3-3-2-2	38.1	1-1-1-1	1,172.2	2-3-2-2	1,784.1	2-1-1-2	1,662.0	2-1-1-3	217.2	1-2-3-2	263.7	3-3-3-2	707.8
3-1-1-1	39.6	1-2-3-3	1,272.3	3-1-1-3	1,929.4	1-2-2-3	1,745.2	2-3-2-2	195.4	3-2-2-1	273.9	2-3-3-3	888.9
2-1-1-2	41.7	3-3-3-1	1,332.4	1-3-3-3	1,969.0	3-1-1-1	1,826.9	1-3-2-3	273.1	2-3-3-3	279.3	2-1-1-1	804.5
2-3-3-2	44.5	3-2-1-1	1,383.4	1-2-3-1	2,002.7	2-1-1-3	1,900.3	1-3-3-2	213.7	3-3-1-3	282.8	2-2-2-1	862.2
1-2-2-2	50.1	1-1-1-2	1,436.9	1-1-2-1	2,044.1	1-2-3-1	2,045.5	3-1-1-3	332.6	3-3-2-2	284.4	1-1-1-2	897.6
3-1-1-2	57.5	1-1-1-3	1,553.9	2-2-2-1	2,118.3	3-3-2-2	2,248.2	3-3-3-1	77.9	1-2-3-3	322.3	1-2-2-2	970.3
2-1-1-3	57.7	2-2-2-1	1,535.8	3-3-2-1	2,154.9	2-2-2-1	2,347.2	1-1-3-1	241.6	3-2-3-1	342.3	1-2-3-1	1,155.1
2-2-2-1	57.9	3-3-3-2	1,521.3	2-3-2-3	2,197.9	3-3-2-3	2,562.1	3-3-2-3	977.5	3-3-3-2	355.5	3-2-2-1	1,272.2
3-3-2-3	58.0	3-2-1-2	1,596.5	1-2-3-2	2,324.4	3-3-3-1	2,543.3	2-3-2-3	595.5	2-1-1-1	366.9	1-1-1-3	1,169.7
1-2-3-1	60.8	3-3-3-3	1,589.5	1-1-2-2	2,352.2	1-1-2-1	2,644.2	3-2-2-1	113.5	3-3-2-3	377.1	2-1-1-2	1,348.3
2-3-3-3	67.9	3-2-1-3	1,677.3	2-2-2-2	2,489.9	2-3-3-2	2,708.8	2-1-2-1	189.0	1-1-1-2	429.2	2-2-2-2	1,498.7
3-3-3-2	69.5	2-2-2-2	1,775.6	3-3-2-2	2,563.6	3-1-1-2	2,724.0	3-3-2-2	320.9	3-3-3-3	471.4	3-1-1-1	1,331.3
1-2-2-3	70.4	2-2-2-3	1,866.9	2-3-3-1	2,611.5	2-3-3-3	3,085.4	2-2-3-1	173.4	1-1-1-3	486.8	1-2-2-3	1,433.1
3-1-1-3	79.8	1-1-2-1	2,181.4	1-1-2-3	2,806.4	3-1-1-3	3,114.6	1-2-2-2	417.7	2-1-2-1	489.3	1-1-1-1	1,350.2
3-2-2-1	84.9	2-2-3-1	2,211.6	1-2-3-3	2,813.8	1-2-3-2	3,208.4	2-3-3-2	476.5	2-2-1-2	500.6	2-2-3-1	1,796.2
1-2-3-2	91.3	2-1-1-1	2,241.4	2-2-2-3	3,038.2	1-2-3-3	3,664.4	1-3-3-3	666.2	1-1-2-2	572.3	2-2-2-3	2,185.5
2-2-2-2	91.4	3-2-2-1	2,470.3	3-2-2-1	3,053.8	2-2-2-2	3,773.9	3-3-3-3	2,384.3	3-1-1-1	583.7	2-1-1-3	1,751.7
1-1-2-1	95.2	1-1-2-2	2,565.9	2-3-3-2	3,102.0	1-1-2-2	3,854.6	2-3-3-3	1,452.5	2-2-1-3	599.6	3-2-2-2	2,189.6
2-2-3-1	105.6	2-2-3-2	2,556.8	3-3-2-3	3,158.0	3-2-2-1	3,926.1	3-1-2-1	286.0	2-1-3-1	611.6	1-2-3-2	2,021.7
3-3-3-3	105.8	2-1-1-2	2,626.0	1-1-3-1	3,554.0	2-2-2-3	4,307.1	3-2-3-1	276.7	1-1-2-3	649.2	3-2-2-3	3,089.0
1-2-3-3	128.4	2-2-3-3	2,688.3	3-2-2-2	3,593.5	1-1-2-3	4,409.2	2-1-3-1	461.1	2-2-2-2	667.5	3-1-1-2	2,228.8
2-2-2-3	130.8	1-1-2-3	2,774.7	2-1-2-1	3,630.1	3-3-3-2	4,720.3	3-3-3-2	782.7	1-1-3-2	715.3	3-2-3-1	2,651.6
1-1-2-2	134.0	2-1-1-3	2,821.4	2-2-3-1	3,683.0	2-2-3-1	4,928.2	2-2-2-2	910.0	3-1-2-1	778.3	1-2-3-3	2,987.3
3-2-2-2	134.7	3-2-2-2	2,850.8	3-3-3-1	3,746.7	3-3-3-3	5,379.5	1-2-2-3	1,127.7	2-2-2-3	799.5	2-2-3-2	3,124.2

Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Require d GZD	Population parameters	Required GZD
3-2-3-1	154.9	1-1-3-1	3,141.2	1-1-3-2	4,089.8	2-1-2-1	5,896.6	1-1-2-2	1,299.3	2-2-3-2	821.6	1-1-2-1	2,924.1
2-2-3-2	166.6	3-1-1-1	3,411.3	2-1-2-2	4,213.2	3-2-2-2	6,374.4	3-2-2-2	1,459.2	3-2-1-2	827.8	2-2-3-3	4,557.2
1-1-3-1	173.5	3-2-3-1	3,557.2	2-2-3-2	4,329.1	3-2-2-3	7,276.9	2-2-2-3	2,442.5	3-1-3-1	972.9	3-1-1-3	2,851.4
1-1-2-3	183.7	1-1-3-2	3,694.9	3-2-2-3	4,382.5	2-2-3-2	7,923.9	3-2-2-3	3,922.4	3-2-1-3	989.5	3-2-3-2	4,565.9
3-2-2-3	193.2	1-1-3-3	3,995.6	3-3-3-2	4,457.3	1-1-3-2	8,093.3	3-1-3-1	697.7	2-2-3-3	999.3	2-1-2-1	4,393.3
3-1-2-1	212.0	2-1-2-1	4,002.5	1-1-3-3	4,879.4	3-2-3-1	8,243.5	2-2-3-2	2,227.0	3-2-2-2	1,103.9	1-1-2-2	4,914.6
2-1-2-2	223.0	3-1-1-2	3,989.5	2-1-2-3	5,058.2	2-1-2-2	8,736.4	1-2-3-3	2,750.8	3-2-2-3	1,319.5	1-1-3-1	6,101.2
2-2-3-3	238.5	3-2-3-2	4,105.2	2-2-3-3	5,282.4	2-2-3-3	9,043.4	2-1-2-2	2,549.5	3-2-3-2	1,379.8	1-1-2-3	6,404.8
1-1-3-2	244.3	3-1-1-3	4,276.9	3-1-2-1	5,301.2	1-1-3-3	9,257.8	1-1-2-3	3,149.2	2-1-1-2	1,400.1	2-1-2-2	7,371.2
3-2-3-2	245.7	3-2-3-3	4,312.9	3-2-3-1	5,309.5	3-1-2-1	9,603.1	1-1-3-2	3,169.2	2-1-1-3	1,575.3	3-1-2-1	7,278.1
2-1-3-1	282.0	2-1-2-2	4,689.2	3-3-3-3	5,490.7	2-1-2-3	9,988.6	3-2-3-2	3,559.3	3-2-3-3	1,649.4	2-1-2-3	9,579.9
3-1-2-2	307.7	2-1-2-3	5,038.2	3-1-2-2	6,156.8	2-1-3-1	12,380.8	3-1-2-2	3,869.1	2-1-2-2	1,867.0	2-1-3-1	9,163.9
2-1-2-3	308.8	2-1-3-1	5,763.6	3-2-3-2	6,247.9	3-2-3-2	13,383.8	2-2-3-3	5,958.0	2-1-2-3	2,100.6	1-1-3-2	10,254.5
1-1-3-3	334.9	3-1-2-1	6,091.5	2-1-3-1	6,311.6	3-1-2-2	14,318.5	3-2-3-3	9,567.9	3-1-1-2	2,228.8	3-1-2-2	12,192.1
3-2-3-3	352.3	2-1-3-2	6,752.4	2-1-3-2	7,325.3	3-2-3-3	15,278.9	2-1-2-3	6,232.0	2-1-3-2	2,333.8	1-1-3-3	13,363.7
3-1-3-1	386.6	3-1-2-2	7,124.0	3-1-2-3	7,382.7	3-1-2-3	16,371.6	3-1-2-3	9,542.7	3-1-1-3	2,509.5	2-1-3-2	15,377.4
2-1-3-2	406.7	2-1-3-3	7,254.9	3-2-3-3	7,619.7	2-1-3-2	18,343.3	2-1-3-2	6,219.0	2-1-3-3	2,625.7	3-1-2-3	15,601.5
3-1-2-3	427.1	3-1-2-3	7,637.2	2-1-3-3	8,794.6	2-1-3-3	20,221.9	1-1-3-3	7,681.8	3-1-2-2	2,972.0	3-1-3-1	15,183.1
3-1-3-2	561.0	3-1-3-1	8,771.7	3-1-3-1	9,217.0	3-1-3-1	20,163.1	3-1-3-2	9,437.6	3-1-2-3	3,346.4	2-1-3-3	19,985.9
2-1-3-3	563.0	3-1-3-2	10,258.6	3-1-3-2	10,704.6	3-1-3-2	30,063.7	2-1-3-3	15,201.6	3-1-3-2	3,714.9	3-1-3-2	25,436.3
3-1-3-3	778.7	3-1-3-3	10,997.5	3-1-3-3	12,836.1	3-1-3-3	34,374.5	3-1-3-3	23,277.1	3-1-3-3	4,182.9	3-1-3-3	32,550.1

TABLE 14.— Gizzard shad (GZD) abundance (#/ha) needed on simulation day 60 (15 August) from warm temperature regime bioenergetics simulations to meet sustainable predator consumption (accounting for non-predation gizzard shad annual mortality rate of 0.7 and the biomass required to sustain population through reproduction with a 233 offspring/individual annual reproductive rate). Population parameters are numerically coded in order as growth-mortality-initial population size-percent by weight gizzard shad; low (1), medium (2), and high (3) parameters corresponded with the 10th percentile, mean, and 90th percentile of published values for each piscivore species. Values are sorted from lowest to highest consumption for each piscivore.

Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD
1-3-1-1	1.2	1-3-1-1	139.1	1-3-1-1	221.1	1-3-1-1	57.1	1-3-1-1	0.3	1-3-1-1	9.7	1-3-1-1	17.2
1-3-1-2	2.2	1-3-1-2	155.6	1-3-1-2	258.8	1-3-1-2	102.3	2-3-1-1	0.7	1-3-2-1	12.9	2-3-1-1	25.4
2-3-1-1	2.3	1-3-1-3	164.2	1-3-1-3	316.2	1-3-1-3	116.5	3-3-1-1	1.1	1-3-3-1	16.1	1-3-1-2	31.9
1-3-1-3	3.2	1-3-2-1	248.5	1-2-1-1	322.4	2-3-1-1	147.6	1-2-1-1	1.2	2-3-1-1	27.7	3-3-1-1	34.7
3-3-1-1	3.6	1-3-2-2	277.8	1-2-1-2	374.3	1-2-1-1	206.2	2-2-1-1	2.4	1-2-1-1	40.8	2-3-1-2	46.7
2-3-1-2	4.5	1-3-2-3	293.2	2-3-1-1	416.4	3-3-1-1	252.3	1-3-1-2	2.7	1-3-1-2	43.8	1-3-1-3	53.9
1-2-1-1	6.1	2-3-1-1	328.9	1-2-1-3	453.1	2-3-1-2	271.0	1-1-1-1	3.3	2-3-3-1	46.2	3-3-1-2	62.8
1-3-2-1	6.7	1-3-3-1	357.8	2-3-1-2	494.5	1-3-2-1	299.9	3-2-1-1	3.9	1-2-2-1	54.4	2-3-1-3	78.3
2-3-1-3	6.9	2-3-1-2	366.4	1-1-1-1	555.0	2-3-1-3	308.9	2-3-1-2	5.9	3-3-1-1	54.1	1-3-2-1	94.5
3-3-1-2	7.0	2-3-1-3	386.3	2-2-1-1	589.0	1-2-1-2	324.1	2-1-1-1	6.5	2-3-2-1	56.3	3-3-1-3	101.5
1-2-1-2	9.2	1-3-3-2	400.0	3-3-1-1	595.4	1-2-1-3	370.1	1-3-1-3	9.2	1-3-2-2	58.4	1-2-1-1	104.3
2-2-1-1	10.7	1-3-3-3	415.5	2-3-1-3	609.4	3-3-1-2	468.9	1-3-2-1	9.3	1-3-1-3	60.2	2-3-2-1	139.2
3-3-1-3	10.7	1-2-1-1	441.3	1-1-1-2	661.0	2-2-1-1	491.2	3-1-1-1	9.8	1-2-3-1	68.0	2-2-1-1	162.6
1-3-2-2	11.7	1-2-1-2	498.6	2-2-1-2	692.4	1-3-2-2	537.5	3-3-1-2	9.6	3-3-2-1	72.1	1-3-2-2	174.5
1-3-3-1	12.1	1-2-1-3	531.0	3-3-1-2	708.4	3-3-1-3	534.0	1-2-1-2	13.4	1-3-3-2	73.0	1-2-1-2	182.8
2-3-2-1	12.4	3-3-1-1	547.6	1-1-1-3	788.6	1-1-1-1	577.6	2-3-2-1	19.1	1-3-2-3	80.3	3-3-2-1	190.1
1-2-1-3	13.0	2-3-2-1	587.3	1-3-2-1	846.0	1-3-2-3	612.5	2-3-1-3	19.7	3-3-3-1	90.1	1-3-3-1	197.1
3-2-1-1	15.6	3-3-1-2	609.9	2-2-1-3	845.0	1-3-3-1	629.6	1-3-3-1	22.6	1-3-3-3	100.3	3-2-1-1	238.8
2-2-1-2	16.8	3-3-1-3	643.0	3-2-1-1	846.2	2-3-2-1	775.9	2-2-1-2	29.1	2-2-1-1	122.8	2-3-2-2	255.6
1-3-2-3	17.4	2-3-2-2	654.3	3-3-1-3	872.2	2-2-1-2	790.0	3-3-2-1	31.0	1-1-1-1	118.4	1-2-1-3	270.2
1-1-1-1	17.1	2-3-2-3	689.7	1-3-2-2	990.3	1-1-1-2	812.7	3-3-1-3	32.1	2-3-1-2	123.6	2-2-1-2	282.9
3-3-2-1	19.4	1-2-2-1	788.1	3-2-1-2	995.9	3-2-1-1	816.3	1-2-2-1	33.7	2-2-2-1	163.8	2-3-3-1	290.5
1-3-3-2	21.3	2-3-3-1	845.7	2-1-1-1	1,013.5	2-2-1-3	902.0	1-2-1-3	38.8	1-1-2-1	165.0	1-3-2-3	295.3
2-3-3-1	22.5	1-2-2-2	890.3	2-1-1-2	1,176.6	1-1-1-3	929.6	1-1-1-2	43.1	2-3-2-2	164.8	3-3-2-2	344.1
2-2-1-3	24.1	2-2-1-1	929.2	1-3-2-3	1,210.0	1-2-2-1	1,083.9	3-2-1-2	46.3	1-2-1-2	166.6	1-3-3-2	364.1
2-3-2-2	24.1	1-2-2-3	948.2	1-2-2-1	1,233.5	1-3-3-2	1,128.6	2-3-3-1	46.6	2-3-1-3	165.4	3-3-3-1	396.6
1-1-1-2	24.6	2-3-3-2	942.1	3-2-1-3	1,214.1	2-1-1-1	1,230.8	2-2-2-1	69.6	1-2-1-3	202.4	3-2-1-2	411.5
3-2-1-2	24.8	3-3-2-1	977.9	2-1-1-3	1,412.8	1-3-3-3	1,285.9	1-3-2-2	76.2	2-2-3-1	204.7	2-2-1-3	412.3
2-1-1-1	28.5	2-3-3-3	993.2	1-2-2-2	1,432.2	3-2-1-2	1,326.3	3-3-3-1	75.5	1-1-3-1	206.3	2-3-2-3	428.8

Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD
1-2-2-1	32.9	2-2-1-3	1,109.2	3-1-1-1	1,474.5	2-3-2-2	1,424.6	2-1-1-2	84.4	1-2-2-2	222.2	3-3-2-3	555.9
1-1-1-3	33.8	3-3-2-2	1,089.1	2-3-2-1	1,593.3	3-2-1-3	1,513.5	2-2-1-3	83.6	2-3-2-3	220.5	1-1-1-1	529.7
3-2-1-3	35.6	1-2-3-1	1,134.9	1-3-3-2	1,721.8	2-3-2-3	1,623.5	1-1-2-1	97.5	3-3-1-2	233.6	1-2-2-1	571.3
3-3-3-1	35.4	3-3-2-3	1,148.1	1-2-2-3	1,733.8	2-3-3-1	1,629.2	1-1-1-3	109.4	1-2-2-3	269.9	3-2-1-3	580.5
2-3-2-3	36.7	1-2-3-2	1,282.0	3-1-1-2	1,712.7	1-2-2-2	1,703.7	3-2-2-1	110.5	1-2-3-2	277.8	1-3-3-3	616.2
3-3-2-2	37.6	1-1-1-1	1,297.1	2-3-2-2	1,892.4	2-1-1-2	1,823.6	3-1-1-2	127.8	2-3-3-3	275.6	3-3-3-2	717.9
3-1-1-1	39.0	1-2-3-3	1,365.4	3-1-1-3	2,053.1	1-2-2-3	1,945.3	3-2-1-3	133.7	3-2-1-1	281.7	2-1-1-1	905.7
2-1-1-2	41.0	3-3-3-1	1,408.2	1-3-3-3	2,103.8	3-1-1-1	1,993.8	2-2-3-1	169.8	3-3-1-3	303.7	2-2-2-1	890.4
2-3-3-2	43.9	3-2-1-1	1,484.3	1-2-3-1	2,144.6	2-1-1-3	2,085.7	2-3-2-2	168.5	3-3-2-2	311.5	2-3-3-3	894.6
1-2-2-2	49.3	1-1-1-2	1,535.6	1-1-2-1	2,197.6	1-2-3-1	2,275.9	2-1-2-1	185.8	1-2-3-3	337.3	1-1-1-2	946.6
3-1-1-2	56.6	3-3-3-2	1,568.3	2-2-2-1	2,254.0	3-3-2-2	2,464.7	1-3-3-2	185.8	2-1-1-1	360.2	1-2-2-2	1,001.2
2-1-1-3	56.8	1-1-1-3	1,683.6	3-3-2-1	2,278.5	2-2-2-1	2,582.2	2-1-1-3	216.7	3-2-2-1	375.6	3-3-3-3	1,160.0
2-2-2-1	57.1	2-2-2-1	1,659.3	2-3-2-3	2,331.8	3-3-2-3	2,806.9	1-1-3-1	237.8	3-3-3-2	389.4	1-2-3-1	1,192.0
3-3-2-3	57.3	3-3-3-3	1,653.3	1-2-3-2	2,490.1	3-3-3-1	2,785.0	1-3-2-3	263.0	3-3-2-3	405.0	1-1-1-3	1,233.1
1-2-3-1	59.9	3-2-1-2	1,668.5	1-1-2-2	2,529.5	1-1-2-1	2,927.6	3-2-3-1	269.6	3-2-3-1	469.5	3-2-2-1	1,307.5
2-3-3-3	67.0	3-2-1-3	1,769.2	2-2-2-2	2,649.5	3-1-1-2	2,974.0	3-1-2-1	280.5	1-1-1-2	473.6	3-1-1-1	1,414.4
3-3-3-2	68.5	2-2-2-2	1,866.0	3-3-2-2	2,710.7	2-3-3-2	2,991.1	3-3-2-2	275.0	2-1-2-1	480.4	1-2-2-3	1,479.6
1-2-2-3	69.3	2-2-2-3	1,980.6	2-3-3-1	2,770.1	3-1-1-3	3,400.0	3-1-1-3	331.4	2-2-1-2	496.3	2-1-1-2	1,518.9
3-1-1-3	78.5	1-1-2-1	2,401.2	1-2-3-3	3,014.5	2-3-3-3	3,408.8	1-2-2-2	383.6	3-3-3-3	506.2	2-2-2-2	1,549.0
3-2-2-1	83.7	2-2-3-1	2,389.4	1-1-2-3	3,017.7	1-2-3-2	3,577.2	2-3-3-2	411.0	1-1-1-3	534.6	2-2-3-1	1,857.9
1-2-3-2	89.9	2-1-1-1	2,446.9	2-2-2-3	3,233.6	1-2-3-3	4,084.5	2-1-3-1	453.2	2-2-1-3	594.5	2-1-1-3	1,966.5
2-2-2-2	90.0	3-2-2-1	2,650.6	3-2-2-1	3,238.1	2-2-2-2	4,152.4	2-3-2-3	565.4	2-1-3-1	600.5	1-2-3-2	2,089.0
1-1-2-1	93.6	2-2-3-2	2,687.0	2-3-3-2	3,290.2	1-1-2-2	4,272.1	1-3-3-3	641.5	1-1-2-2	631.5	3-2-2-2	2,252.9
2-2-3-1	104.0	1-1-2-2	2,742.1	3-3-2-3	3,337.6	3-2-2-1	4,290.7	3-1-3-1	684.3	2-2-2-2	661.8	2-2-2-3	2,257.4
3-3-3-3	104.4	2-1-1-2	2,782.9	1-1-3-1	3,820.8	2-2-2-3	4,741.4	3-3-3-2	670.9	1-1-2-3	712.8	3-1-1-2	2,368.3
1-2-3-3	126.4	2-2-3-3	2,852.1	3-2-2-2	3,810.8	1-1-2-3	4,886.2	2-2-2-2	835.3	1-1-3-2	789.3	3-2-3-1	2,728.2
2-2-2-3	128.8	1-1-2-3	3,006.3	2-1-2-1	3,878.3	3-3-3-2	5,174.9	1-2-3-2	935.7	2-2-2-3	792.8	3-1-1-3	3,029.9
1-1-2-2	131.7	2-1-1-3	3,028.9	2-2-3-1	3,919.0	2-2-3-1	5,421.7	3-3-2-3	920.4	2-2-3-2	827.2	1-1-2-1	3,082.8
3-2-2-2	132.7	3-2-2-2	2,979.4	3-3-3-1	3,961.5	3-3-3-3	5,893.4	1-2-2-3	1,112.3	1-1-3-3	891.0	1-2-3-3	3,087.2

Flathead catfish		White bass		Striped bass		Walleye		Largemouth bass		Blue catfish		White crappie	
Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD	Population parameters	Required GZD
3-2-3-1	152.6	1-1-3-1	3,457.8	1-1-3-2	4,398.0	2-1-2-1	6,469.6	3-2-2-2	1,329.6	2-2-3-3	991.0	2-2-3-2	3,232.0
2-2-3-2	164.1	3-1-1-1	3,701.4	2-1-2-2	4,502.3	3-2-2-2	6,971.7	2-3-3-3	1,379.1	3-2-1-2	1,106.9	3-2-3-2	4,700.8
1-1-3-1	170.7	3-2-3-1	3,816.8	2-2-3-2	4,606.6	3-2-2-3	7,955.4	2-2-3-2	2,037.5	3-1-2-1	1,264.3	2-2-3-3	4,710.1
1-1-2-3	180.6	1-1-3-2	3,948.6	3-2-2-3	4,645.7	2-2-3-2	8,718.5	3-3-3-3	2,245.2	3-2-1-3	1,287.8	2-1-2-1	4,959.3
3-2-2-3	190.3	3-1-1-2	4,208.1	3-3-3-2	4,713.0	1-1-3-2	8,969.9	2-1-2-2	2,422.8	2-1-1-2	1,375.7	1-1-2-2	5,183.0
3-1-2-1	208.6	1-1-3-3	4,329.1	1-1-3-3	5,246.8	3-2-3-1	9,008.9	2-2-2-3	2,397.6	3-2-2-2	1,476.1	1-1-3-1	6,432.2
2-1-2-2	219.4	3-2-3-2	4,290.3	2-1-2-3	5,406.1	2-1-2-2	9,585.6	1-2-3-3	2,713.1	2-1-1-3	1,548.3	3-2-3-3	6,632.7
2-2-3-3	234.9	2-1-2-1	4,369.4	2-2-3-3	5,622.1	2-2-3-3	9,955.1	1-1-3-2	3,018.2	3-1-3-1	1,580.4	1-1-2-3	6,752.0
1-1-3-2	240.2	3-1-1-3	4,566.3	3-1-2-1	5,642.1	1-1-3-3	10,259.2	1-1-2-3	3,139.0	3-2-2-3	1,717.2	3-1-2-1	7,744.4
3-2-3-2	242.0	3-2-3-3	4,549.3	3-2-3-1	5,630.0	3-1-2-1	10,480.3	3-2-3-2	3,243.3	2-1-2-2	1,834.4	2-1-2-2	8,317.0
2-1-3-1	277.5	2-1-2-2	4,969.3	3-3-3-3	5,803.1	2-1-2-3	10,963.2	3-1-2-2	3,666.2	3-2-3-2	1,845.0	2-1-3-1	10,347.7
3-1-2-2	302.7	2-1-2-3	5,408.6	3-1-2-2	6,553.5	2-1-3-1	13,604.4	3-2-2-3	3,835.5	2-1-2-3	2,064.5	2-1-2-3	10,767.6
2-1-2-3	303.8	2-1-3-1	6,291.9	3-2-3-2	6,625.7	3-2-3-2	14,638.1	2-1-3-2	5,909.9	3-2-3-3	2,146.5	1-1-3-2	10,814.4
1-1-3-3	329.3	3-1-2-1	6,609.6	2-1-3-1	6,743.2	3-1-2-2	15,632.4	2-2-3-3	5,848.3	2-1-3-2	2,293.0	3-1-2-2	12,967.9
3-2-3-3	347.0	2-1-3-2	7,155.8	2-1-3-2	7,828.0	3-2-3-3	16,703.4	2-1-2-3	6,216.8	2-1-3-3	2,580.6	1-1-3-3	14,088.1
3-1-3-1	380.4	3-1-2-2	7,514.4	3-1-2-3	7,856.1	3-1-2-3	17,871.6	1-1-3-3	7,657.0	3-1-1-2	3,564.5	3-1-3-1	16,158.8
2-1-3-2	400.1	2-1-3-3	7,788.4	3-2-3-3	8,077.3	2-1-3-2	20,126.3	3-1-3-2	8,942.9	3-1-1-3	3,940.0	3-1-2-3	16,590.2
3-1-2-3	420.2	3-1-2-3	8,154.0	2-1-3-3	9,399.5	3-1-3-1	22,004.8	3-2-3-3	9,355.9	3-1-2-2	4,753.1	2-1-3-2	17,353.7
3-1-3-2	552.0	3-1-3-1	9,517.8	3-1-3-1	9,809.7	2-1-3-3	23,018.7	3-1-2-3	9,508.4	3-1-2-3	5,253.8	2-1-3-3	22,466.7
2-1-3-3	553.9	3-1-3-2	10,820.6	3-1-3-2	11,394.4	3-1-3-2	32,822.4	2-1-3-3	15,164.4	3-1-3-2	5,941.3	3-1-3-2	27,057.9
3-1-3-3	766.1	3-1-3-3	11,741.8	3-1-3-3	13,659.2	3-1-3-3	37,523.9	3-1-3-3	23,193.4	3-1-3-3	6,567.1	3-1-3-3	34,615.9

TABLE 15.—Comparison of estimated annual gizzard shad consumption (kg/ha) in current study with those estimated in Norris Reservoir, TN (Raborn et al. 2002; Raborn et al. 2007) and Smith Mountain Lake, VA (Cyterski et al. 2002). Population parameters were categorized from data provided in referenced publications to match the current study's ranking system where parameters were numerically coded in order as growth-mortality-initial population size-percent by weight gizzard shad; low (1), medium (2), and high (3) parameters corresponded with the 10th percentile, mean, and 90th percentile of published values for each piscivore species.

	Original study consumption estimate	Input parameter coding	Current study consumption estimate
Norris Reservoir, TN			
Largemouth bass	23	(2-3-3-3)	19
Striped bass	49	(3-3-2-3)	46
Walleye	38	(3-1-1-3)	38
Smith Mountain Lake, VA			
Largemouth bass	23	(3-2-2-2)	19
Striped bass	49	(1-1-2-1) – (2-1-2-1)	28 – 49

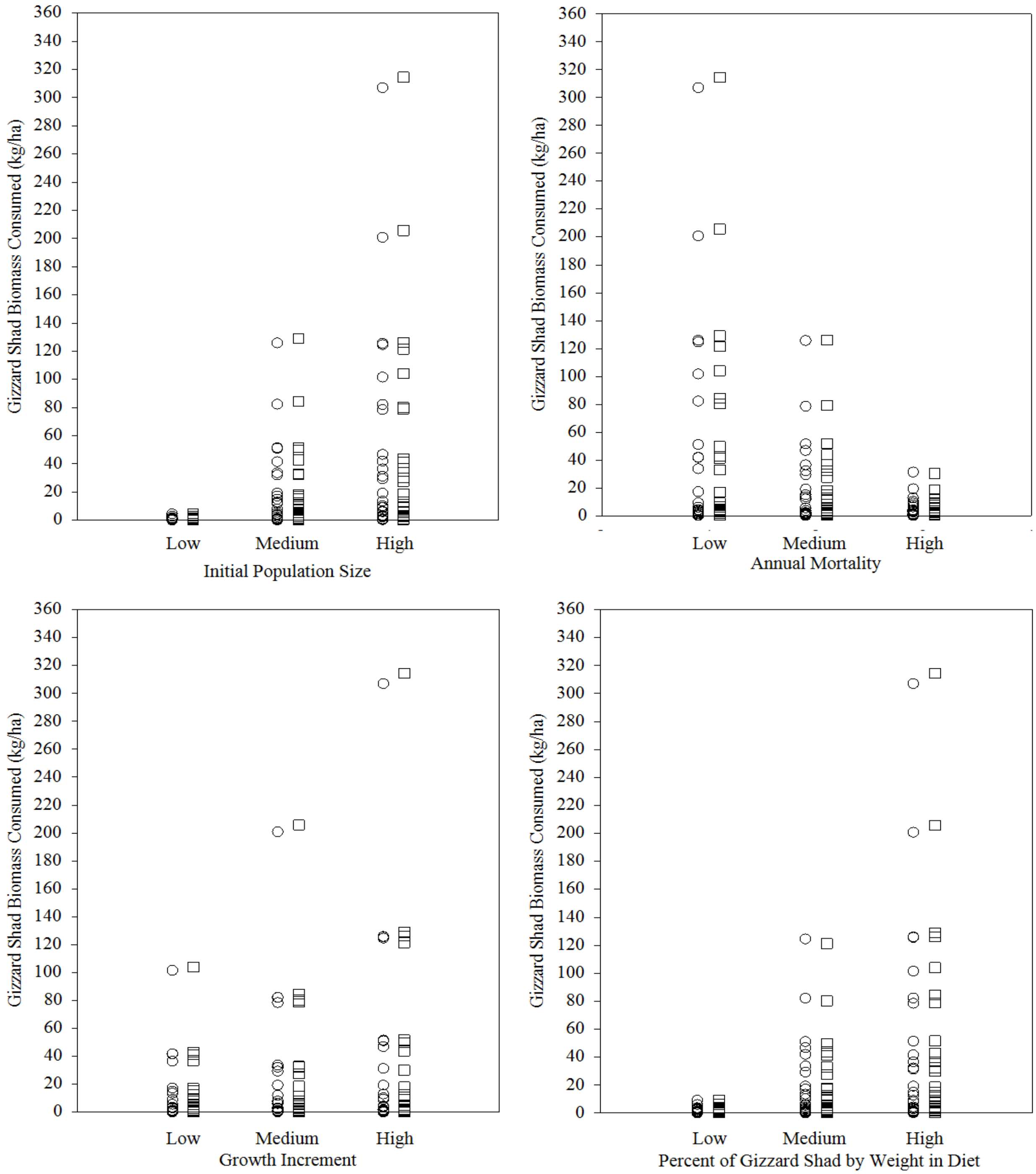

FIGURE 1.— Effect of individual input parameters on gizzard shad consumption by Largemouth bass; cool temperature simulations (circles), warm temperature simulations (squares). Low, medium, and high parameters corresponded with the 10th, average, and 90th percentiles of published values.

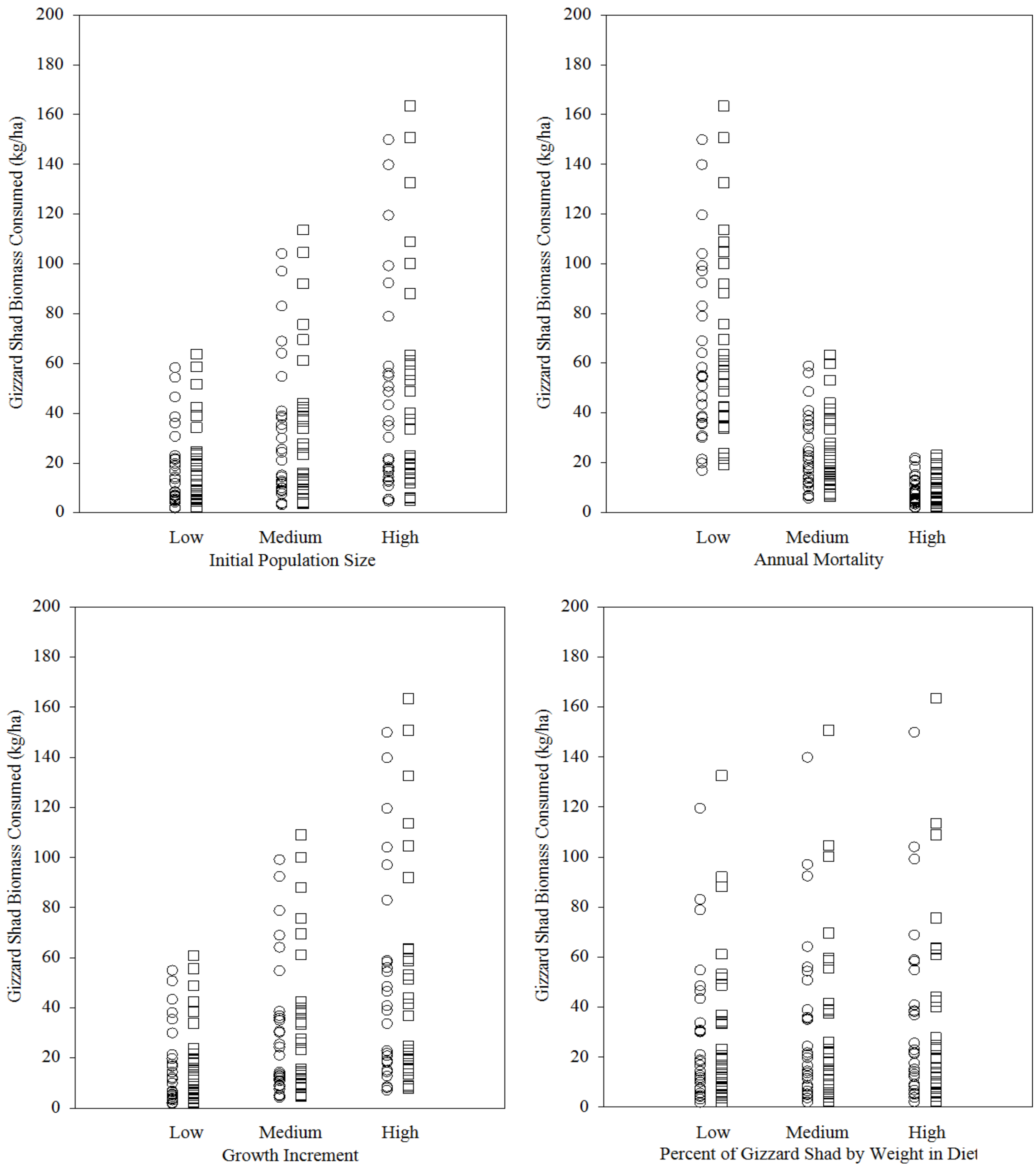

FIGURE 2.—Effect of individual input parameters on gizzard shad consumption by white bass; cool temperature simulations (circles), warm temperature simulations (squares). Low, medium, and high parameters corresponded with the 10th, average, and 90th percentiles of published values.

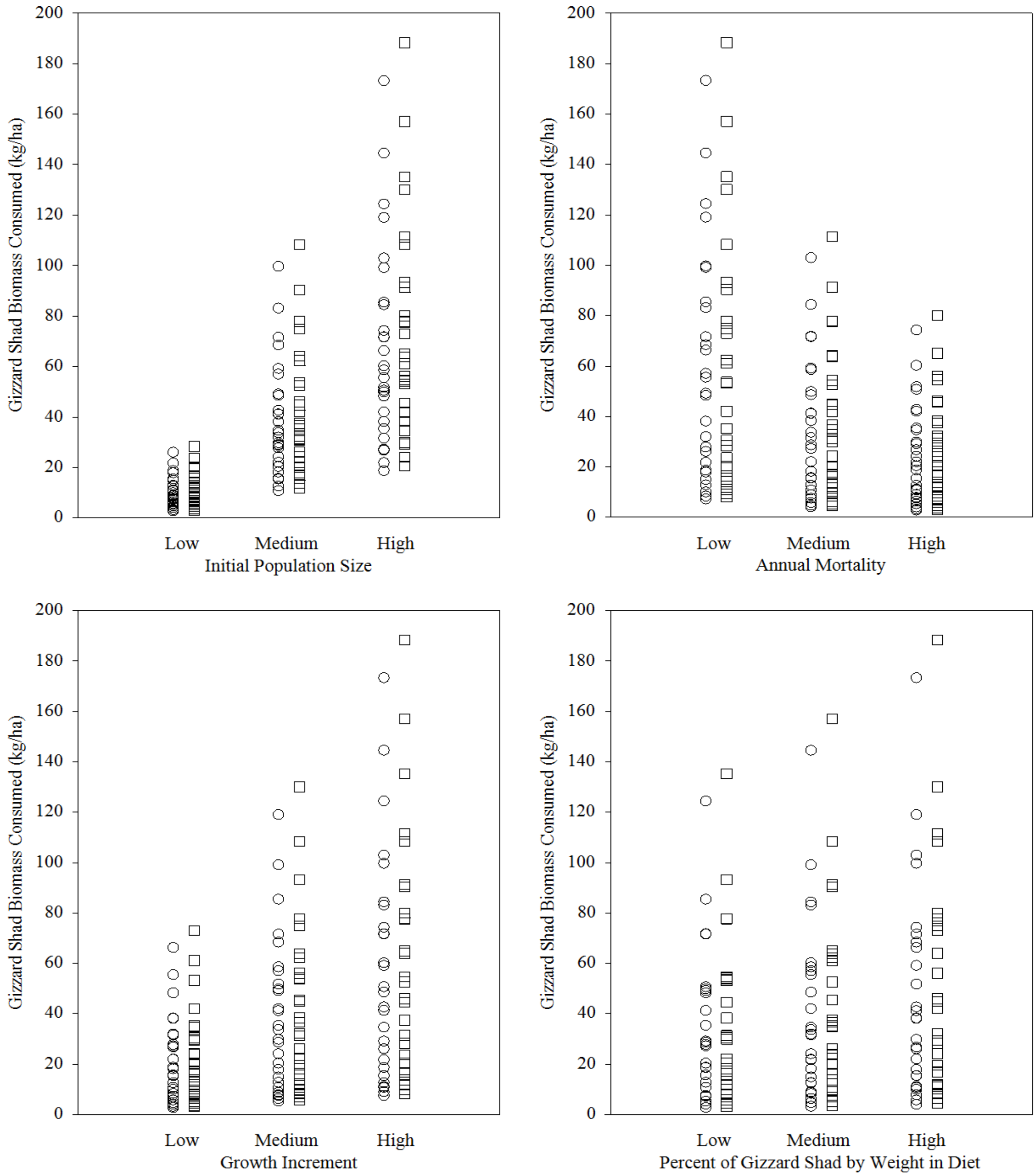

FIGURE 3.—Effect of individual input parameters on gizzard shad consumption by striped bass; cool temperature simulations (circles), warm temperature simulations (squares). Low, medium, and high parameters corresponded with the 10th, average, and 90th percentiles of published values.

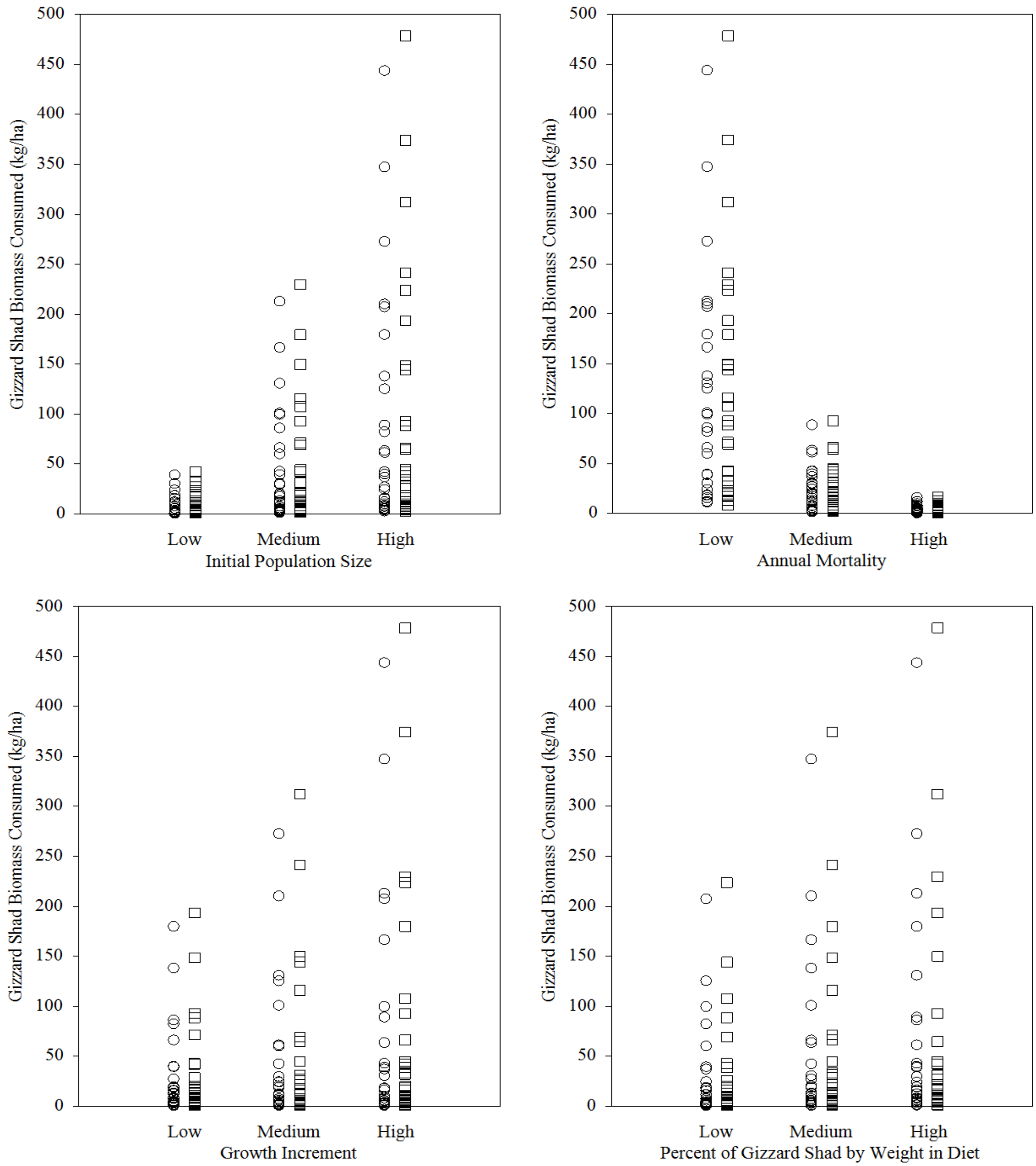

FIGURE 4.—Effect of individual input parameters on gizzard shad consumption by white crappie; cool temperature simulations (circles), warm temperature simulations (squares). Low, medium, and high parameters corresponded with the 10th, average, and 90th percentiles of published values.

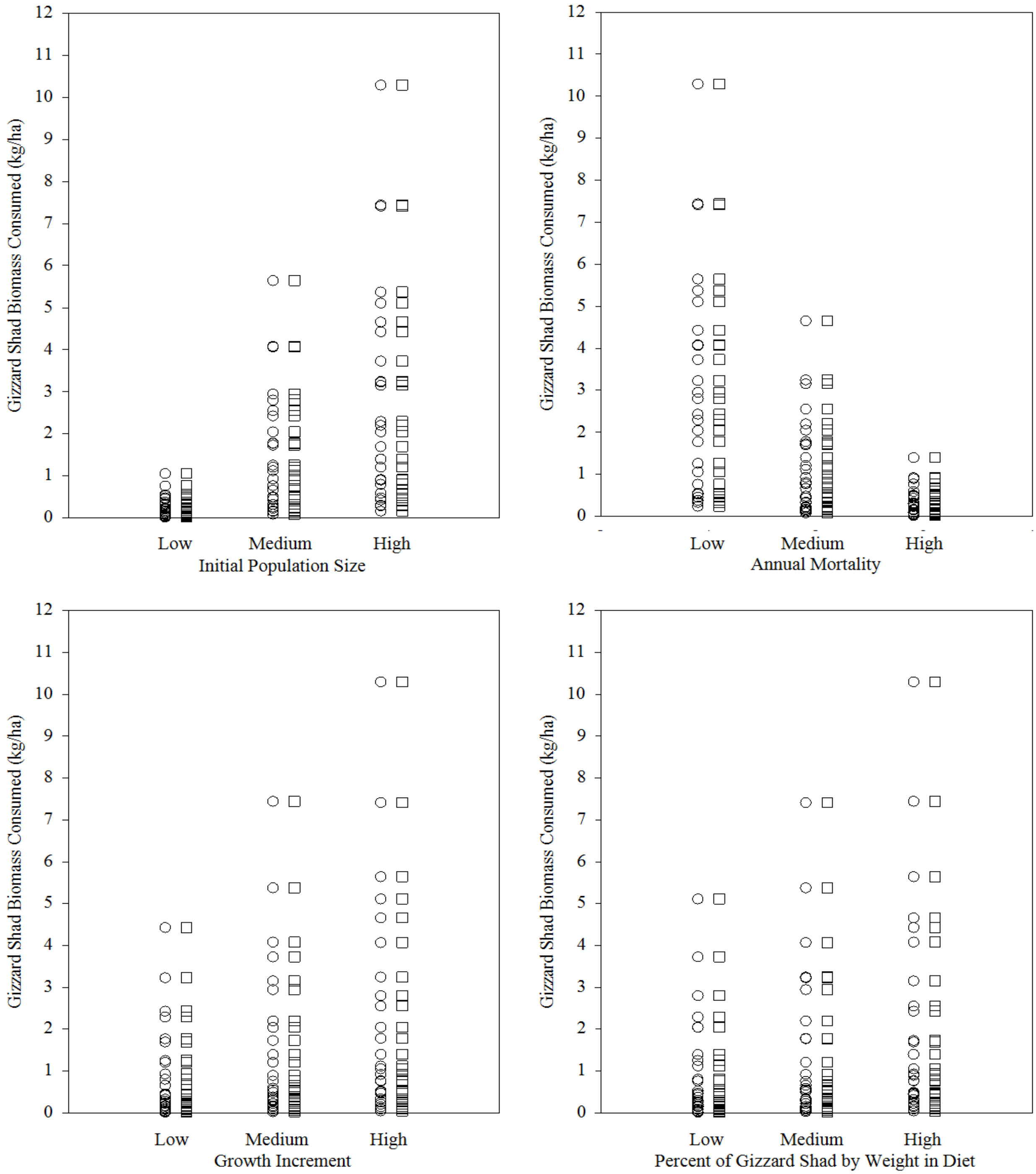

FIGURE 5.—Effect of individual input parameters on gizzard shad consumption by flathead catfish; cool temperature simulations (circles), warm temperature simulations (squares). Low, medium, and high parameters corresponded with the 10th, average, and 90th percentiles of published values.

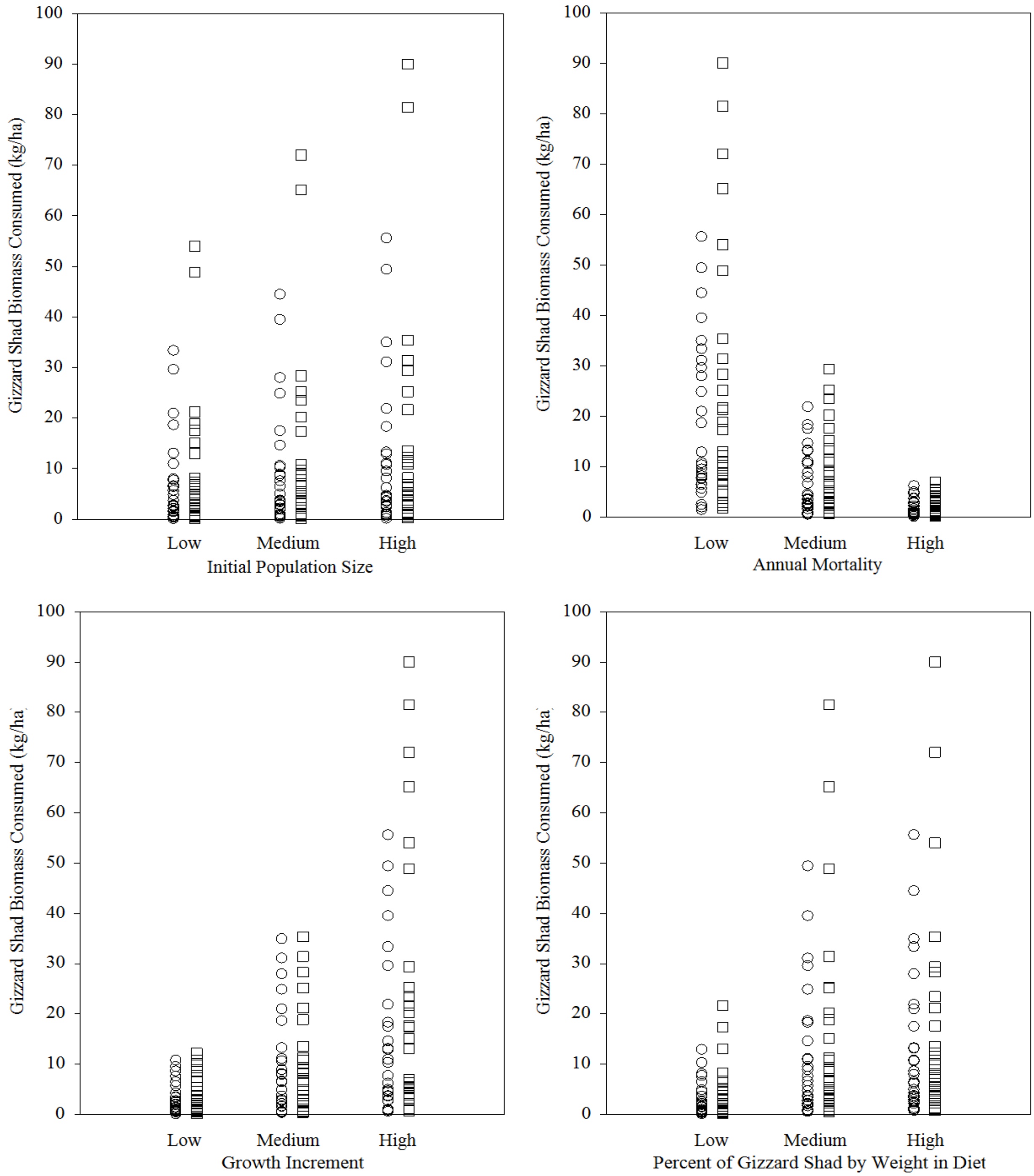

FIGURE 6.—Effect of individual input parameters on gizzard shad consumption by blue catfish; cool temperature simulations (circles), warm temperature simulations (squares). Low, medium, and high parameters corresponded with the 10th, average, and 90th percentiles of published values.

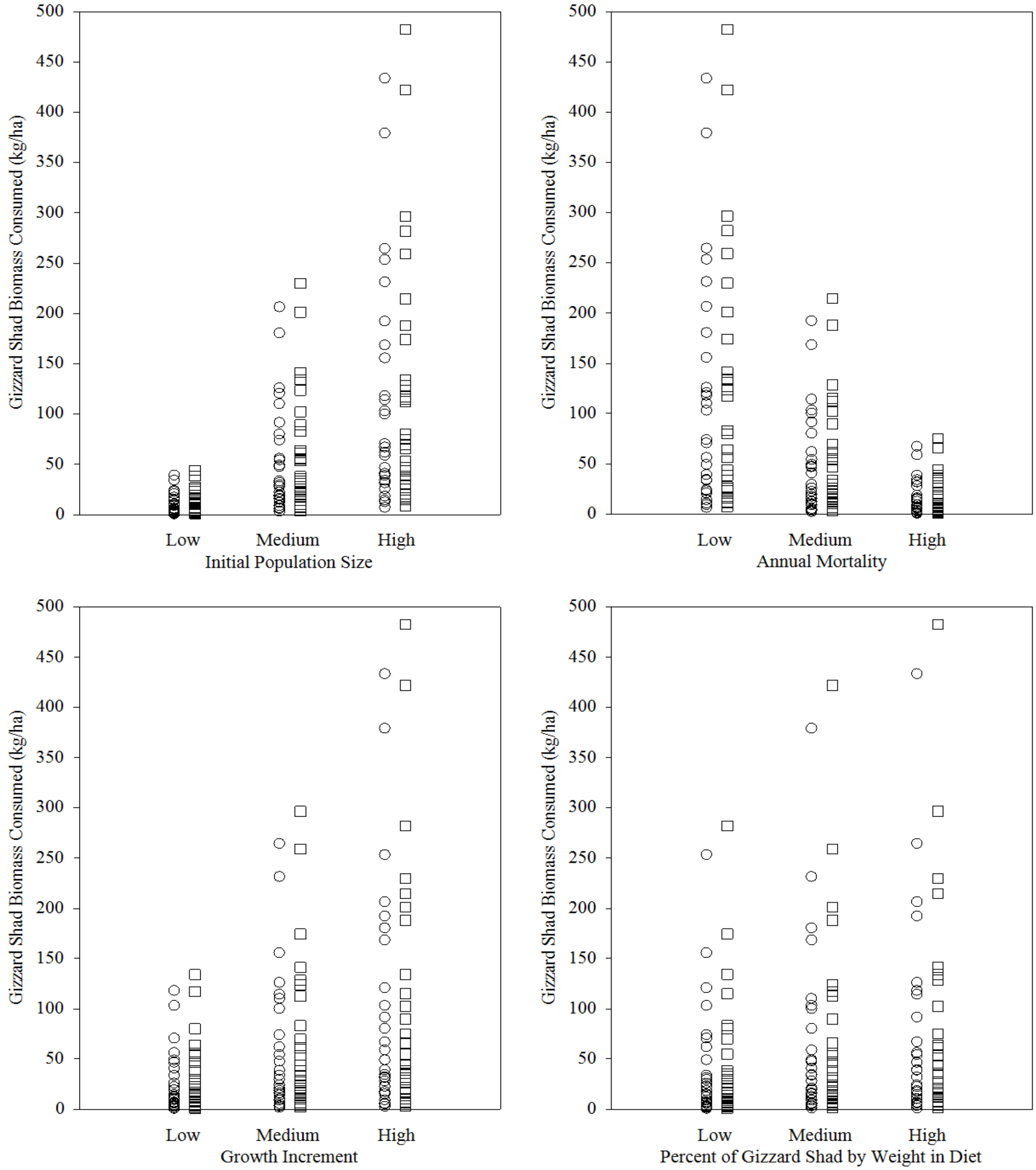

FIGURE 7.—Effect of individual input parameters on gizzard shad consumption by walleye; cool temperature simulations (circles), warm temperature simulations (squares). Low, medium, and high parameters corresponded with the 10th, average, and 90th percentiles of published values.

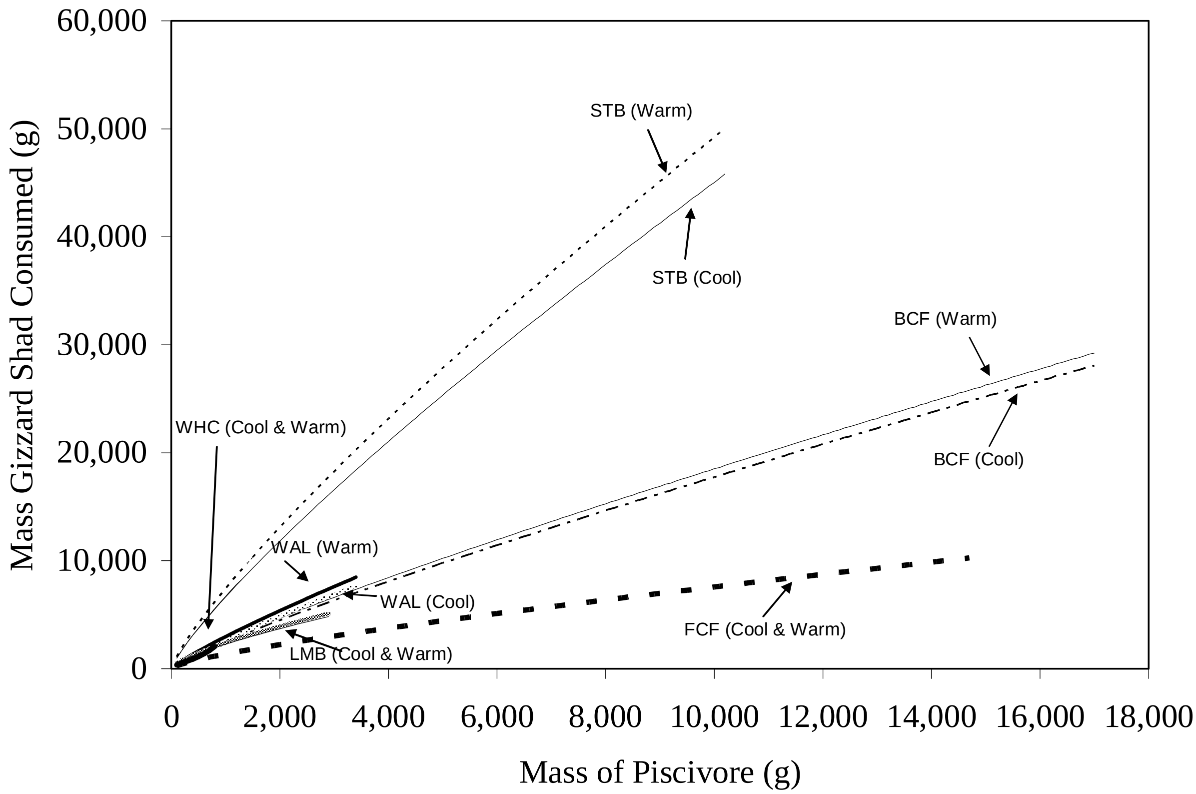

FIGURE 8.—Effect of the species models on mass-specific gizzard shad consumption under two temperature regimes. All species were modeled as 100-g cohorts, cohort size = 1, no mortality, 100% gizzard shad diet. Maximum mass of individual species was determined using published mass-transformed mean length-at-age data; LMB = largemouth bass, STB = striped bass, BCF = blue catfish, WHC = white crappie, WAL = walleye, FCF = flathead catfish. White bass line trajectory is equal to that of the lower portion of striped bass.

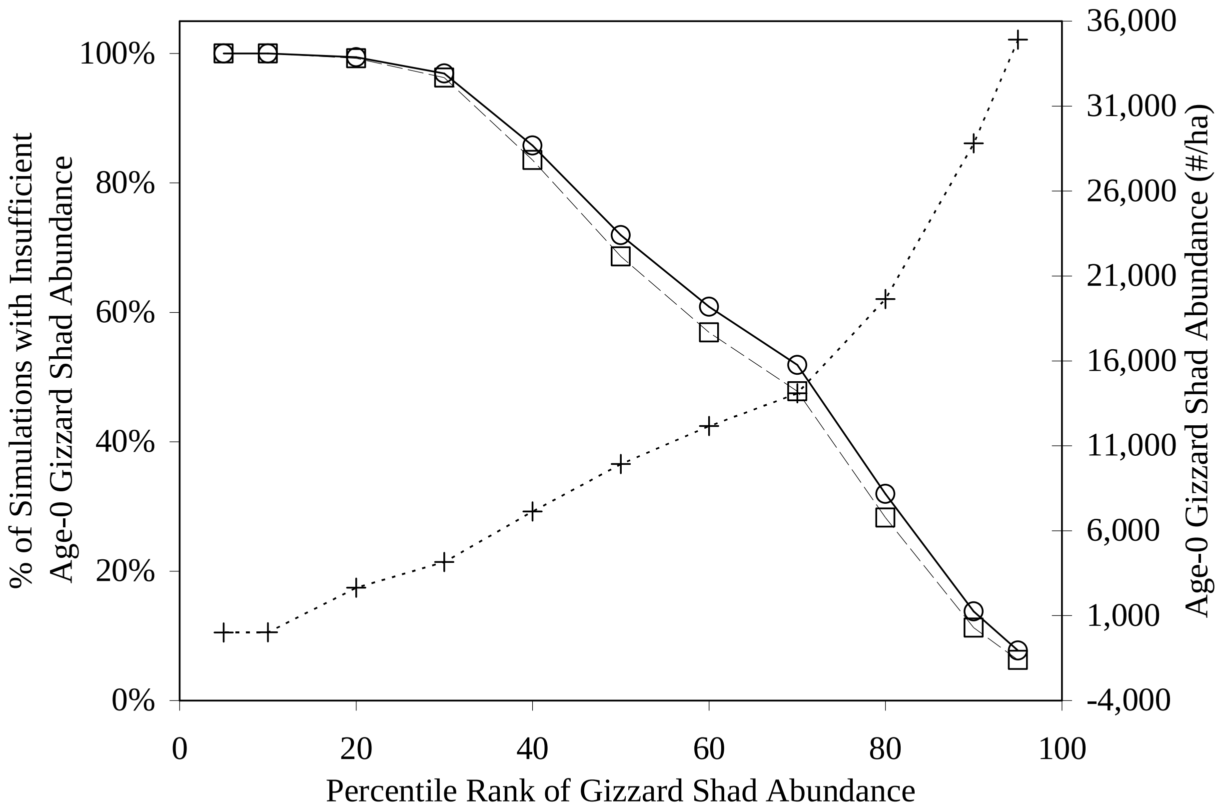

FIGURE 9.—Percent unsuccessful Monte Carlo simulations for cool (squares and dashed line) and warm temperature regime (circles and solid line) and published late summer age-0 gizzard shad biomass (crosses and dotted line) at different shad abundances (percentiles of values from published literature).

VITA

Nathan Thomas Evans

Candidate for the Degree of

Master of Science

Thesis: AGE-0 GIZZARD SHAD PREY SUPPLY AND PREDATOR DEMAND: ANALYSIS OF THE TROPHIC SUPPORT CAPACITY OF SOUTHERN U.S. RESERVOIRS

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Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: AGE-0 GIZZARD SHAD PREY SUPPLY AND PREDATOR DEMAND: ANALYSIS OF THE TROPHIC SUPPORT CAPACITY OF SOUTHERN U.S. RESERVOIRS

Pages in Study: 98 Candidate for the Degree of Master of Science

Major Field: Natural Resource Ecology and Management

Scope and Method of Study:

Gizzard shad *Dorosoma cepedianum*, the primary prey in many lakes and reservoirs of the southern U.S., often comprise a majority of the prey biomass in the systems in which they are found. However, they rapidly grow to a size that surpasses the preferred prey sizes of most piscivores. Lakes and reservoirs may, therefore, be prey limited if age-0 gizzard shad abundances are low. Previous studies have not considered the effect of the prey supply of age-0 gizzard shad on the entire piscivore community in a reservoir or the effect of age-0 gizzard shad availability on the growth and condition of piscivores in reservoirs. This study used bioenergetics modeling and Monte Carlo simulations to quantify the abundance of age-0 gizzard shad necessary to sustain seven sport fish, common to the southern U.S., at diverse growth rates, population sizes, mortality rates, and proportions of gizzard shad diets.

Findings and Conclusions:

The potential for gizzard shad prey resource limitation in reservoirs of the southern U.S. is high according to the performed simulations. Annual necessary gizzard shad abundance (accounting for non-predation mortality and reproductive surplus required for prey sustainability) estimates ranged from < 10/ha/piscivore population to > 128,000/ha/piscivore population. Monte Carlo simulations indicated insufficient gizzard shad abundance, required to support piscivores, at the 50^{th} percentile of published age-0 gizzard shad abundances ≥ 69% of the time. The findings of this study support the hypothesis that systems must have high prey resource availability if they are to support diverse sport fish communities with high-condition and abundance.

ADVISER'S APPROVAL: Dr. Daniel E. Shoup