



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

# 1 Graphical Abstract

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

4 J. Peirce<sup>1,4</sup>, G. Sandland<sup>3,4</sup>, B. Bennie<sup>1</sup>, R.A. Erickson<sup>2</sup>

## 6 Highlights

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

9 J. Peirce<sup>1,4</sup>, G. Sandland<sup>3,4</sup>, B. Bennie<sup>1</sup>, R.A. Erickson<sup>2</sup>

10 • Research highlight 1

11 • Research highlight 2

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

J. Peirce<sup>1,4</sup>, G. Sandland<sup>3,4</sup>, B. Bennie<sup>1</sup>, R.A. Erickson<sup>2</sup>

<sup>1</sup> University of Wisconsin - La Crosse, Mathematics & Statistics Department

<sup>2</sup> U.S.G.S. Upper Mississippi Environmental Science Center

<sup>3</sup> University of Wisconsin - La Crosse, Biology Department

<sup>4</sup> River Studies Center

---

## Abstract

Gizzard shad (*Dorosoma cepedianum*) are a common freshwater fish found 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 (IPM) for gizzard shad based on empirical data and include in the model density-dependent survival in age-0 fish. Integral projection models 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 (La Grange Reach). 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 leading to its dominance within 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, gizzard shad 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 connection 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 throughout 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 both the growth and survival patterns observed in populations of these fish. For example, (Buynak et al., 1992) reported an inverse relationship between densities and the lengths of age-0 gizzard shad. Similarly (Welker et al., 1994) found that high densities of age-0 shad were negatively associated with both fish length and survival under both field and semi-natural conditions. Finally, (Michaletz, 2010) reported that the densities of age-0 gizzard shad were negatively correlated with survival in two Missouri lakes. These patterns were attributed to intraspecific competition among young shad for prey (zooplankton) resources. Although intraspecific competition may be influencing life-history traits in subsequent stages of gizzard shad development, little work has actually been conducted to address this (Di-

Cenzo et al., 1996). There is also evidence that the densities of other co-occurring fish species (such as invasive carps) may also 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 population dynamics in this species. Work by Catalano and Allen (2010, 2011) used empirically-based simulations of gizzard shad to assess population-level responses in this species. As part of this process, the authors investigated population-structure using fish lengths but did not consider the impacts of gizzard shad densities on population patterns. 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 the dynamics reported for this fish species in a well-studied pool of the Illinois River (La Grange Reach). Results from this work suggest that our model 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

Mature gizzard shad tend to mate between May and June, although this can vary based on water temperatures.. 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 leading to density-dependent survival. The strength of competition may then subside as fish transition to feeding on different food items during latter stages of development.

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
$\alpha_s$	inflection point	104.34	Estimated from LTRM dataset
$\beta_s$	slope	-637.93	Estimated from LTRM dataset
Growth function, $G(z, z')$			
$L_{\infty}$	maximum length (in mm)	394.30	(Catalano and Allen, 2010)
$K_g$	growth rate	0.26	(Michaletz, 2017)
$\sigma_g$	growth standard deviation	25	(Michaletz, 2017)
Normal distribution of length of age-1, $C_1(z')$			
$\mu_r$	mean length of recruitment (in mm)	105	(Michaletz, 2017)
$\sigma_r$	standard deviation of length	25	(Michaletz, 2017)
Eggs produced, $\text{egg}(z)$			
$\text{egg}_{\max}$	maximum number of eggs produced	742,094	Estimated from (Jons and Miranda, 1997)
$\alpha_e$	inflection point	314.44	Estimated from (Jons and Miranda, 1997)
$\beta_e$	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			
$\nu$	probability that egg becomes viable	0.002	(Bodola, 1955)
$p_b$	probability that female spawns	0.90	

## 2.2. Equations

We used an integral projection model (IPM) to describe the life history of gizzard shad in the Upper Mississippi River (UMR) system. IPMs were first introduced by Easterling (Easterling et al., 2000), as a generalization of stage-based, matrix population models. Since that time, IPMs have been used to describe a wide range of organisms (Ellner et al., 2016; Merow et al., 2014; Rees et al., 2014), but have only recently been used to model fish populations (Erickson et al., 2017; Liao et al., 2019; White et al., 2016; Pollesch et al., 2022). Fish are an ideal group to investigate using this approach as many species have been well studied and are therefore associated with robust information about life-history traits (i.e. growth and reproduction). Gizzard shad are one such species and have been the subject of numerous laboratory and field studies over the decades making it a logical choice for IPMs. In our model specifically, we incorporate data from studies on 1) egg production in different size classes of fish, 2) density-dependent survival of age-0 shad, and 3) length distributions of gizzard shad in the UMRS that span nearly thirty years.

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 individual's 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 compartments: 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  $\Delta z$ , 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  $t$ .

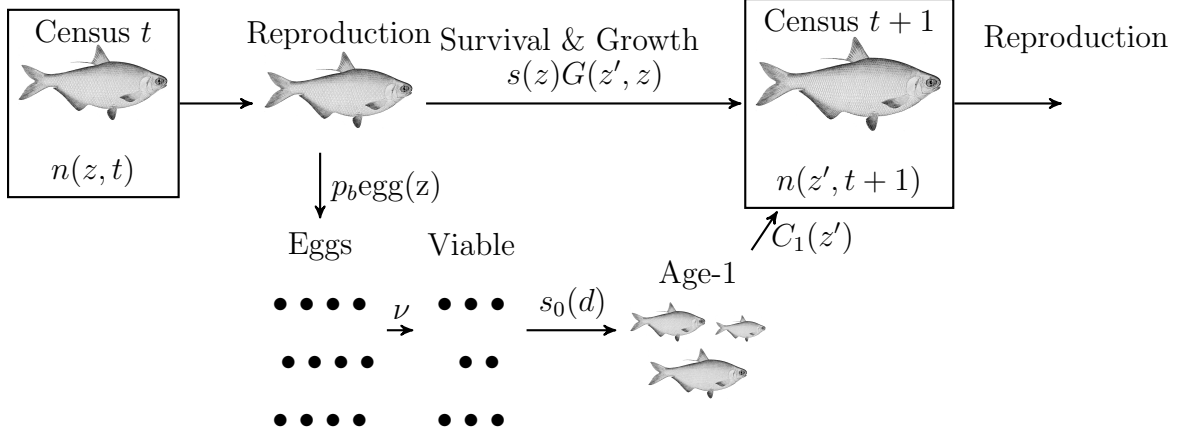


Figure 2: Life cycle diagram and census points for pre-reproduction census of gizzard shad.

### 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,  $s_{\max}$ ; an intercept parameter,  $\alpha_s$ ; and a slope parameter,  $\beta_s$  (Bolker, 2008).

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  $L_{\infty}$  is maximum asymptotic length,  $K$  is the growth rate, and  $t_0$  is the initial time. The expected fish length the following year is:

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

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  $\sigma_g$  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,  $\nu$  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 gizzard shad survival during their first year can depend on many factors (Michaletz, 2010) including predation, temperature, the mean total length of fish, and the 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 m<sup>3</sup>,

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

Finally, we computed the total number of eggs that result in age-1 fish and multiplied this number with a normal distribution of length,  $C_1(z') = \text{NormalPDF}(\mu_r, \sigma_r)$  where  $\mu_r$  is the mean length of age-1 gizzard shad and  $\sigma_r$  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. The LTRM and model parameterization

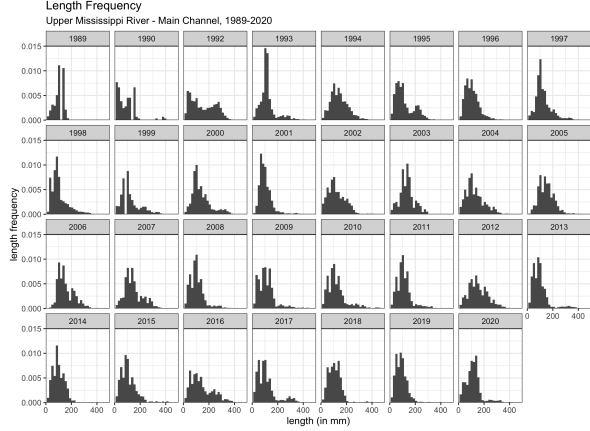
The integrity and health of the UMRs is assessed through Long Term Resource Monitoring (LTRM) which is overseen by a number of agencies including the U.S. Army Corp of Engineers, the United States Geological Survey and the United States Fish and Wildlife Service. The goal of the LTRM is track changes in the condition and/or stability of the UMRs ecosystem and participate in restoration activities throughout the region. In order to achieve this goal, numerous features of the UMRs, such as aquatic vegetation, bathymetry, fish, land use/land cover, and water quality are continually surveyed from Navigation Pool 1 (at Minneapolis, Minnesota) south to the confluence of the Mississippi and Ohio Rivers at Cairo, Illinois. The LTRM fish surveys are conducted at five locations along the main channel of the Upper Mississippi River (Pools 4, 8, 13, 26, and the Open River Reach) and at one location along the Illinois River (La Grange Reach) (Figure 3a). Fish are captured using a multiple gear approach (including netting and electrofishing) in order to monitor the responses and health of fish communities along these two very important waterways over time (Gutreuter et al., 1995). Specific capture methodologies, protocols and modifications to the LTRM can be found in Gutreuter et al. (1995), and Ickes and Burkhardt (2002). In terms of gizzard shad, fish lengths have been recorded since 1989 with approximately 3000 collections per year along the Mississippi River (Figure 3b). For the La Grange Reach of the Illinois River, gizzard shad have been collected since 1990 with approximately 500 samples conducted per year.

#### 3.2. Research area used for model validation

The location of La Grange Reach has two important features motivation its choice for the methods of our study. First, we were able to parameterized the IPM using data collected from the main channel of the UMRs. As a part of Illinois River and UMRs, La Grange Reach is upstream and relatively independence from main channel of the Mississippi River. In recent years, there have been concerns with the threatening introduction of invasive carp to the Great Lakes. As a consequence, the impact of invasive carp on the native fish populations in the pools leading to the Great Lakes have received an elevated level of



(a)



(b)

Figure 3: (a) Site source of image. (b) Length frequency of sampled gizzard shad in the main channel of the Upper Mississippi River system.

attention. Understanding the population dynamics of gizzard shad in La Grange Reach, may make it easier, in the future, to assess the impacts carp has on native fish populations.

### 3.3. Parameterization

#### 3.3.1. Fecundity and recruitment

The maturity of female gizzard shad begin at approximately 140 mm and the number of eggs that are produced increases as the females increase in size (Jons and Miranda, 1997). The logistic parameters for the mean number of eggs produced by females of a certain length were obtained by fitting the three-parameter logistic function (Equation 3) to the data for 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 (Equation 4) were determined by fitting equation 4 to the survival means for 2003-2007 cohorts of gizzard shad in five Missouri reservoirs (Michaletz, 2010). To complete the recruitment process we assign a length to the recruited individuals by simulating a Gaussian random variable with mean  $\mu_c$  and standard deviation  $\sigma_c$ . These 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 LTRM dataset of the main channel of the UMRS.

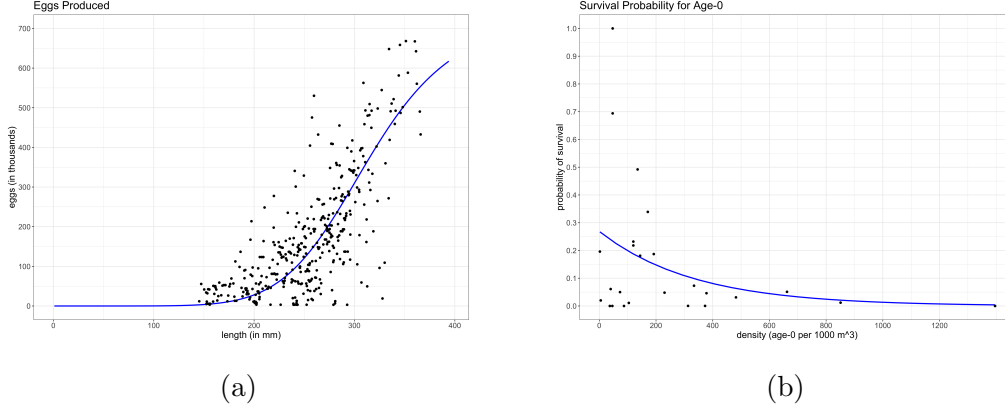


Figure 4: (a) Mean number of eggs produced by female gizzard shad  $\text{egg}(z)$ . Data from (Jons and Miranda, 1997). (b) Age-0 density-dependent survival function  $s_0(d)$ . Data from (Michaletz, 2010).

### 3.3.2. 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. We assume that the probability of adult survival is related to the length by a four-parameter logistic function (Equation 1). An investigation of gizzard shad in Lake Erie (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 3b), we assumed that solutions of our model will exhibit periodic behavior every 8-9 years. We used a least squares method to estimate the  $\alpha_s$  and  $\beta_s$  parameters that minimized the total square-distance between the (observed) pre-carp LTRM length distribution in the main channel of the UMRS and (predicted) model equilibrium,  $n(z, t)$  during a 8-year period 100 years after initialization. The slope parameter  $\beta_s$  was found to be large in magnitude resulting in a primarily two-valued survival probability. Gizzard shad less than  $\alpha_s$  mm in length have a very low survival rate ( $s_{\min}$ ) while lengths larger than  $\alpha_s$  mm have the maximum survival rate  $s_{\max}$ . This survival pattern has been reported for a number of fish species and can arise for a number of reasons including feeding attributes in predators (i.e. gape limitations, reduced abilities to catch prey, etc.) (Pepin et al., 1992; Nowlin et al., 2006).

## 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  $0.5L_\infty$  and standard deviation  $\sigma_0 = 30$ . 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. Survival of age-0 cohort

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 5).

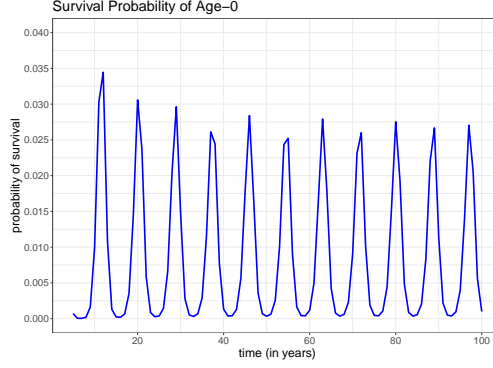


Figure 5

Figure 6: Survival probability of age-0 gizzard shad.

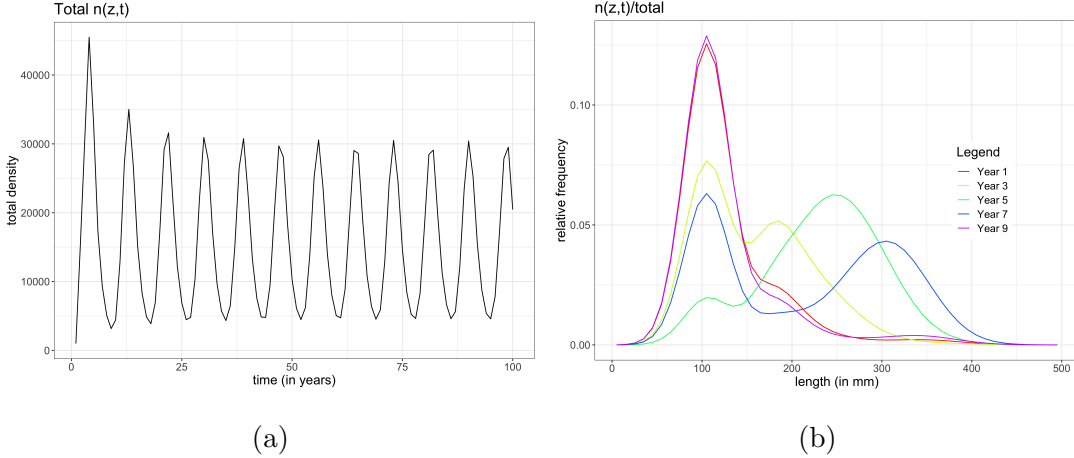


Figure 7: (a) The total number of gizzard shad in La Grange Reach predicted by IPM for first 100 years. (b) Simulated length distributions during an 8 year interval of time (approximately 1 period of the the total density function)

#### 4.1.2. Periodic orbit and validation with external dataset

The total number of gizzard shad in our simulation reached a stable periodic orbit (Figure 7a) within 50 years. The length distributions during the periodic orbit (Figure 7b) has similarities to length observations from La Grange found in the LTRM fish dataset (Figure 8a). In addition, the average simulated length distribution compares favorably to the length frequencies of observations from La Grange. (Figure 8b).

After simulating an additional 50 years, we fit a periodic function to the annual density of gizzard shad and determined a period of approximately 8.5 years. Figure 7b illustrates

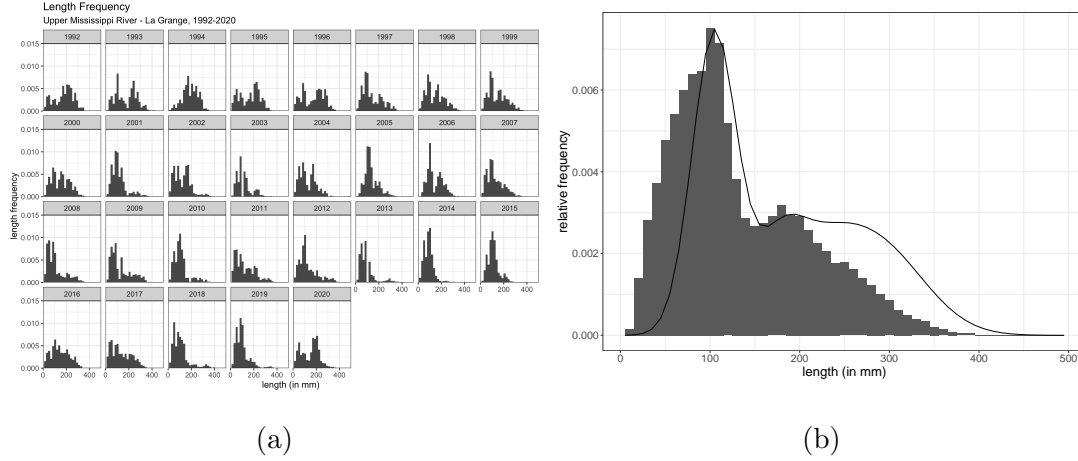


Figure 8: (a) Length frequencies of sampled gizzard shad in La Grange for each year, 1992-2020. (b) Length frequencies of sampled gizzard shad in La Grange from 1992-2020 compared with average (over 1 period) simulated length frequency.

the periodic length dynamics within the gizzard shad population during a 8-year window of the periodic orbit. The ebb and flow of the frequency of the age-1 cohort are associated with the density-dependent survival function for age-0 fish as explained in Section 4.1.1. In addition, Figure 7b captures the cohort length dynamics of the gizzard shad. Specifically, the peak length frequency of age-1 fish in Year 1 near  $z = 105$  mm is seen as a peak in Year 3 near 185 mm, a peak near 305 mm in Year 3, before becoming nearly unidentifiable in the graphs for Years 7 and 9. This is consistent with the lifespan reported for gizzard that can range, on average, between 4 and 6 years (CITATION). The change in the location of these relative maximum influences the number of eggs being produced and consequently the density of age-0 fish the next year. An increase in the frequency of larger adults leads to a subsequent reduction in the resulting age-1 cohort due to our density-dependent survival function in age-0 fish.

## 5. Discussion

Gizzard shad are common in freshwater systems of North America where they are important components of the aquatic communities. Given this, it is important to understand how populations of this species vary with changing environmental circumstances, such as the occurrence of invasive species. Herein we use both LTRM data and parameters gleaned

from other empirical studies to develop an integral projection model for gizzard shad and test model outputs against patterns reported from a well-studied population of this species from the La Grange Reach of the Illinois River.

After fitting two adult survival parameters using LTRM data from the main channel of the Mississippi River, we compared a simulated length distribution with LTRM data collected from the La Grange Reach of the Illinois River from 1992 to 2020. The resulting simulated length distributions (Figure 7b) reflected a number of the empirical patterns observed in gizzard shad captured from the La Grange Reach over the same timeframe (Figure 8a). Specifically, the two peaks in Year 1 of our simulations are similar to the length patterns in gizzard shad collected from the La Grange Reach in 1997. In the following year, the higher frequency of age-1 fish in our simulations was also seen in the LTRM data (Year 2).

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 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 LTRM 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.

While not all observed length distributions are reflected in the simulations, the similarity in the average length distributions (Figure 8b) suggest that our IPM could serve as a tool for predicting length distributions for gizzard shad across different study areas. (LAST SENTENCE NEEDS A LOT MORE CLARITY)

Gaining an understanding of how length distributions of gizzard shad emerge under density-dependent survival in the age-0 class will serve as a foundation for investigating density effects at subsequent stages in the life cycle. In addition, this single-species model could also be expanded to incorporate interspecific interactions between gizzard shad and



species such as invasive carp, which appear to negatively impact gizzard shad life-histories through competition for food resources.

## 6. Acknowledgments

These data are a product of the U.S. Army Corps of Engineer’s Upper Mississippi River Restoration Program (UMRR) Long Term Resource Monitoring (LTRM) element implemented by the U.S. Geological Survey in collaboration with the five Upper Mississippi River System (UMRS) states of Illinois, Iowa, Minnesota, Missouri, and Wisconsin. The U.S. Army Corps of Engineers (Corps) provides guidance and has overall program responsibility.

We thank the U.S. Geological Survey Biothreats program and Great Lakes Restoration Initiative for funding. In addition, research was supported by NSF-DMS Grant #1852224, “REU Site: Ecological Modeling of the Mississippi River Basin”.

## 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 .
- M. E. Mather, M. J. Vanni, T. E. Wissing, S. A. Davis, M. H. Schaus, Regeneration of nitrogen and phosphorus by bluegill and gizzard shad: effect of feeding history, Canadian Journal of Fisheries and Aquatic Sciences 52 (11) (1995) 2327–2338.
- M. H. Schaus, M. J. Vanni, Effects of gizzard shad on phytoplankton and nutrient dynamics: role of sediment feeding and fish size, Ecology 81 (6) (2000) 1701–1719.

- D. D. Aday, R. J. H. Hoxmeier, D. H. Wahl, Direct and indirect effects of gizzard shad on bluegill growth and population size structure, *Transactions of the American Fisheries Society* 132 (1) (2003) 47–56.
- J. H. Thorp, M. C. Thoms, M. D. Delong, The riverine ecosystem synthesis: biocomplexity in river networks across space and time, *River Research and Applications* 22 (2) (2006) 123–147.
- G. L. Buynak, R. S. Hale, B. Mitchell, Differential growth of young-of-year gizzard shad in several Kentucky reservoirs, *North American Journal of Fisheries Management* 12 (3) (1992) 656–662.
- M. T. Welker, C. L. Pierce, D. H. Wahl, Growth and survival of larval fishes: roles of competition and zooplankton abundance, *Transactions of the American Fisheries Society* 123 (5) (1994) 703–717.
- V. J. DiCenzo, M. J. Maceina, M. R. Stimpert, Relations between reservoir trophic state and gizzard shad population characteristics in Alabama reservoirs, *North American journal of fisheries management* 16 (4) (1996) 888–895.
- K. S. Irons, G. Sass, M. McClelland, J. Stafford, Reduced condition factor of two native fish species coincident with invasion of non-native Asian carps in the Illinois River, USA Is this evidence for competition and reduced fitness?, *Journal of Fish Biology* 71 (2007) 258–273.
- S. A. Love, N. J. Lederman, R. L. Anderson, J. A. DeBoer, A. F. Casper, Does aquatic 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 im-  
poundment 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 struc-  
tured 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 pro-  
jection 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.
- S. Ramula, M. Rees, Y. M. Buckley, Integral projection models perform better for small demographic data sets than matrix population models: a case study of two perennial herbs, *Journal of Applied Ecology* 46 (5) (2009) 1048–1053.
- J. L. Williams, T. E. Miller, S. P. Ellner, Avoiding unintentional eviction from integral projection models, *Ecology* 93 (9) (2012) 2008–2014.
- R Core Team, *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria, URL <https://www.R-project.org/>, 2017.