



Figure 1: Life cycle diagram and census points for pre-reproduction census of gizzard shad.

1 Graphical Abstract

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3 **density-dependent age-0 survival**

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Highlights

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- Research highlight 1

- Research highlight 2

An integral projection model for gizzard shad (*Dorosoma cepedianum*) utilizing density-dependent age-0 survival

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Abstract

Gizzard shad (*Dorosoma cepedianum*) are a common freshwater fish throughout the central and eastern portions of North America. Within these areas, gizzard shad play a number of critical roles in the freshwater community. Because of this, it is important that we understand how gizzard shad populations respond to environmental changes and what these changes may mean for aquatic communities in general and fish assemblages in particular. Here we introduce an integral projection model for gizzard shad based on empirical data and include density-dependent survival in age-0 fish. Integral projection models (IPM) are a generalization of stage-based, matrix population models that have been used to describe a wide range of organisms. IPMs are a natural choice for gizzard shad since many aspects of their life cycle have been studied. In this paper, we compared model outcomes to empirical patterns reported for this fish species at a key location along the Illinois River. Results of our work suggest that this model could serve as an important tool for predicting gizzard shad population responses to changing environmental conditions, including those mediated through species invasions.

Keywords: population dynamics, fisheries, Mississippi River basin, population ecology, invasive species impact

1. Introduction

Gizzard shad (*Dorosoma cepedianum*) is a laterally compressed, deep-bodied fish species that occupies numerous aquatic systems throughout central, southern and eastern regions of the United States (Pierce et al., 1981; Vanni et al., 2005). In more eutrophic habitats,

such as reservoirs, gizzard shad can reach high abundances and can come to dominate fish assemblages. Because of this, gizzard shad have the potential to influence freshwater systems in a number of ways. First, young shad often serve as a critical food source for many fish species, including those of commercial and recreational importance (such as walleye and largemouth bass)(Jester et al., 1972). Thus, this species can serve as an important trophic link within aquatic food webs. Second, because detritus can serve as a primary food source throughout much of gizzard shad development (i.e. from the age-0 stage onward), these fish can transport nutrients from benthic regions into pelagic habitats (Mather et al., 1995; Schaus and Vanni, 2000; Vanni et al., 2005). This process can result in an increase in the nutrients available to organisms within the water column leading to increases in phytoplankton biomass, algal blooms, and, due to these conditions, shifts in freshwater community structure (Aday et al., 2003; Schaus and Vanni, 2000). Finally, the fact that detritus can comprise a substantial portion of gizzard shad diet also makes this species an important connector between terrestrial inputs and aquatic processes (Schaus and Vanni, 2000). Given its potentially important role in aquatic ecosystems, interest has intensified in understanding how gizzard shad populations respond to environmental changes (both natural and anthropogenic) and what these changes may mean for freshwater communities in general and fish assemblages in particular.

Interactions within and between species in interconnected environments can have important consequences for fish populations across space and time (Thorp et al., 2006). For gizzard shad, previous work has suggested that fish densities can play an important role in the length-distribution patterns observed in populations. For example, (Buynak et al., 1992) and (Welker et al., 1994) reported inverse relationships between densities and lengths in age-0 gizzard shad under both field and semi-natural conditions. These patterns were attributed to intraspecific competition among young shad for prey (zooplankton) resources. Although intraspecific competition may be occurring in subsequent stages of gizzard shad development, little work has actually been conducted to address this (DiCenzo et al., 1996). There is also evidence that the densities of other co-occurring fish species (such as invasive carps) can negatively influence aspects of gizzard shad biology, such as body condition (Irons et al., 2007; Love et al., 2018).

Although substantial empirical work on gizzard shad biology has accumulated over the decades, few if any studies have attempted to use these data to model the population dynamics of the gizzard shad. Work by Catalano and Allen (2010, 2011) used empirically-based simulations of gizzard shad and focused on population-level responses. This work did examine population-structure by examining length and did not explore different sources of density feedback on the population dynamics. Here, we introduce an integral projection model for gizzard shad based on empirical data with density-dependent survival in age-0 fish. We then compare model outcomes to dynamics reported for this fish species in the La Grange Station along the Illinois River. The model itself could be an important tool for predicting gizzard shad population responses to changing environmental conditions, including those mediated through species invasions (i.e., silver and bighead carp).

2. Model Development

2.1. Gizzard shad life history

Mating within this species can be temperature-dependent, but tends to occur between May and June. Males and females aggregate and then broadcast gametes into the surrounding water; fertilized eggs then settle and adhere to the bottom substrates. After a period of days, eggs hatch and fish develop from the larval stage to juveniles and eventually to adults. In many habitats, individuals can reach sexual maturity within a year. As gizzard shad mature, their diet preferences typically shift from phytoplankton and zooplankton early in development to detritus and zooplankton as adults. Given the large number of eggs produced by shad females ($> 300,000/\text{year}$), there is evidence that intraspecific competition can be intense during early developmental stages in this species. However, the strength of competition can subside as fish transition to different food types during latter stages of development.

2.2. Equations

We used an integral projection model to describe the life history of gizzard shad in the Upper Mississippi River (UMR) system. Integral projection models (IPM) were introduced by Easterling (Easterling et al., 2000), as a generalization of stage-based, matrix population

Table 1: A summary of parameters, their biological meaning, and source for mean values.

Parameter	Meaning (units)	Mean	Source
Logistic survival probability function, $s(z)$			
s_{\min}	minimum survival	0.002	(Bodola, 1955)
s_{\max}	maximum survival	$1 - 8.871K^{0.73}L_{\infty}^{-0.33}$	THEN 2015
α_s	inflection point	104.34	Estimated from LTRM dataset
β_s	slope	-637.93	Estimated from LTRM dataset
Growth function, $G(z, z')$			
L_{∞}	maximum length (in mm)	394.30	(Catalano and Allen, 2010)
K_g	growth rate	0.26	(Michaletz, 2017)
σ_g	growth standard deviation	25	(Michaletz, 2017)
Normal distribution of length of age-1, $C_1(z')$			
μ_r	mean length of recruitment (in mm)	105	(Michaletz, 2017)
σ_r	standard deviation of length	25	(Michaletz, 2017)
Eggs produced, $\text{egg}(z)$			
egg_{\max}	maximum number of eggs produced	742,094	Estimated from (Jons and Miranda, 1997)
α_e	inflection point	314.44	Estimated from (Jons and Miranda, 1997)
β_e	slope	-7.12	Estimated from (Jons and Miranda, 1997)
Survival of age-0, $s_0(d(t))$			
a_0	intercept	0.27	Estimated from (Michaletz, 2010)
b_0	decay rate	0.003	Estimated from (Michaletz, 2010)
Spawning			
ν	probability that egg becomes viable	0.002	(Bodola, 1955)
p_b	probability that female spawns	0.90	

models. IPMs have been used to describe a wide range of organisms (Ellner et al., 2016; Merow et al., 2014; Rees et al., 2014) and have only recently be used to model fish populations (Erickson et al., 2017; Liao et al., 2019; White et al., 2016; Pollesch et al., 2022). The availability of empirical size observation to aid with model parameterization makes IPM a natural choice for gizzard shad since many aspects of their life cycle have been studied. Specifically, functions used in our model incorporate data from studies on egg production and adult size, survival of the age-0 stage and density, and nearly thirty years of length measurements in the main channel of the Upper Mississippi River system.

We assumed that variations among individual gizzard shad can be summarized by its length z (in mm) ranging from the minimum possible length L to the maximum value U . The state of the population at time t (in years) is described by the length distribution $n(z, t)$. Specifically, for each time t , $n(z, t)$ is a smooth function of z such that the number of individuals of length z in the interval $[a, b]$ at time t is $\int_a^b n(z, t) dz$.

Between times t and $t + 1$, individual gizzard shad may grow, die, and produce offspring that vary in length depending on the individuals current length (Figure ??). At time $t + 1$ the population will have a length distribution defined by $n(z, t + 1)$. For our model, we partition the life cycle of gizzard shad into two stages: 1) survival and growth, and 2) reproduction. For an individual of length z at time t , $P(z', z)\Delta z$ is the probability that the individual is alive at time $t + 1$, and its size is in the interval $[z', z' + \Delta z]$ (as with $n(z, t)$ this is an approximation that is valid for small Δz , and the exact probability is given by an integral like the one above). Similarly, $F(z', z)\Delta z$ is the number of new offspring in the interval $[z', z' + \Delta z]$ present at time $t + 1$, per length- z individual at time t .

2.2.1. Growth and survival

We define $P(z'z) = s(z, T)G(z', z)$ where $s(z)$ is the adult annual survival probability and $G(z', z)$ describes the annual length transitions. We assumed that the survival function is a logistic function,

$$s(z, T) = s_{\min} + \frac{s_{\max} - s_{\min}}{1 + e^{\beta_s(\ln(z) - \ln(\alpha_s))}}. \quad (1)$$

with four parameters: the minimum survival rate s_{\min} ; a maximum survival rate, s_{\max} ; and intercept parameter, α_s ; and a slope parameter, β_s (Bolker, 2008).

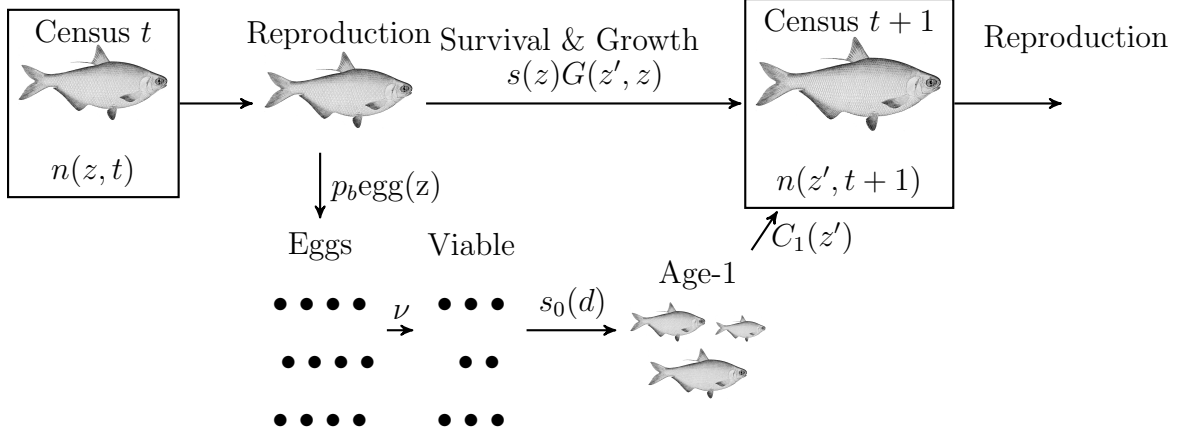


Figure 2: Life cycle diagram and census points for pre-reproduction census of gizzard shad.

We assumed that the growth function is a two-variable normal distribution centered around a modified von Bertalanffy function of the length at time t . The von Bertalanffy equation, commonly used to describe the length of a fish over time, is given by $z(t) = L_\infty (1 - e^{-K(t-t_0)})$ where L_∞ is maximum asymptotic length, K is the growth rate, and t_0 is the initial time. The expected length in the next year

$$\begin{aligned} z' = z(t+1) &= L_\infty (1 - e^{-K(t+1-t_0)}) = L_\infty - L_\infty e^{-K(t-t_0)} e^{-K} \\ &= L_\infty - (z(t) - L_\infty) e^{-K} = L_\infty (1 - e^{-K}) + z(t) e^{-K}. \end{aligned}$$

Consequently, we assumed that $G(z', z) = \text{Prob}(z' | z, L_\infty, K_g) = \text{NormalPDF}(\mu_g, \sigma_g)$ where K_g is the individual growth rate, $\mu_g = L_\infty (1 - e^{-K_g}) + z(t) e^{-K_g}$, and σ_g is the standard deviation.

2.3. Fecundity

We define the fecundity kernel,

$$F(z', z) = p_b \text{egg}(z) \nu s_0(n(z, t)) C_1(z') \quad (2)$$

where p_b is the probability of reproducing, $\text{egg}(z)$ is the mean number of eggs produced, ν is the probability that an egg is viable, $s_0(n(z, t))$ is the density-dependent probability of surviving to age-1, and $C_1(z')$ is the length distribution of new recruits at age-1 (when they are first censused).

We assumed that the mean number of eggs produced by females of a certain length is a three-parameter logistic function,

$$\text{egg}(z) = \frac{\text{egg}_{\max}}{1 + e^{\beta_e(\ln(z) - \ln(\alpha_e))}}. \quad (3)$$

The probability of survival of gizzard shad during their first year may depend on many factors (Michaletz, 2010) such as mean temperature, mean total length, the present density of age-0 fish. In this study, we focus only on the density factor and define the probability of survival of age-0 fish as the exponential function

$$s_0(d(t)) = a_0 e^{-b_0 d(t)} \quad (4)$$

where a_0 is the intercept, b_0 the decay rate, and $d(t)$ is the density at time t of age-0 gizzard shad per 1000 m³,

$$d(t) = 10^{-3} \int_L^U p_b \text{egg}(z) \nu n(z, t) dz.$$

Finally, after computing the total number of viable eggs produced and survive to age-1 fish, we multiplied this number with a normal distribution of length, $C_1(z') = \text{NormalPDF}(\mu_r, \sigma_r)$ where μ_r is the mean length of age-1 gizzard shad and σ_r is the standard deviation.

2.4. Dynamical Model

The population at time $t + 1$ is the sum of the contributions from each individual alive at time t ,

$$n(z', t + 1) = \int_L^U K(z', z) n(z, t) dz, \quad (5)$$

where $K(z', z) = s(z)G(z', z) + F(z', z)$ and $[L, U]$ is the range of all possible lengths.

3. Methods

3.1. Study Area and LTRMP Data Collection

The 129 km long La Grange Reach is located between La Grange Lock and Dam (L&D) and Peoria L&D on the Illinois River, U.S., and is about midway between the Mississippi River and Lake Michigan. The Illinois River is a major tributary of the Mississippi River, draining nearly two-thirds of the state of Illinois. Along with the main channel of the UMR,

the fish community of La Grange Reach has been monitored by the Long-term Resource Monitoring Program (LTRMP) from 1990 to the present, with approximately 500 random collections each year from 15 June to 31 October. The LTRMP fish collection methodology included a multiple gear approach (netting and electrofishing) to monitor the general fish community of the UMR system through time (Gutreuter et al., 1995). The total lengths were recorded for all fishes captured. Methodology, protocols and modifications to the LTRMP can be found in Gutreuter et al. (1995), and Ickes and Burkhardt (2002).

The location of La Grange Reach has two important features motivation its choice for the methods of our study. First, we parameterized the IPM using data from the main channel of the UMR. As a part of Illinois River and UMR, La Grange Reach is upstream from the main channel (should we include figure/map?). The proximity to, but relative independence from, the main channel, made it a good choice. Secondly, La Grange Reach is a large pool between the main channel of the Mississippi River and Lake Michigan. In recent years, there have been concerns with the threatening introduction of invasive carp to the Great Lakes. Consequently, the impact of invasive carp on the native fish populations in the pools leading to the Great Lakes have received an elevated level of attention. Understanding the population dynamics of gizzard shad, may in the future make it easier to assess the impacts carp has on native fish populations.

3.2. Parameterization

3.3. Growth and survival of adults

The parameters for the growth function were chosen as the mean values published on a study of gizzard shad located in large impoundments (Michaletz, 2017). The survival rate of adults gizzard shad dependent on their length is not well documented and required us to make some additional modeling assumptions. An investigation of gizzard shad in Lake Eerie (Bodola (1955)) provided the minimum and maximum survival rate of adults.

Based on the observed length distributions of gizzard shad sampled from the main channel of the Mississippi River (Figure ??), we assumed that solutions of our model will exhibit periodic behavior every 8-9 years. We used a least squares method to estimate the α_s and β_s parameters that minimized the total square-distance between the (observed) pre-carp

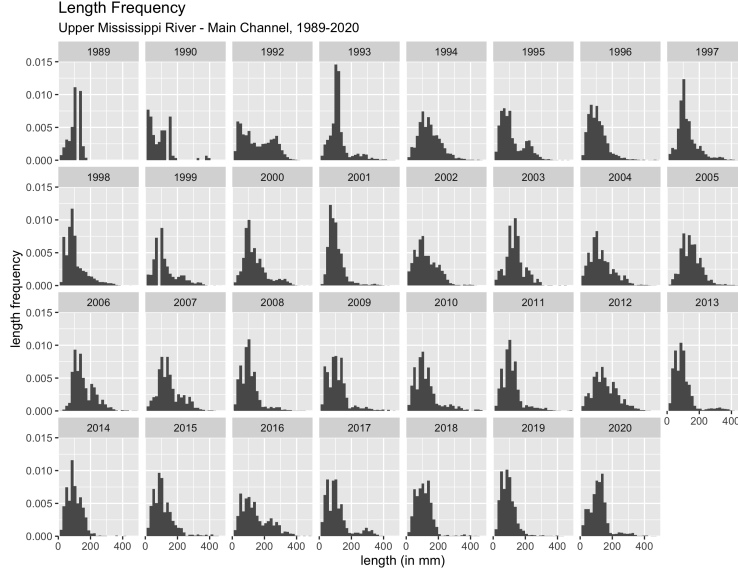


Figure 3: Length frequency of sampled gizzard shad in the main channel of the Upper Mississippi River system.

LTRMP length distribution in the main channels of the UMR (pools 4, 8, 13, 26, and the open river) and (predicted) model equilibrium, $n(z, t)$ during a 8-year period 100 years after initialization. The slope parameter β_s was found to be large in magnitude resulting in a primarily two-valued survival probability. Gizzard shad less than α_s mm in length have a very low survival rate (s_{\min}) while lengths larger than α_s mm have the maximum survival rate s_{\max} . A two-valued survival probability model are common in fisheries model (GREG - CITATIONS)

3.3.1. Fecundity and recruitment

Maturity of female gizzard shad corresponds with lengths of approximately 140 mm and the number of eggs produced increase as the females increase in size (Jons and Miranda, 1997). The logistic parameters for mean number of eggs produced by females of a certain length were obtained by applying fitting a dose-response model to batch fecundity versus length (Jons and Miranda, 1997) (Figure 4a). The survival to age-0 was assumed to be dependent on the density of age-0 gizzard shad (Figure 4b). Parameters for the exponentially decaying age-0 survival function were determined by fitting equation 4 to the survival means for 2003-2007 cohorts of gizzard shard in five Missouri reservoirs (Michaletz, 2010). To

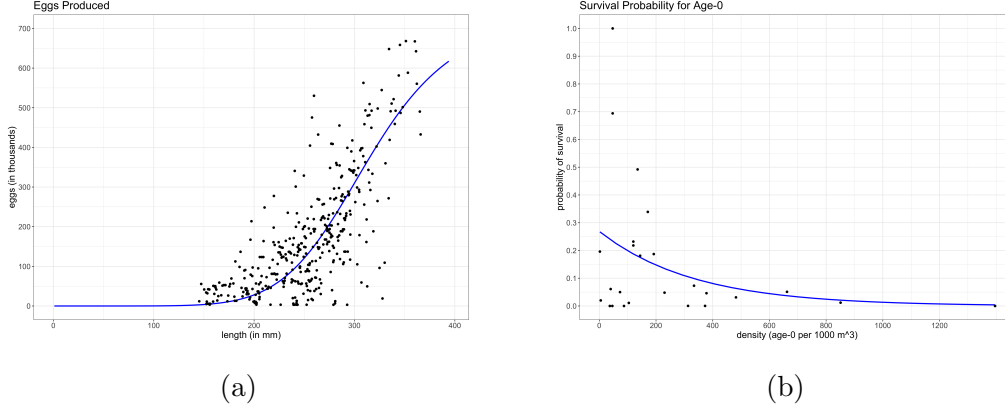


Figure 4: (a) Mean number of eggs produced by female gizzard shad $\text{egg}(z)$. Data from (Jons and Miranda, 1997). (b) Age-0 density-dependent survival function $s_0(d)$. Data from (Michaletz, 2010).

complete the recruitment process we assign a length to the recruited individuals by simulating a Gaussian random variable with mean μ_c and standard deviation σ_c . The parameters for the size distribution of age-1 fish were gleaned from a study of gizzard shad located in large impoundments (Michaletz, 2017) and the historic 1990-2020 LTRMP dataset of gizzard shad in La Grange Reach.

4. Analysis and Results

We numerically solved the integral model using the Midpoint Rule with large approximating matrices (Burden and Faires, 2005). The Midpoint Rule has been commonly used for integral projection models because of its simplicity and effectiveness (Ellner and Rees, 2006; Ramula et al., 2009; Merow et al., 2014). During the course of model development, we explored different step sizes for the Midpoint Rule and found that about 50 points provided numerically stable results. We integrated over lengths from 0 mm to 500 mm. The upper limit was chosen based upon numerical stability and consistency of the system (e.g., avoiding eviction or the loss of individuals due to numerical errors (Williams et al., 2012)).

4.1. Initial conditions

We assumed that the initial density of gizzard shad was $d_0 = 964.7$, the annual average density of gizzard shad observed in La Grange Reach from 1993-2019. The probability of an individual being length z at time $t = 0$ was assumed to be normally distributed with mean

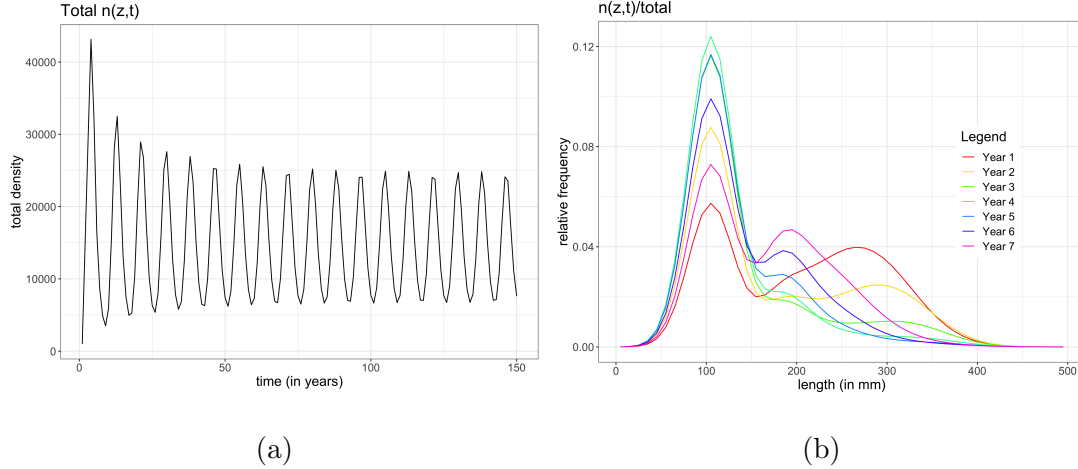


Figure 5: (a) The total number of gizzard shad in La Grange Reach predicted by IPM for first 150 years. (b) Simulated length distributions during an 8 year period of time (approximately 1 period of the total number function)

0.5 L_{∞} and standard deviation $\sigma_0 = 30$ (similar to observations (1990-2020) in LTRMP fish dataset). As a result, we initialized our model with length distribution

$$n(z, 0) = d_0 \text{Norm}(0.5L_{\infty}, \sigma_0) = 964.7 \text{Norm}(166, 30). \quad (6)$$

The model was coded in R (R Core Team, 2017) and the scripts are published on JP github page <https://github.com/jppeirce>.

4.1.1. Periodic orbit and comparison with the LTRMP La Grange dataset

The total number of gizzard shad in our simulation reached a stable periodic orbit (Figure 6a) within 50 years. The length distributions during the periodic orbit (Figure 6b) has similarities to length observations from La Grange found in the LTRMP fish dataset (Figure ??). In addition, the average simulated length distribution compares favorably to the length frequencies of observations from La Grange. (Figure ??). We notice that the peak frequencies are near the same length with the model predicting slightly more adults lengths and fewer juvenile lengths than the observations. This may be explained by gear bias. The methods used to capture fish make it more likely to record longer lengths ($> 200\text{mm}$). Studies [CITATION] suggest that due to the environmental stochasticity and other effects, smaller recruitment fish densities can fluctuate annually and be difficult to measure accurately. While

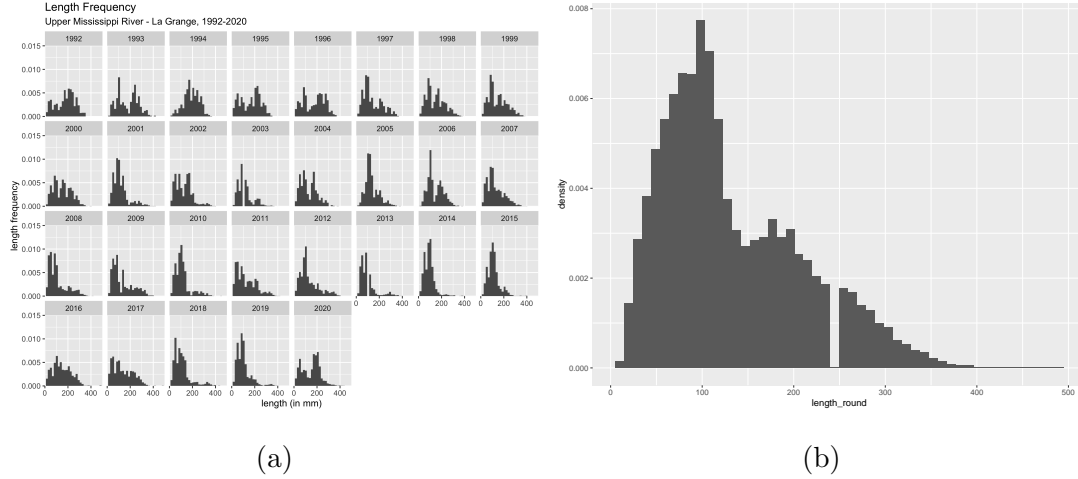


Figure 6: (a) Length frequencies of sampled gizzard shad in La Grange for each year, 1992-2020. (b) Length frequencies of sampled gizzard shad in La Grange from 1992-2020 compared with average (over 1 period) simulated length frequency.

our model uses age-0 density to effect age-0 survival, we assumed constant viability which may be sensitive to the external factors mentioned above. In addition, the location of the maximum length and the variation in the of length of new recruits recorded in the LTRMP data, suggests that there may be smaller age-0 fish in La Grange Reach than in study location (Michaletz, 2017) used to parameterize the model.

4.1.2. Survival and Relative Growth

The dependence on survival of next generation of age-0 fish on the present density of age-0 fish strongly influences the density, at all ages, of gizzard shad within the population. When the fish density is large, there may be more fish at longer lengths and consequently a greater number of eggs produced. More eggs leads to a higher density of age-0 fish and reflectively a reduction in the survival to age-1. If this reduced survival continues for a few years, the overall density of fish may decline and there may not be as many larger fish reproducing. If fewer eggs are spawned, there are less age-0 fish and the reduced density leads to a better survival probability. For these years we would expect the overall density to increase. This cycle of oscillation continues, reflected in our model by the time-dependent survival probability of age-0 recruits(Figure 7).

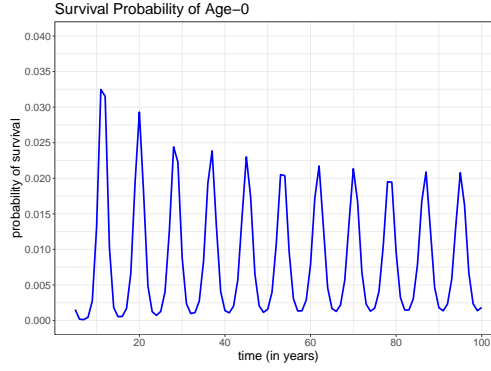


Figure 7

Figure 8: Survival probability of age-0 gizzard shad.

4.2. Time Evolution of Initial State

Starting with $n(z, 0)$ defined by Equation 6, we computed the length distribution for 4 years. In year 1, there are two relative maximum frequencies corresponding to the recruitment of age-1 fish and the survival of the adults.

4.2.1. Dynamics of the Age-1 Over Time - Fixed Frame

The greatest value of $n(z, 1)$ during year one is centered at the mean length of recruitment. In the following years, the decrease in the maximum value is a result of the two factors: the reduction in the density of adults and the density-dependent survival function for age-0 fish. Starting in year 1, there is a reduction in the number of egg-producing adults (lengths above 140 mm) compared with the initial population. From Figure 4a, fewer longer adults implies fewer eggs produced. The eggs that are produced, however, may have a greater chance of survival to the age-1 census (Figure ??). This is evident in the increase in density of recruits (NEED TO SHOW?) but is illustrated in lower frequency of recruits (Figure 9)

[Theme: Dynamics of a cohort - moving frame] Figure XXX also demonstrates the growth in gizzard shad population. The peak length frequency of age-1 fish in $n(z, 1)$ near $z = 105$ mm is seen as a peak in $n(z, 2)$ near 160 mm, and again as a peak in $n(z, 3)$ at about 210 mm. MORE DISCUSSION NEEDED

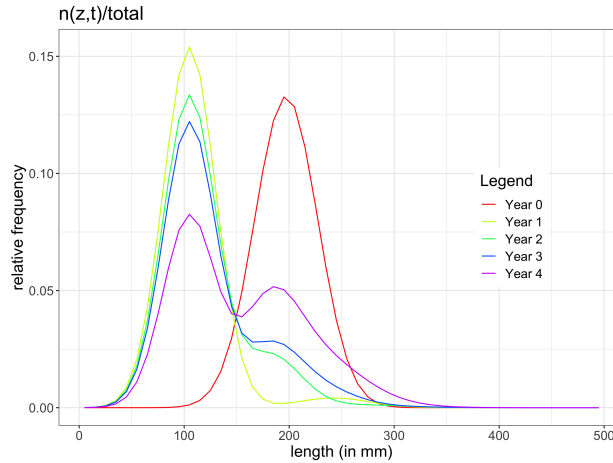


Figure 9: Simulated frequency of lengths of gizzard shad. Initial density and $N=50$

5. Discussion

We compare a simulated length distribution with U.S. Geological Survey (USGS) Long-Term Resource Monitoring (LTRMP) data from the La Grange Reach of the Illinois River from 1992-2019. The La Grange Reach of the Illinois River is a 125 km segment of the lower Illinois River between the La Grange Lock and Dam at RKM 129 and the Peoria Lock and Dam at RKM 254. It is characterized by a wide floodplain surrounding the main channel and a mosaic of side channels, fully connected backwaters, and semi-connected backwaters.

[Comparison of Frequency plots vs Simulation - Similarities] In these data, we see similar patterns as displayed in Figure XXX. Specifically, from years 2010-2012...

[Comparison of Frequency plots vs Simulation - Differences]

[Possible explanation of differences and future direction]

[More future direction - two species model]

1. Summary of findings and key discussion points

- (a) Comparison to empirical data
- (b) Deviations from empirical data
- (c) discussion about sameness and differences
- (d) Sources of density within our model

2. Comparison to existing literature

- (a) Talk about Matt's work (Catalano and Allen, 2010, 2011)

(b) Broader need for models such as this

3. Implications for management of species

(a) Invasive species

(b) Impact of size on harvest

(c) impact of size on movement

4. Future ideas to explore

(a) Multi-species model

(b) Spatial impacts

(c) Climate on density

(d) Changing climate scenarios

6. Acknowledgments

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References

- R. J. Pierce, T. E. Wissing, B. A. Megrey, Aspects of the feeding ecology of gizzard shad in Acton Lake, Ohio, Transactions of the American Fisheries Society 110 (3) (1981) 391–395.
- M. J. Vanni, K. K. Arend, M. T. Bremigan, D. B. Bunnell, J. E. Garvey, M. J. Gonzalez, W. H. Renwick, P. A. Soranno, R. A. Stein, Linking landscapes and food webs: effects of omnivorous fish and watersheds on reservoir ecosystems, BioScience 55 (2) (2005) 155–167.
- D. B. Jester, B. L. Jensen, et al., Life history and ecology of the gizzard shad, *Dorosoma cepedianum* (Le Sueur) with reference to Elephant Butte Lake .

- 299 M. E. Mather, M. J. Vanni, T. E. Wissing, S. A. Davis, M. H. Schaus, Regeneration of
300 nitrogen and phosphorus by bluegill and gizzard shad: effect of feeding history, Canadian
301 Journal of Fisheries and Aquatic Sciences 52 (11) (1995) 2327–2338.
- 302 M. H. Schaus, M. J. Vanni, Effects of gizzard shad on phytoplankton and nutrient dynamics:
303 role of sediment feeding and fish size, Ecology 81 (6) (2000) 1701–1719.
- 304 D. D. Aday, R. J. H. Hoxmeier, D. H. Wahl, Direct and indirect effects of gizzard shad
305 on bluegill growth and population size structure, Transactions of the American Fisheries
306 Society 132 (1) (2003) 47–56.
- 307 J. H. Thorp, M. C. Thoms, M. D. DeLong, The riverine ecosystem synthesis: biocomplexity
308 in river networks across space and time, River Research and Applications 22 (2) (2006)
309 123–147.
- 310 G. L. Buynak, R. S. Hale, B. Mitchell, Differential growth of young-of-year gizzard shad
311 in several Kentucky reservoirs, North American Journal of Fisheries Management 12 (3)
312 (1992) 656–662.
- 313 M. T. Welker, C. L. Pierce, D. H. Wahl, Growth and survival of larval fishes: roles of
314 competition and zooplankton abundance, Transactions of the American Fisheries Society
315 123 (5) (1994) 703–717.
- 316 V. J. DiCenzo, M. J. Maceina, M. R. Stimpert, Relations between reservoir trophic state and
317 gizzard shad population characteristics in Alabama reservoirs, North American journal of
318 fisheries management 16 (4) (1996) 888–895.
- 319 K. S. Irons, G. Sass, M. McClelland, J. Stafford, Reduced condition factor of two native
320 fish species coincident with invasion of non-native Asian carps in the Illinois River, USA
321 Is this evidence for competition and reduced fitness?, Journal of Fish Biology 71 (2007)
322 258–273.
- 323 S. A. Love, N. J. Lederman, R. L. Anderson, J. A. DeBoer, A. F. Casper, Does aquatic
324 invasive species removal benefit native fish? The response of gizzard shad (*Dorosoma*

cepedianum) to commercial harvest of bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*H. molitrix*), *Hydrobiologia* 817 (1) (2018) 403–412.

M. J. Catalano, M. S. Allen, A size-and age-structured model to estimate fish recruitment, growth, mortality, and gear selectivity, *Fisheries Research* 105 (1) (2010) 38–45.

M. J. Catalano, M. S. Allen, A whole-lake density reduction to assess compensatory responses of gizzard shad *Dorosoma cepedianum*, *Canadian Journal of Fisheries and Aquatic Sciences* 68 (6) (2011) 955–968.

A. Bodola, The life history of the gizzard shad, *Dorosoma cepedianum*, in western Lake Erie, Ph.D. thesis, Doctoral dissertation. Ohio State University, Columbus, 1955.

P. Michaletz, Variation in characteristics among gizzard shad populations: The role of impoundment size and productivity, *Fisheries Management and Ecology* 24 (5) (2017) 361–371.

G. Jons, L. Miranda, Ovarian weight as an index of fecundity, maturity, and spawning periodicity, *Journal of Fish Biology* 50 (1) (1997) 150–156.

P. H. Michaletz, Overwinter survival of age-0 gizzard shad in Missouri reservoirs spanning a productivity gradient: roles of body size and winter severity, *Transactions of the American Fisheries Society* 139 (1) (2010) 241–256.

M. R. Easterling, S. P. Ellner, P. M. Dixon, Size-specific sensitivity: applying a new structured population model, *Ecology* 81 (3) (2000) 694–708.

S. P. Ellner, D. Z. Childs, M. Rees, et al., Data-driven modelling of structured populations, A practical guide to the Integral Projection Model. Cham: Springer .

C. Merow, J. P. Dahlgren, C. J. E. Metcalf, D. Z. Childs, M. E. Evans, E. Jongejans, S. Record, M. Rees, R. Salguero-Gómez, S. M. McMahon, Advancing population ecology with integral projection models: a practical guide, *Methods in Ecology and Evolution* 5 (2) (2014) 99–110.

- M. Rees, D. Z. Childs, S. P. Ellner, Building integral projection models: a user's guide, *Journal of Animal Ecology* 83 (3) (2014) 528–545.
- R. A. Erickson, E. A. Eager, M. K. Brey, M. J. Hansen, P. M. Kocovsky, An integral projection model with YY-males and application to evaluating grass carp control, *Ecological Modelling* 361 (2017) 14–25.
- B. Liao, X. Shan, C. Zhou, Y. Han, Y. Chen, Q. Liu, A dynamic energy budget–integral projection model (DEB-IPM) to predict population-level dynamics based on individual data: a case study using the small and rapidly reproducing species *Engraulis japonicus*, *Marine and Freshwater Research* 71 (4) (2019) 461–468.
- J. W. White, K. J. Nickols, D. Malone, M. H. Carr, R. M. Starr, F. Cordoleani, M. L. Baskett, A. Hastings, L. W. Botsford, Fitting state-space integral projection models to size-structured time series data to estimate unknown parameters, *Ecological Applications* 26 (8) (2016) 2677–2694.
- N. Pollesch, K. Flynn, S. Kadlec, J. Swintek, S. Raimondo, M. Etterson, Developing integral projection models for ecotoxicology, *Ecological Modelling* 464 (2022) 109813.
- B. M. Bolker, *Ecological models and data in R*, Princeton University Press, 2008.
- S. Gutreuter, R. Burkhardt, K. S. Lubinski, Long Term Resource Monitoring Program procedures [microform] .
- B. S. Ickes, R. W. Burkhardt, Evaluation and proposed refinement of the sampling design for the Long Term Resource Monitoring Program's fish component, Tech. Rep., Geological Survey La Crosse WI Upper Midwest Environmental Sciences Center, 2002.
- R. Burden, J. D. Faires, *Numerical analysis* 8th ed, Thomson Brooks/Cole .
- S. P. Ellner, M. Rees, Integral projection models for species with complex demography, *The American Naturalist* 167 (3) (2006) 410–428.

374 S. Ramula, M. Rees, Y. M. Buckley, Integral projection models perform better for small
375 demographic data sets than matrix population models: a case study of two perennial
376 herbs, *Journal of Applied Ecology* 46 (5) (2009) 1048–1053.

377 J. L. Williams, T. E. Miller, S. P. Ellner, Avoiding unintentional eviction from integral
378 projection models, *Ecology* 93 (9) (2012) 2008–2014.

379 R Core Team, R: A Language and Environment for Statistical Computing, R Foundation
380 for Statistical Computing, Vienna, Austria, URL <https://www.R-project.org/>, 2017.