FINAL REPORT

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THE ENDANGERED SPECIES PROGRAM

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Endangered and Threatened Species Conservation

Distribution, Status, Habitat Preferences, and Reproductive Ecology of Smalleye Shiner and Sharpnose Shiner in the Brazos River

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20 March 2007

FINAL REPORT

STATE: ____Texas________________ **GRANT NUMBER:** ___E - 55___________

REPORTING PERIOD: ____10/01/04 to 9/30/06__

PROJECT TITLE: Distribution, Status, Habitat Preferences, and Reproductive Ecology of Smalleye Shiner and Sharpnose Shiner in the Brazos River

OBJECTIVE(S):

Over a two year period, study and record for smalleye shiner and sharpnose shiner:

- Temporal Variation in Fish Assemblages in the Upper Brazos River
- Distribution and Abundance
- Habitat Preferences
- Reproductive Ecology
- Discharge-related Population Dynamics Model

Summary of Progress:

See Attachment A.

Significant Deviation:

Distribution and Abundance

Due to hydrologic conditions (floods) we were unable to sample the lower Brazos River in 2005. The researchers plan to conduct these surveys in summer 2007.

Location: Brazos River, various counties, Texas.

Cost: ____

Prepared by: _Craig Farquhar______________ **Date:** _20 Mar 2007

Approved by: ________________________________ **Date:**_________________________

Neil (Nick) E. Carter

DISTRIBUTION, STATUS, HABITAT PREFERENCES, AND REPRODUCTIVE ECOLOGY OF SMALLEYE SHINER AND SHARPNOSE SHINER IN THE BRAZOS RIVER

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19 March 2007

Final Report Submitted to:

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STUDY OBJECTIVES

The objectives of this study were to conduct a comprehensive two-year study of: (1) the status, (2) distribution, (3) habitat preferences, and (4) reproductive ecology of the sharpnose shiner and smalleye shiner, and to use data collected during these studies to develop a model that relates sharpnose shiner and smalleye shiner population dynamics to river discharge. The results of this study and the constructed models will provide information necessary for management and conservation of both sharpnose shiner and smalleye shiner. Further, these results and models will be useful to managers who will be responsible for assessment and mitigation of proposed and future modifications of the Brazos River.

ACKNOWLEDGMENTS

A number of persons have made substantial contributions to this project. We wish to thank Doug Knable, Aaron Urbanczyk, Erin Hoelting, Brandi McFadden, Mike Laman, Curtis Stennett, and Chris Chizinski.for help in the field and lab. We thank Craig Farquhar and Kevin Mayes, Texas Parks and Wildlife Department, for helpful discussions and other contributions to this project. We acknowledge Texas Parks and Wildlife Department for supporting this study.

SUMMARY

We sampled the Brazos River fish assemblage at $N = 23$ sites that were sampled during previous surveys. In addition we selected four sampling sites on the upper Brazos River at which we monitored the fish assemblage, assessed microhabitat use, and collected fishes for reproductive studies. We collected a total of 24,629 specimens representing 15 families, and 45 species and two at least two hybrid combinations. The two most abundant species were red shiner *Cyprinella lutrensis* and bullhead minnow *Pimephales vigilax*. These species accounted for 58% of fishes captured. Sharpnose shiner and smalleye shiner were collected only from the upper Brazos River, upstream from Possum Kingdom Reservoir and were among the most common species in this area. Sharpnose shiner represented 20.7% of fishes sampled, whereas the smalleye shiner represented 11.6% of the assemblage in the upper Brazos River.

There was no significant ($P = 0.8530$) temporal trend in sharpnose shiner catches in the upper Brazos River, but there was evidence of a significant ($P = 0.0070$) decrease in the lower Brazos River. For smalleye shiner, there was no evidence of a significant temporal trend in catches in either the upper ($P = 0.2172$) or lower Brazos River ($P = 0.3029$). Our results show no evident change in the distribution of either species in the upper Brazos River since early surveys, but they do suggest a change in relative abundance of sharpnose shiner and smalleye shiner since the late 1990s when sharpnose shiner and smalleye shiner represented 7 and 17%, respectively. Despite making large collections at several sites in the lower river at which sharpnose shiner and smalleye shiner historically were common, we collected no specimens of either species. Although both species historically inhabited the lower Brazos River, they represented only a small proportion of the assemblage.

Sharpnose shiner and smalleye shiner occurred in microhabitats characterized by a wide range of physical and chemical conditions. There was no obvious habitat selection by either species based on water temperature, dissolved oxygen concentration, pH, or conductivity. Sharpnose shiner and smalleye shiner do appear to select microhabitat based on depth and current velocity. Both species were most common in currents between 20 and 40 cm s^{-1} and depths between 20 and 40 cm. There was no selection by channel-habitat type.

Sharpnose shiner and smalleye shiner populations in the upper Brazos River undergo asynchronous oocyte development and spawn repeatedly during a protracted reproductive period. Patterns in GSI and ova size appear to indicate that sharpnose shiner and smalleye shiner populations batch-spawn ova in distinct episodes during the reproductive season. However, spent follicles were observed in the ovaries of sharpnose shiner and smalleye shiner on nearly all of the sampling dates, indicating that in addition to batch-spawning, some baseline level of spawning within the populations occurs on a daily basis.

Using the results of our reproductive studies, we developed population dynamics models sharpnose shiner and smalleye shiner. Elasticity analysis and sensitivity simulations of population dynamics models for both species indicate that age-0 survival and age-1 fecundity have the greatest effect on overall population growth. Thus, these are the life history stages that should be targeted by management activities.

Our population dynamics models predicted the observed abundance of smalleye shiner extremely well and predicted sharpnose shiner abundance closely except for 2006. Our models should be useful in assessing the effects of past and future modifications to the upper Brazos River on populations of sharpnose shiner and smalleye shiner. For example, impoundment of Lake Alan Henry in 1993 resulted in a 14% reduction in mean summer discharge. Our model indicates that this might have resulted in as much as a 49% decrease in abundance of sharpnose shiner and a 48% decrease in abundance of smalleye shiner. If a proposed reservoir on the upper Brazos River, immediately downstream from the confluence of the Double Mountain Fork of the Brazos River and the Salt Fork of the Brazos River, is constructed discharge at downstream sites will decrease by about 55% during the summer reproductive period. Our models predict that, over a 13-year period the average abundance of sharpnose shiner and smalleye shiner will decease 87%; however, our model also suggests that neither species will persist for more than a few years.

The main limitation of our models is due to the limited availability of standardized catch data for sharpnose shiner and smalleye shiner in the Brazos River. Our model explicitly assumes that age-0 survival is related to discharge and then uses historic population data to estimate the exact form of the survival-discharge relationship. Continued sampling, or monitoring, of the sharpnose shiner and smalleye shiner abundance in the upper Brazos River should be given a high priority, to insure the health of populations of both species, to better understand the change in relative abundance of both species that has occurred in the past 10 years, and to allow further improvement of the models presented herein.

INTRODUCTION

The sharpnose shiner *Notropis oxyrhynchus* and smalleye shiner *Notropis buccula* are endemic to the Brazos River, Texas (Cross 1953; Cross et al. 1986). The sharpnose shiner historically occurred in portions of the South Wichita River, north of Seymour, Texas (Cross et al. 1986), but has not been collected there since the 1960s (Wilde et al. 1996). The distribution and abundance of sharpnose shiner and smalleye shiner in the Brazos River have been reduced since the 1960s and both may warrant state or federal protection (Moss and Mayes 1993). Both species are considered high priority species by the State of Texas (Linam 1995; Texas Parks and Wildlife Department 2007) and are considered Candidate Species for listing by the U.S. Fish and Wildlife Service.

Historically, the sharpnose shiner and smalleye shiner were common throughout the mainstem Brazos River. As recently as 1991, the sharpnose shiner occurred in both the upper and lower Brazos River. In the lower river, downstream from Marlin, Texas, the sharpnose shiner comprised 0-3% of the fish assemblage (Moss and Mayes 1993), and much less than 1% (3 specimens out of 44,122 fishes collected) at the confluence of Allens Creek and the Brazos River (Gelwick and Li 2002). However, collections made in 2000 and 2001 throughout the lower river included no specimen of sharpnose shiner (Wilde, unpublished), suggesting an ongoing population decline. The sharpnose shiner still occurs in the Brazos River upstream from Possum Kingdom Reservoir, where it comprises 7% of the fish assemblage (Ostrand 2000). The smalleye shiner is now restricted to the river above Possum Kingdom Reservoir, where it comprises 17% of the fish assemblage (Ostrand 2000), although Zeug et al. (2005) reported catches of a small number of smalleye shiner in oxbow lakes along the lower Brazos River.

The Brazos River is among the most modified rivers in Texas (Anderson et al. 1995). The fish fauna of the Brazos River, including the sharpnose shiner and smalleye shiner, has been greatly affected by the construction of several reservoirs throughout the middle to upper reaches of the river (Anderson et al. 1995; Hubbs et al. 1997; Wilde and Ostrand 1999). Continued modification of the river is likely. Initial planning is underway for construction of additional reservoirs and three chloride control projects on tributaries to the Brazos River.

Changes in the distribution and abundance of sharpnose shiner and smalleye shiner in the Brazos River are most likely due either to habitat loss (Moss and Mayes 1993) or reproductive failure (e.g., Bonner 2000) as a result of reservoir construction and other habitat changes (i.e., Anderson et al. 1995). Although food habits (Marks et al. 2001), seasonal variation in abundance (Ostrand and Wilde 2002), and tolerances to temperature, oxygen, and salinity (Ostrand and Wilde 2001) are known for the smalleye shiner and sharpnose shiner, essentially nothing is known of the specific habitat requirements and reproductive ecology of these species. It is impossible to assess the impact of various existing and proposed modifications of the Brazos River, or to propose methods to mitigate project effects, on sharpnose shiner and smalleye shiner populations without detailed knowledge of their habitat requirements and reproductive ecology.

The objectives of this study were to study the distribution and, habitat preferences, and reproductive ecology of the sharpnose shiner and smalleye shiner in the Brazos River. Using results of this study, we develop population models for the sharpnose shiner and smalleye shiner that relate population dynamics to river discharge. These models will provide information necessary for management and conservation of both species and will guide assessment and mitigation of proposed and future modifications of the Brazos River.

STUDY AREA

The Brazos River Basin originates in eastern New Mexico near the Texas border and extends east and south through Texas, for approximately 1700 km, before terminating in the Gulf of Mexico at Freeport, Texas. The Brazos River Basin is geographically extensive and drains approximately one-sixth of the total land area of Texas. Mean annual precipitation in the basin is 75 cm, but this ranges from 40 cm in the northwest to 120 cm in the southeast (Hendrickson 2002). This study was conducted in the upper portion of the Brazos River, Texas where precipitation during the year is sporadic and localized leading to highly variable stream discharge (Echelle et al. 1972). The Brazos River itself originates in springs along the east face of the Llano Estacado that feed two small rivers, the Salt Fork of the Brazos River and Double Mountain Fork of the Brazos River, and their tributaries. The Brazos River mainstem is formed by the confluence of the Salt Fork of the Brazos River and Double Mountain Fork of the Brazos River in northeastern Stonewall County, Texas. The upper Brazos River and its tributaries typically become intermittent during summer months. When this occurs, all surface water is restricted to isolated streambed pools (Echelle et al. 1972; Wilde and Ostrand 1999). In general, the upper Brazos River and its tributaries are shallow, with braided channels flowing over sand and clay substrate and have a distinct lack of instream vegetation or shading canopy (Ostrand and Wilde 2002, 2004).

METHODS

Fish Distribution and Abundance

We sampled the Brazos River fish assemblage at $N = 23$ sites previously studied by Moss and Mayes (1993), Ostrand (2000), and Ostrand and Wilde (2002, 2004). Fishes were collected at 20 of these sites (Table 1). Samples were made by seining in the early (June) and late summer (August). At each site, seining was conducted for 45 minutes and all available microhabitat types were sampled. Seining was used because it is recommended for characterization of assemblages of small fishes (Bayley and Herendeen 2000). Larger specimens were identified and released in the field. Small fishes were anesthetized in a lethal dose (500 mg/l) of MS-222 and preserved in 10% buffered formalin for identification in the lab.

To summarize the results of our surveys, we used detrended correspondence analysis to ordinate the fish assemblage and sampled sites based on their location along an upstream-downstream gradient. The ordinations were performed using PC-ORD (McCune and Mefford 1999).

Population Monitoring

We selected four sampling sites on the upper Brazos River at which we monitored the fish assemblage, assessed microhabitat use, and collected fishes for reproductive studies. These sites were chosen based on location, accessibility, and potential species composition (Figure 1). Site 1 was located on the mainstem of the Brazos River in Baylor County, TX (33° 34’ 9” N; 99° 16’ 1” W). Site 2 was located on the mainstem of

Table 1. Sites sampled in the Brazos River in June and August 2006 to determine the distribution and abundance of sharpnose shiner and smalleye shiner.

Site Number	Site
1	Brazos River Hwy 7 west of Marlin, TX
2	Brazos River Hwy 485 west of Hearne, TX
3	Brazos River Hwy 21 west of Bryan, TX
4	Brazos River Hwy 105 west of Navasota, TX
5	Brazos River Hwy 290 west of Hemphstead, TX
6	Brazos River Hwy 159 southwest of Hemphstead, TX
7	Brazos River Hwy 529 east of Bellville, TX
8	Brazos River Hwy 1093 west of Simonton, TX
9	Clear Fork, Brazos River Hwy 578 Crystal Falls area, TX
10	Brazos River Hwy 67 south of Grahm, TX
11	Brazos River Hwy 79 east of Elbert, TX
12	North Fork of Double Mountain Fork, Brazos River Hwy 207 north of Post, TX
13	South Fork of Double Mountain Fork, Brazos River Hwy 84 at Justiceberg, TX
14	North Fork of Double Mountain Fork, Brazos River Hwy 380 east of Post, TX
15	Double Mountain Fork, Brazos River Hwy 208 southwest of Clairmont, TX
16	Salt Fork, Brazos River Hwy 380 southwest of Jayton, TX
17	Double Mountain Fork, Brazos River Hwy 70 north of Rotan, TX
18	Double Mountain Fork, Brazos River Hwy 83 south of Aspermont, TX
19	Clear Fork, Brazos River Hwy 6 at Lenders, TX
20	Brazos River at Seymour, TX
21	Brazos River Hwy 6 south of Benjamin, TX
22	Salt Fork, Brazos River Hwy 83 north of Aspermont, TX
23	Salt Fork, Brazos River Hwy 380 east of Jayton, TX

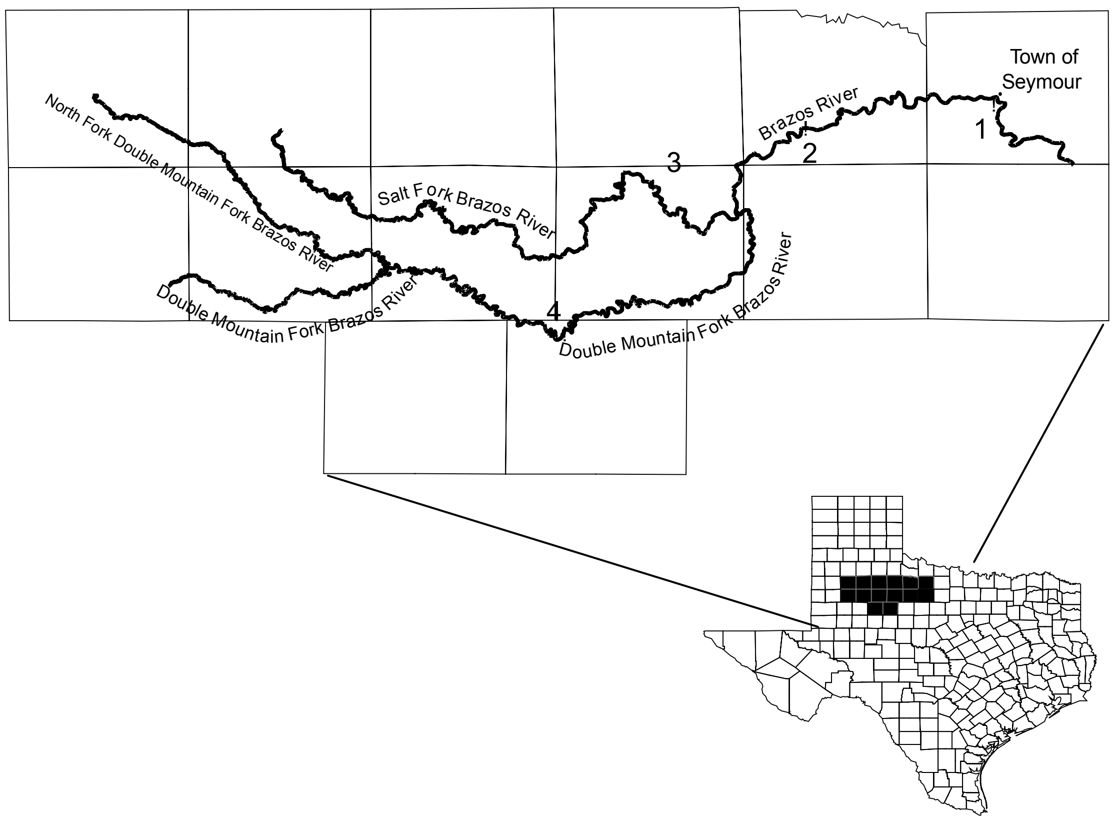


Figure 1. Study area and location of sampling sites on the upper Brazos River, Texas, for population monitoring and collection of samples for reproductive studies and assessment of habitat utilization by sharpnose shiner and smalleye shiner.

the Brazos River in Knox County, TX (33° 30’ 03” N; 99° 48’ 1” W”). Site 3 was located on the Salt Fork of the Brazos River in Stonewall County, TX (33° 20’ 02” N; 100° 14’ 2” W). Site 4 was located on the South Fork of the Double Mountain Fork of the Brazos River in Fisher County, TX (32° 55’ 8” N; 100° 29’ 3” W). We obtained stream-discharge data from the USGS gaging station nearest to each site. For sites 1 and 2, we obtained discharge data from station number 08082500, which was located at site 1. We obtained discharge data for site 3 from gaging station number 08082000, which is located at the sampling site. We obtained discharge data for site 4 from gaging station number 08080500, which was located approximately 30-km downstream from the sampling site.

Fish were collected monthly at each site from April 2004 through August 2006, except during the spawning season, May through September, during which samples were made twice each month. Seine data were summarized as either total numbers of fish captured, or as catch per effort, expressed as the number captured per seine haul.

Flood events occasionally precluded field sampling, particularly in November 2004. High salinity in the Salt Fork of the Brazos River throughout the study resulted in the collection of very few sharpnose shiner and smalleye shiner specimens at site 3. Therefore, we did not include samples from site 3 in our reproductive analyses.

Microhabitat Use

Matthews and Hill (1979, 1980) suggested that 50 seine hauls and associated habitat information were adequate to characterize habitat availability and preferences at a site. We made 50 seine hauls, at Site 1, on each sampling date, as described above.

Transects were sampled in a downstream-upstream direction to minimize impacts on adjacent transects (Matthews and Hill 1979). Each seine haul covered a distance of 5 m and was made in a downstream direction, with the current, over homogenous habitat (Matthews and Hill 1979). At the center of the area sampled, habitat type (i.e., pool, backwater, main channel), substrate type, current velocity, and physicochemical data (temperature, conductivity, dissolved oxygen concentration, and pH) were recorded.

Microhabitat use was assessed by comparing means $\pm$ 95% confidence intervals for physicochemical measurements in samples in which sharpnose shiner (or smalleye shiner) was present with those in which they were absent. Non-overlap of 95% confidence intervals was taken as evidence of microhabitat selection for values of that physicochemical variable. We also used linear and quadratic regression to determine whether there was an association ($P \geq 0.05$) between physicochemical measurements and abundance of sharpnose shiner and smalleye shiner.

Habitat and substrate data were summarized for each site and date by comparing the proportion of seine hauls in which sharpnose shiner, or smalleye shiner, was present versus the proportion from which it was absent. Chi-square tests were used to assess heterogeneity in habitat use. The null hypotheses tested were, assuming no selection for a specific habitat characteristic, that the proportion of seine hauls from a given habitat in which sharpnose shiner, or smalleye shiner, was captured would be equal to proportion from that same habitat in which sharpnose shiner, or smalleye shiner ,was absent. A significant test result, thus, is evidence of selection for specific habitats or habitat characteristics.

Population Size-structure

All fish collected were identified to species and measured to standard length (SL, mm). We constructed length-frequency histograms for sharpnose shiner and smalleye shiner collected from each site. We inferred population age-structure from visual inspection of the number of modes present in length-frequency histograms (Anderson and Neumann 1996). We superimposed normal probability density functions over the length-frequency histograms to assess between site differences in fish length. The normal probability density functions were calculated using the mean and standard deviation for fish collected at each site, on each date.

Reproductive Ecology

<u>Ovarian Development</u>

For each sampling site and date, we attempted to collect a target sample of 25 sexually mature individuals (>25 mm, SL) of sharpnose shiner and smalleye shiner for dissection and inspection of ovarian development. On a few occasions, we were unable to collect enough fish at a site to reach the target sample size. We removed the gonads of sampled fish and determined the sex of each individual by macroscopic inspection of the gonads. Gonads of all female fish were further classified as belonging to one of four stages of ovarian development following the classification system of Phillip (1993) and Bonner (2000). Stage I ovaries were classified as resting, with no evidence of developing ova. Stage II ovaries were classified as developing and contained small translucent ova in the early stages of yolk deposit. Stage III ovaries were classified as mature with many large cream colored, vitellogenic ova. Stage IV ovaries were classified as spent and contained few or no vitellogenic ova. We weighted ovaries and testes to the nearest 0.0001 g. We used gonads weights to calculate a gonadosomatic index (GSI = gonad weight / total body weight × [100]). We calculated mean GSIs for males and females separately, by site and date.

Oocyte Development

For each site and date, we removed ovaries from up to five Stage III female sharpnose shiner and smalleye shiner, when available, for histological analyses and ova counts. For each fish, we used one half of the ovary for histological analysis and the other half to determine number and size of vitellogenic ova. Preparation of ovaries for histological analysis followed the procedures of Crim and Glebe (1990), Hinton (1990), Patiño and Takashima (1995), and Bonner (2000). Ovaries were embedded in paraffin and sectioned longitudinally to a thickness of 5-7 µm. We fixed the sections to a microscope slide and stained them with Weigert's hematoxylin and eosin stain. We viewed slides under a compound microscope at 40× magnification and classified all oocytes in one complete section into one of the following groups: perinucleolar (PN), cortical alveoli (CA), early vitellogenic (EV), late vitellogenic (LV), germinal vesicle breakdown (GB), spent follicle (SP), and atretic follicle (AT).

Ova Size and Fecundity

We used one half of each ovary to assess size-frequency distributions of ova and to determine fecundity of sharpnose shiner and smalleye shiner. We attached a plankton counting wheel to the stage of a dissecting microscope and filled the wheel with water.

Each ovary was placed in the well and individual ova were separated from using forceps. We counted all vitellogenic ova and measured at least 100 ova to the nearest 0.1 mm with a calibrated ocular micrometer.

Statistical Analyses

Standard length and mean GSI for each species were compared among years, sites, and sampling dates by fitting a generalized linear model to the data. Because samples were collected at the same sites on each sampling date, site was treated as a repeated measure in all models. Models were fit to the data using a normal error distribution with an identity link function. General linear models were fit to data using maximum likelihood methods; therefore, significance was based on the X^2 distribution. In all cases, when fish lengths or GSI differed significantly among sites, pair-wise contrasts were evaluated to determine the nature of the differences.

Population Age-structure

We inferred population age-structure from length-frequency distributions and from inspection of annual growth-increments on otoliths. We determined population age structure from samples collected in April and May because samples collected at this time were representative of populations at the start of the spawning season. Length-frequency histograms indicated, and otoliths confirmed, that individuals of both species $\leq$ 45-mm standard length (SL) were age 1 and fish > 45 mm were age 2. Although we collected a small number of large individuals (>70-mm SL) of both species during routine sampling, no age-3 individuals were present in samples for which otoliths were removed and growth increments enumerated.

Development of Leslie Matrix-type Population Dynamics Models

The Leslie Matrix

To model population dynamics of sharpnose shiner and smalleye shiner we developed two Leslie matrix population models. The Leslie matrix has a long history of use in natural resource management, particularly in fisheries. The full model consists of two matrices. The first, the projection matrix, is an $n \times n$ square matrix of age-specific fecundity and survival rates, where n is the number of age classes. This matrix commonly is referred to as a projection matrix. The second matrix is an $n \times 1$ vector of counts of the number of individuals in each of the n age classes.

The traditional Leslie matrix model is a deterministic model that allows projection of future population size. However, the models for sharpnose shiner and smalleye shiner were then modified age-0 survival to assess the implications of variation in river discharge on age-0 survival, because reproductive success of many Great Plains fishes are believed to be related to magnitude and variability in discharge (Moore 1944; Bottrell et al. 1964; Cross et al. 1985; Bestgen et al. 1989; Platania and Altenbach 1998; Bonner 2000). Age-0 survival was modified by multiplying it by a river-discharge factor.

Age-specific Fecundity

We determined age-specific fecundity from histological analysis of ovarian tissue and total oocyte counts. The ovaries of both species contained mature oocytes and spent follicles throughout the reproductive season, indicating asynchronous ovarian development and multiple spawning by individuals (Heins and Rabito 1986; Ali and Kadir 1996; Lowerre-Barbieri et al. 1996). Estimates of annual fecundity for multiple spawning species cannot be inferred from counts of existing oocytes because new oocytes are recruited and spawned throughout the reproductive season. Counts taken from existing oocytes will result in an underestimate of annual reproductive output for multiple spawners (Parrish et al 1986; Weddle and Burr 1991; Lowerre-Barbieri et al. 1996). Therefore, we calculated annual fecundity using the equation developed by Hubbs et al. (1968):

$$\text{Annual Fecundity} = (S/I)(C),$$

where S is the spawning season length in days, I is the mean interval between spawning events in days, and C is the mean number of ova spawned in each spawning event. We calculated S as the period of time between the first and last spent follicle observed in the histological samples. At least one spent follicle or follicle undergoing germinal vesicle breakdown was observed in 57% and 62% of sharpnose shiner and smalleye shiner individuals, respectively. Based on this information, we assumed that spawning occurred on a daily basis ($I = 1$). Oocytes undergoing germinal vesicle breakdown are those that are in the process of being ovulated and spawned. Spent follicles are residual cells that remain in the ovarian tissue after ovulation and spawning of an oocyte has occurred. At water temperatures between 25 and 30°C, which are common in the Brazos River during summer, spent follicles remain in the ovary for a very short time, perhaps no longer than 15-24 hours (Fitzhugh and Hettler 1995). Therefore, we estimated *C* by calculating the mean number of spent follicles and follicles in germinal vesicle breakdown on each sampling date.

Age-specific Survival

Based on the results of the otolith analysis we used simple proportions of fish > 45-mm and ≤ 45-mm to determine age-specific survival. Survival from age 1 to age 2 was estimated to be 0.1218 for sharpnose shiner and 0.1070 for smalleye shiner. We assumed that survival of age-2 fish was nil.

From available data, we were able to develop estimates of all necessary population parameters except survival from age 0 (ovum) to age 1 to parameterize the projection matrix (de Kroon et al. 1986; Caswell 2001) of a Leslie matrix model for sharpnose shiner and smalleye shiner. If all elements of the projection matrix are known, the rate of population growth λ can be estimated (Caswell 2001). Alternatively, if the rate of population growth is known, or is assumed to take some value, any one missing element of the projection matrix can be estimated (Vaughan and Saila 1976; Vélez-Espino et al. 2006). Therefore, we assumed that sharpnose shiner and smalleye shiner populations were static, with a rate of population growth $\lambda = 1$ and used the method of Vaughan and Saila (1976) to estimate the survival rate from age 0 to age 1.

Elasticity and Sensitivity Analyses

We used elasticity and sensitivity analysis (Benton and Grant 1999; Caswell 2001) to identify the life history stages, or parameters, that most influenced population growth. Elasticity analysis estimates the proportional change in the population growth rate for a given change in a population parameter (fecundity, survival) and can be used to identify stages that might be most influenced by conservation or management practices (Benton and Grant 1999). Mills et al. (1999) suggested the use of simulations to better understand the limitations of matrix models and their dependence on parameter estimates. This approach provides a quantitative assessment of the potential effects of uncertainty in parameter estimates. For each age class, we modeled age-specific fecundity as a normally-distributed variable with mean ($\bar{x}$) and variance (s^2) equal to the square root of the mean. The simulations intentionally encompassed an extremely wide range of potential fecundities. Age-specific survival (*S*) was modeled as a positive normally distributed variable with the mean equal to the observed survival and variance equal to the absolute value of $\bar{x} \times (1-\bar{x})$. One thousand simulations were conducted and the resulting elasticity estimates were compiled into histograms for each parameter in the projection matrix.

Alternative Models

Because the reproductive success of broadcast spawning species depends on stream discharge (Durham and Wilde 2006), we parameterized our population dynamics model to include a discharge factor (DEST) that adjusted the age-0 survival parameter by multiplying the original estimate by a stream discharge factor. This factor was obtained by maximum likelihood methods (Hilborn and Mangel 1997), and was estimated separately for sharpnose shiner and smalleye shiner. Stream discharge information was obtained from USGS gaging station 08082500 located near the town of Seymour in Baylor County, Texas. The discharge model was parameterized using mean daily discharge data during May through September, which corresponds to the reproductive season for sharpnose shiner and smalleye shiner in the Brazos River.

In addition to the discharge-related model, we constructed two alternative (null) population models for sharpnose shiner and smalleye shiner. These models were constructed to allow an assessment of the predictive capabilities of the discharge model versus those of reasonable null alternatives (e.g., Hilborn and Mangel 1997). One alternative model, the static model, assumes no change in abundance through time and was parameterized by calculating the mean population size, across all years, and assuming this value in each year. The other alternative model, constant lambda model, assumes a constant population growth rate (λ) based on observed population abundance across all years.

Model Assessment

To assess the utility of the discharge model, we predicted population size with each model and compared it to catch per unit effort data from fish collections in the upper Brazos River made during 1997-1998 and 2003-2006. We used the Akaike information criterion (AIC) to evaluate the three alternative models for each species (Hilborn and Mangel 1997; Burnham and Anderson 2002). Because the number of samples (years) in our study was small compared with the number of estimated parameters in each model, we used the second-order AIC (AIC_c) as recommended by Burnham and Anderson (2002).

Temporal Trends in Sharpnose Shiner and Smalleye Shiner Abundance

We examined and compiled museum records and published accounts on the Brazos River fish assemblage to determine whether trends in abundance of sharpnose shiner and smalleye shiner could be identified. We then attempted to use this trend information to model the abundance of sharpnose shiner and smalleye shiner as a function of timing, magnitude, and variability in river discharge to better understand effects of river modification on population declines. We used regression and age-structured matrix models to assess effects of discharge on population abundance of both species.

RESULTS

Fish Distribution and Abundance

During both surveys, we collected a total of 24,629 specimens representing 15 families, and 45 species and two at least two hybrid combinations (Table 2). A greater number of fishes (N = 15,210) was captured in the August survey than in the June survey (N = 9,419) due to the presence of a large number of young-of-year fishes in the second survey. By far, the two most abundant species were red shiner *Cyprinella lutrensis* and bullhead minnow *Pimephales vigilax*. These species accounted for 58% of fishes in the June survey and 59% in the August survey. No other species represented more than 8% of fishes captured.

Table 2. Species captured, and total number of individuals captured, during two surveys of the Brazos River, during June and August 2006.

Species	June 2006		August 2006	
	Number	%	Number	%
Alligator gar *Atractosteus spatula*			2	0.0
Spotted gar *Lepisosteus oculatus*	1	0.0	2	0.0
Longnose gar *Lepisosteus osseus*	21	0.2	8	0.1
Pirate perch *Aphredoderus sayanus*	2	0.0	28	0.2
Gizzard shad *Dorosoma cepedianum*	37	0.4	32	0.2
Threadfin shad *Dorosoma petenense*	155	1.6	13	0.1
Inland silverside *Menidia beryllina*	109	1.2	426	2.8
Western mosquitofish *Gambusia affinis*	161	1.7	879	5.8
Red River pupfish *Cyprinodon rubrofluviatilis*	376	4.0	1205	7.9
Plains killifish *Fundulus zebrinus*	312	3.3	269	1.8
Blackspotted topminnow *Fundulus olivaceus*	1	0.0	34	0.2
Common carp *Cyprinus carpio*	1	0.0		
Fathead minnow *Pimephales promelas*	3	0.0		
Bullhead minnow *Pimephales vigilax*	1170	12.4	4350	28.6
Bluntnose minnow *Pimephales notatus*	4	0.0	750	4.9
Red shiner *Cyprinella lutrensis*	4336	46.0	4649	30.6
Blacktail shiner *Cyprinella venusta*	19	0.2	6	0.0
Sharpnose shiner *Notropis oxyrhynchus*	663	7.0	809	5.3
Chub shiner *Notropis potteri*			6	0.0
Plains minnow *Hybognathus placitus*	586	6.2	310	2.0
Smalleye shiner *Notropis buccula*	356	3.8	467	3.1
Ghost shiner *Notropis buchanani*	743	7.9	442	2.9
Silverband shiner *Notropis shumardi*	33	0.4	50	0.3
Mimic shiner *Notropis volucellus*			2	0.0
Weed shiner *Notropis texanus*	5	0.1		
Speckled chub *Macrhybopsis hyostoma*	125	1.3	227	1.5
River carpsucker *Carpiodes carpio*	38	0.4	24	0.2
Smallmouth buffalo *Ictiobus bubalus*	1	0.0		
Spotted sucker *Minytrema melanops*	2	0.0		
Grey redhorse *Moxostoma congestum*			2	0.0
Channel catfish *Ictalurus punctatus*	18	0.2	28	0.2
Blue catfish *Ictalurus furcatus*			44	0.3
Flathead catfish *Pylodictis olivaris*	1	0.0	2	0.0

Table 2. Concluded.

Species	June 2006		August 2006	
	Number	%	Number	%
Green sunfish *Lepomis cyanellus*	11	0.1	3	0.0
Bluegill *Lepomis macrochirus*	26	0.3	64	0.4
Orangepotted sunfish *Lepomis humilis*	5	0.1	9	0.1
Longear sunfish *Lepomis megalotis*	10	0.1	14	0.1
Redear sunfish *Lepomis microlophus*			2	0.0
Hybrid sunfish *Lepomis spp.*	36	0.4	29	0.2
Largemouth bass *Micropterus salmoides*	13	0.1	2	0.0
Spotted bass *Micropterus punctulatus*	14	0.1	1	0.0
White crappie *Pomoxis annularis*	9	0.1		
White bass *Morone chrysops*	4	0.0		
Hybrid white bass *Morone chrysops x M. saxatilis*			2	0.0
Bigscale logperch *Percina macrolepida*	7	0.1	8	0.1
Dusky darter *Percina sciera*	1	0.0		
Striped mullet *Mugil cephalus*	4	0.0	10	0.1
Total Number Captured	9419		15210	

Sharpnose shiner and smalleye shiner were collected only from the upper Brazos River, upstream from Possum Kingdom Reservoir during the June and August 2006 surveys. A total of 1,472 sharpnose shiners were collected from eight of 11 sites in the upper Brazos River and a total of 823 smalleye shiners were collected at six sites (Table 3). In the upper Brazos River, sharpnose shiner represented 20.7% of fishes sampled, whereas the smalleye shiner represented 11.6% of the assemblage.

We used detrended correspondence analysis ordinations to provide a summary of major patterns in composition of the fish assemblage. The first two axes of the ordination accounted for nearly 26% of the variance in abundance of 30 species for which at least 10 specimens were captured, across 20 sites and two dates (Figure 2). The first axis accounted for 17.6% of the variation and mainly differentiated upper Brazos River and lower Brazos River sites. Red River pupfish *Cyprinodon rubrofluviatilis* and plains killifish *Fundulus zebrinus* had the highest scores on DCA 1 (Figure 3). Other salt-tolerant species, which are most common in the upper Brazos River, including plains minnow *Hybognathus placitus*, sharpnose shiner, and smalleye shiner, also had high scores on this axis.

The second detrended correspondence axis, which accounted for 8.5% of the variation in fish abundance, mainly contrasted sites located in the Clear Fork of the Brazos River (sites 9 and 19, Table 1) with sites in the lower Brazos River (Figure 2). In particular, this axis contrasts the presence of orangespotted sunfish *Lepomis humilis*, bluegill sunfish *L. macrochirus* threadfin shad *Dorosoma petenense*, and blackspotted topminnow *Fundulus olivaceous* which are common only in the Clear Fork of the

Table 3. Numbers of sharpnose shiner, smalleye shiner, and total fishes caught in the upper Brazos River (upstream from Possum Kingdom Reservoir) during June and August 2006.

Month	Site	Sharpnose shiner	Smalleye shiner	Total Fishes Caught
June	10	4	0	217
June	11	22	72	574
June	13	0	0	311
June	16	8	173	307
June	17	10	36	291
June	18	185	15	311
June	19	0	0	205
June	20	113	18	215
June	21	321	42	433
June	22	0	0	142
June	23	0	0	172
August	10	0	34	559
August	11	124	19	379
August	13	0	0	631
August	16	0	0	319
August	17	44	82	247
August	18	139	7	252
August	20	350	78	609
August	21	152	247	417
August	22	0	0	20
August	23	0	0	504
Total		1472	823	7115

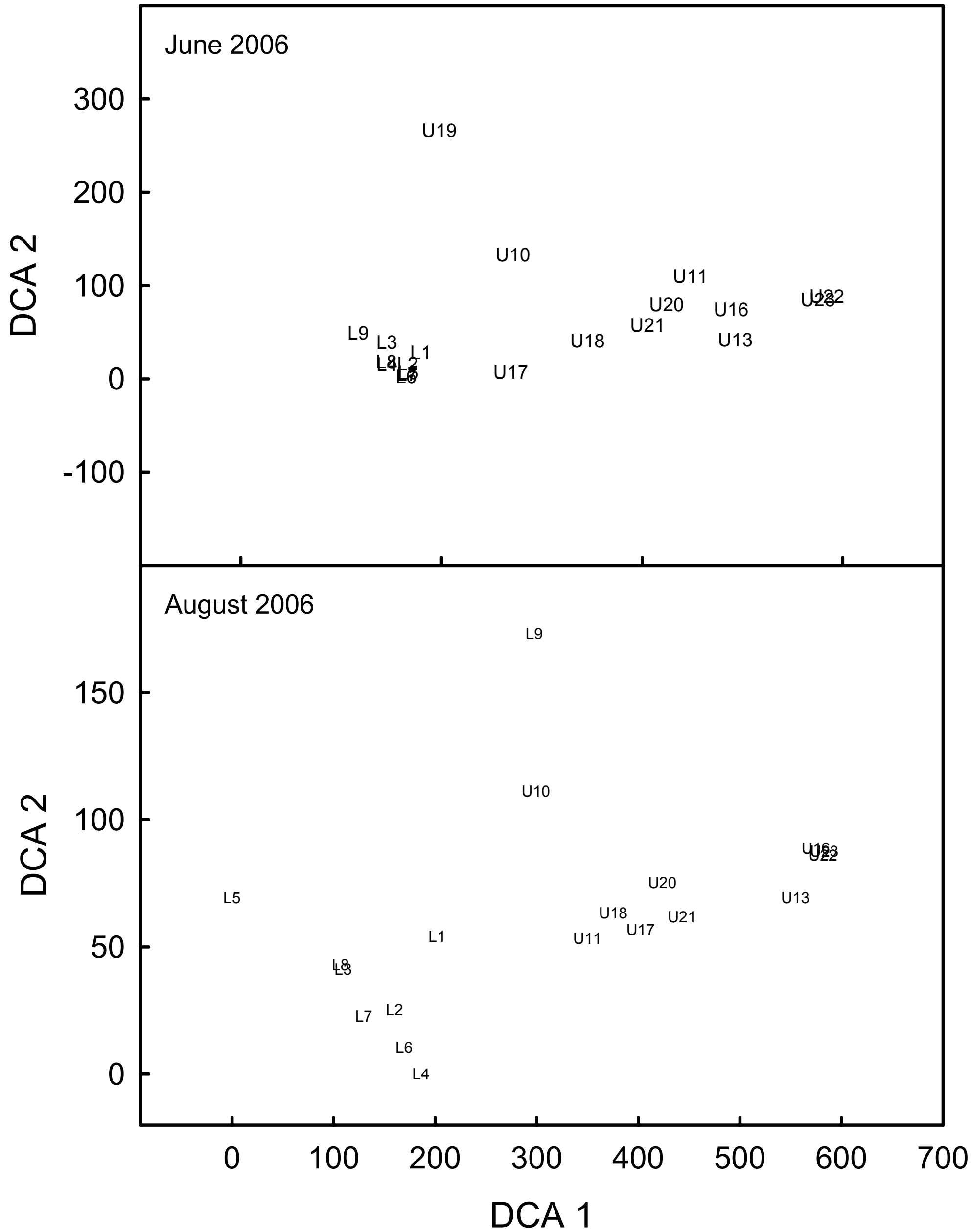


Figure 2. Detrended correspondence analysis ordination of sites sampled during June and August 2006 surveys of the Brazos River, Texas. Site numbers are as in Table 1. The labels, L and U, indicate sites located in the lower Brazos River (below Possum Kingdom Reservoir and including the Clear Fork of the Brazos River) and sites located in the upper Brazos River, respectively.

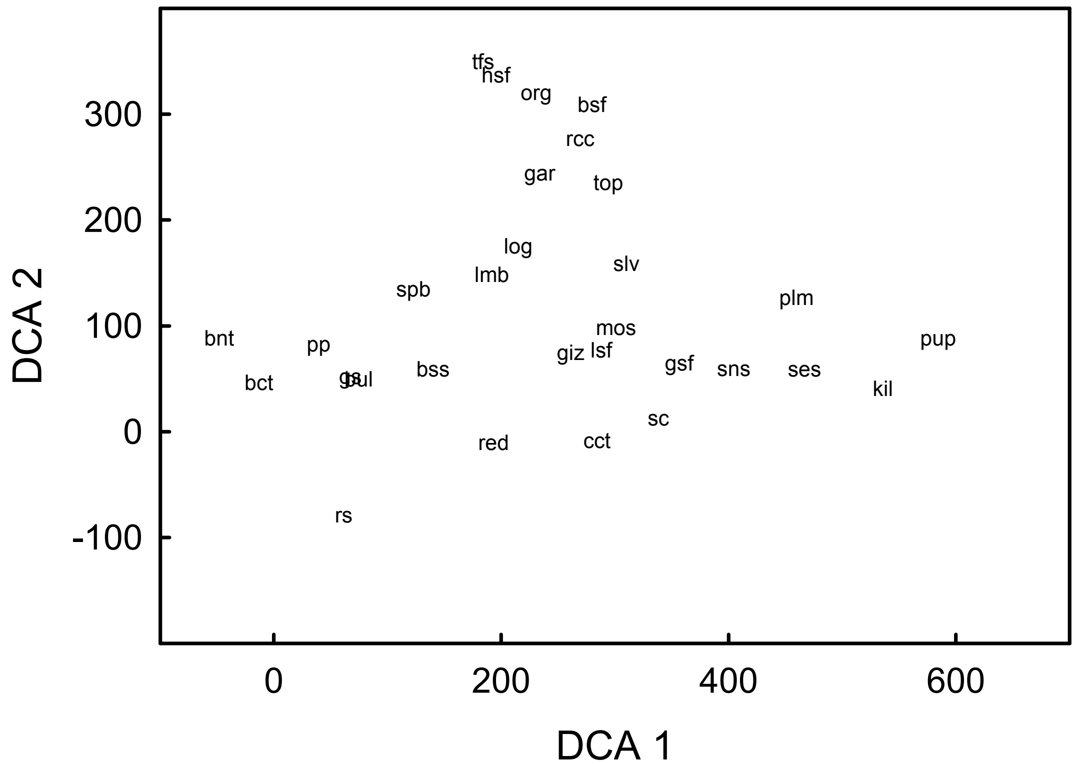


Figure 3. Detrended correspondence analysis ordination of species collected during June and August 2006 surveys of the Brazos River, Texas. Species labels are: (red shiner red, sharpnose shiner sns, smalleye shiner ses, speckled chub sc, red river pupfish pup, plains killifish kil, western mosquitofish mos, plains minnow plm, bullhead minnow bul, bluntnose minnow bnt, inland silverside slv, gizzard shad giz, threadfin shad tfs, green sunfish gsf, orangepotted sunfish org, bluegill bsf, longear sunfish lsf, river carpsucker rcc, largemouth bass lmb, spotted bass spb, channel catfish cct, blue catfish bct, pirate perch pp, ghost shiner gs, hybrid sunfish hsf, silverband shiner rs, longnose gar gar , blackspotted topminnow top, bigscale logperch log, and blacktail shiner bss.

Brazos River, with silverband shiner *Notropis shumardi,* which is present only in the lower Brazos River.

Population Monitoring

A total of 2,313 specimens, representing 12 families, were collected during routine population monitoring at Site 1, Seymour, Texas, during April 2004 through March 2005 (Table 4). Sharpnose shiner (61% of the assemblage), speckled chub *Macrhybopsis hyostoma* (18%), smalleye shiner (13%), and plains minnow (6%) were the most common fishes at this site. No other species represented one percent of the assemblage.

During the study period, sharpnose shiner was most abundant in April, May, and June, during which time 168 (April) to 712 (June) fish were captured (Figure 4). Catches of sharpnose shiner decreased during the summer and remained less than 100 per sampling date through the fall and winter. Smalleye shiner catches ranged from a low of seven individuals in October to 81 individuals captured in January. There was no evident seasonal pattern in the abundance of smalleye shiner.

Microhabitat Use

Sharpnose shiner was collected from a wide range of microhabitat types, as defined by physicochemical variables. Sharpnose shiner occurred in samples ranging from 5.6 to 33.7^{o}C, but showed no obvious pattern of occurrence based on water temperature (Figure 5). Sharpnose shiner were collected from waters with dissolved oxygen concentrations ranging from 3.3 to 11.2 ppm, conductivities ranging from 2.7 to

Table 4. Abundance of fishes captured during monthly sampling at Site 1, Seymour, Texas in the upper Brazos River, during April 2004 to March 2005.

Species	Number
Sharpnose shiner *Notropis oxyrhynchus*	1417
Speckled chub *Macrhybopsis hyostoma*	427
Smalleye shiner *Notropis buccula*	291
Plains minnow *Hybognathus placitus*	152
Western mosquitofish *Gambusia affinis*	15
Red River pupfish *Cyprinodon rubrofluviatilis*	3
Red shiner *Cyprinella lutrensis*	2
Channel catfish *Ictalurus punctatus*	2
Plains killifish *Fundulus zebrinus*	1
Gizzard shad *Dorosoma cepedianum*	1
Chub shiner *Notropis potteri*	1
Largemouth bass *Micropterus salmoides*	1
Total	2313

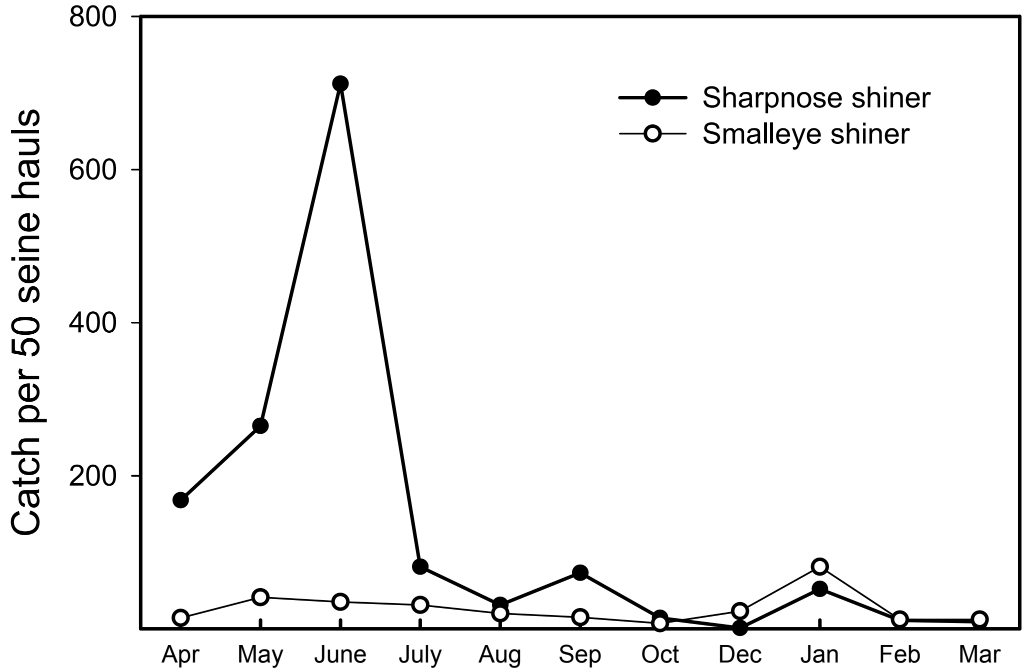


Figure 4. Relative abundance of sharpnose shiner and smalleye shiner at Site 1, Seymour, Texas, during April 2004 to March 2005.

18.3 mS/cm, and turbidities ranging from 10.4 to 631 NTU. Overall, there was little difference in water temperature, dissolved oxygen, conductivity, and turbidity among samples that included sharpnose shiner and those than did not (Figure 5) and there was no significant (*P* = 0.0759 to *P* = 0.9779) association between sharpnose shiner abundance and water temperature, dissolved oxygen, conductivity, and turbidity.

Smalleye shiner was collected from a wide range of microhabitat types, as defined by physicochemical variables. Smalleye shiner occurred in samples ranging from 5.1 to 33.7^{o}C, but showed no obvious pattern of occurrence based on water temperature (Figure 6). Smalleye shiner were collected from waters with dissolved oxygen concentrations ranging from 4.8 to 11.4 ppm, conductivities ranging from 2.8 to 18.3 mS/cm, and turbidities ranging from 10.438 to 631 NTU. Overall, there was little difference in water temperature, dissolved oxygen, conductivity, and turbidity among samples that included smalleye shiner and those than did not (Figure 6). There was no significant (*P* = 0.3616 to *P* = 0.9908) association between smalleye shiner abundance and water temperature, dissolved oxygen, conductivity, and turbidity.

Sharpnose shiner was collected from waters with current velocities ranging from 0 to 75 cm/s. There generally was little evidence of habitat selection by sharpnose shiner, except during periods when discharge exceeded about 40 cm/s (Figure 5) when sharpnose shiner showed a preference for slower waters. Smalleye shiner was collected from waters with current velocities ranging from 0 to 64 cm/s. On almost all sampling dates, smalleye shiner showed a preference for slower waters (Figure 6). The preferences shown by both species were slight. On every date, 95% confidence intervals about the

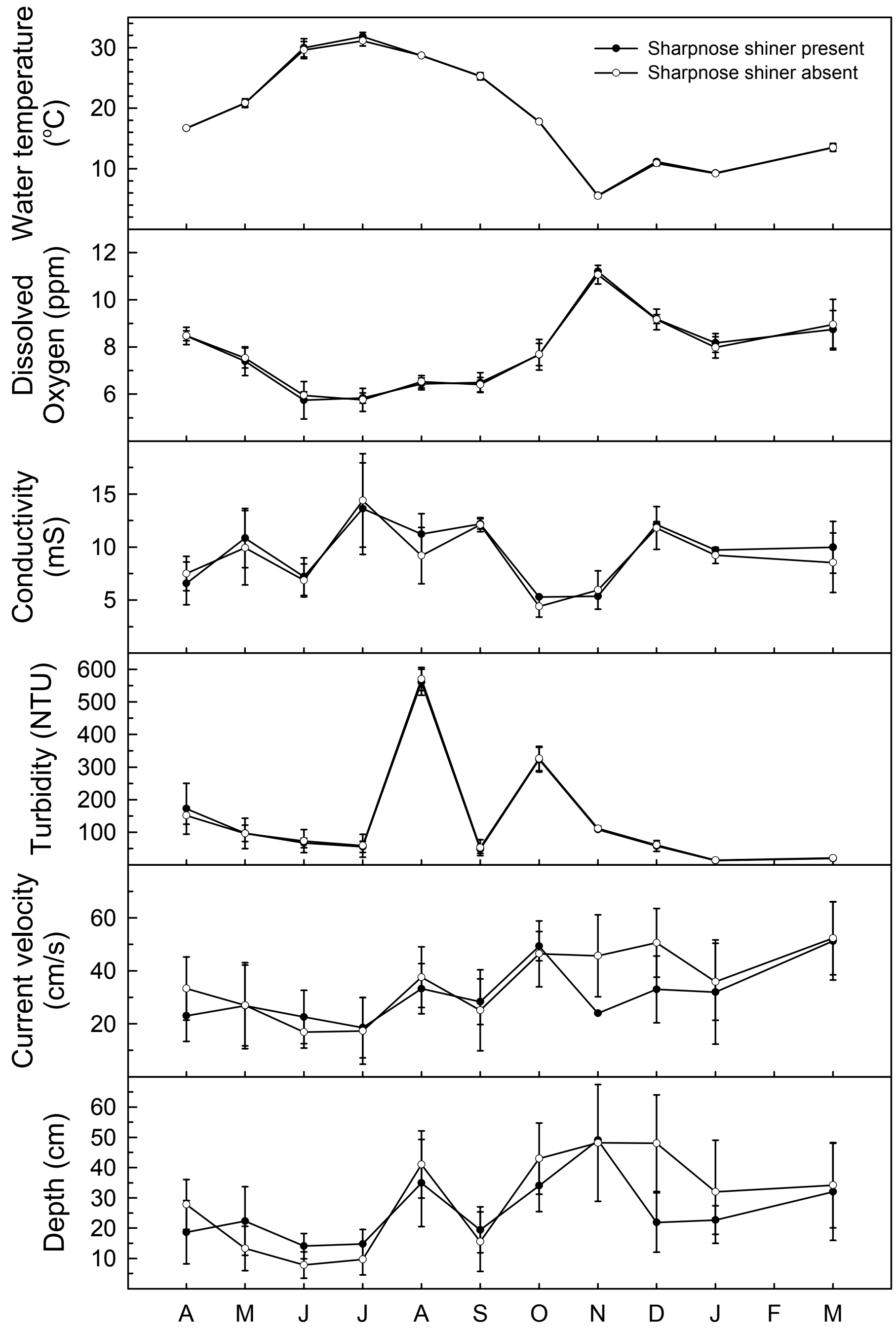


Figure 5. Mean physicochemical conditions in samples that contained sharpnose shiner (closed circles) versus that those that did not (open circles) in the Brazos River, Texas, from April 2004 to March 2005.

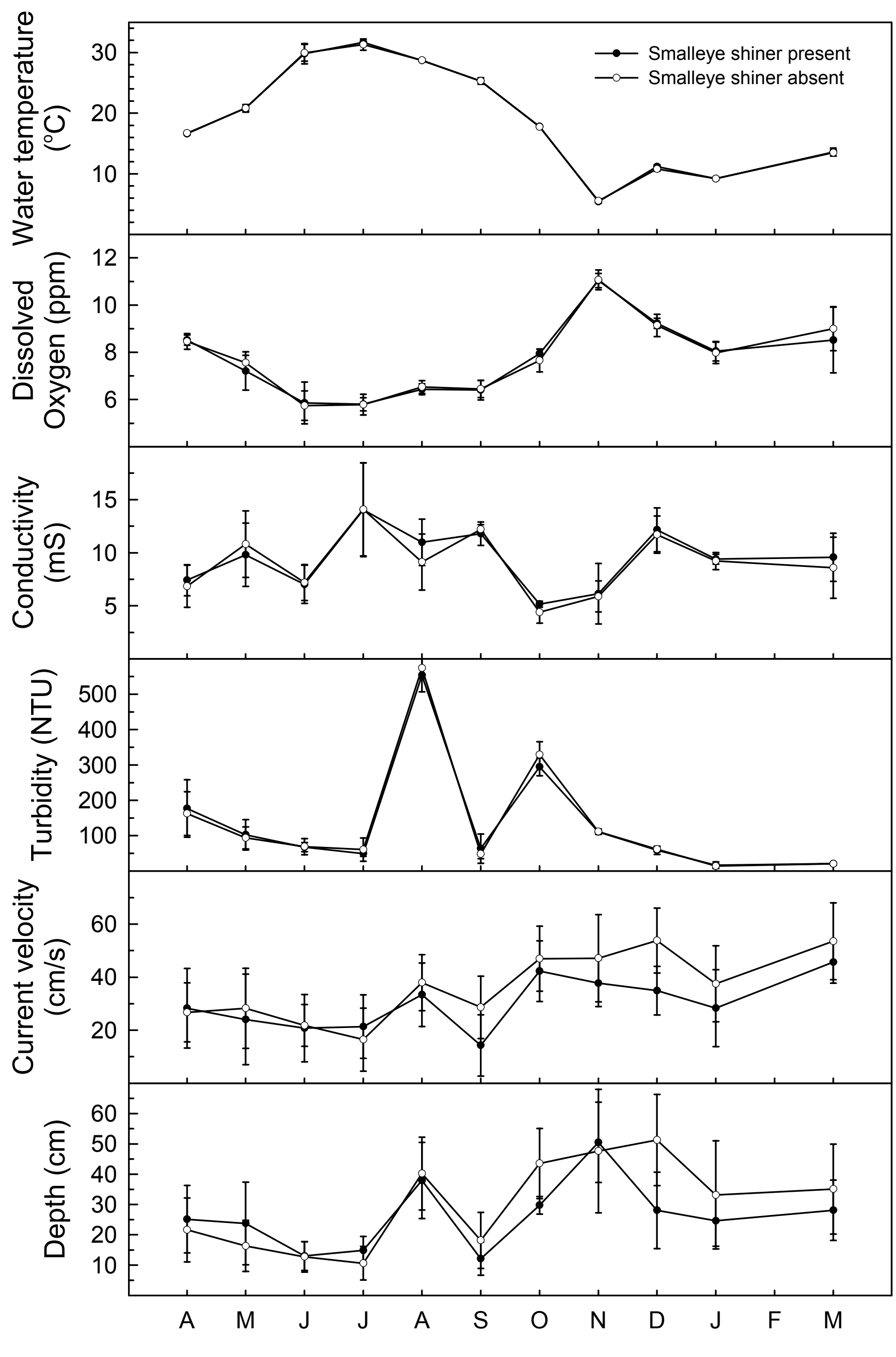


Figure 6. Mean physicochemical conditions in samples that contained smalleye shiner (closed circles) versus that those that did not (open circles) in the Brazos River, Texas, from April 2004 to March 2005.

mean current velocity for samples in which either species was present or absent showed substantial overlap. There was no evidence of any difference among sharpnose shiner and smalleye shiner based on current velocity (Figure 7). Current velocity was the only physical or chemical parameter with which sharpnose shiner catches were significantly related ($P = 0.0355$), but there was no such association ($P = 0.2928$) with catches of smalleye shiner.

Sharpnose shiner was collected from waters ranging in depth from 4 to 64 cm (Figure 5) and smalleye shiner were collected from waters ranging in depth from 3 to 65 cm (Figure 6). Based on available habitat, both species appeared to prefer depths ranging from approximately 20 to 40 cm, but these preferences were not pronounced and there was little evidence that sharpnose shiner and smalleye shiner segregated based on depth (Figure 7). Neither sharpnose shiner ($P = 0.3324$) nor smalleye shiner abundance ($P = 0.4600$) was related to depth.

Most samples (> 80%) were collected from main channel habitats (Figure 8). There was no obvious evidence of selection or avoidance of any particular habitat type by sharpnose shiner ($P > 0.1106$) or smalleye shiner ($P > 0.0017$) suggesting nonrandom utilization of various habitats.

Most samples were collected over sandy substrata (Figure 9). The remainder of samples was collected over silt, gravel, and cobble substrata. Sharpnose shiner occurred over silt ($X^2 = 20.6200$, 1 df, $P < 0.0001$) and gravel ($X^2 = 28.6023$, 1 df, $P < 0.0017$) substrates more frequently than expected, but showed no positive or negative associations with other substrate types ($P > 0.05$). Smalleye shiner occurred over silt ($X^2 = 28.6023$, 1 df, $P < 0.0001$) substrates much more frequently than expected (Figure 9) and occurred

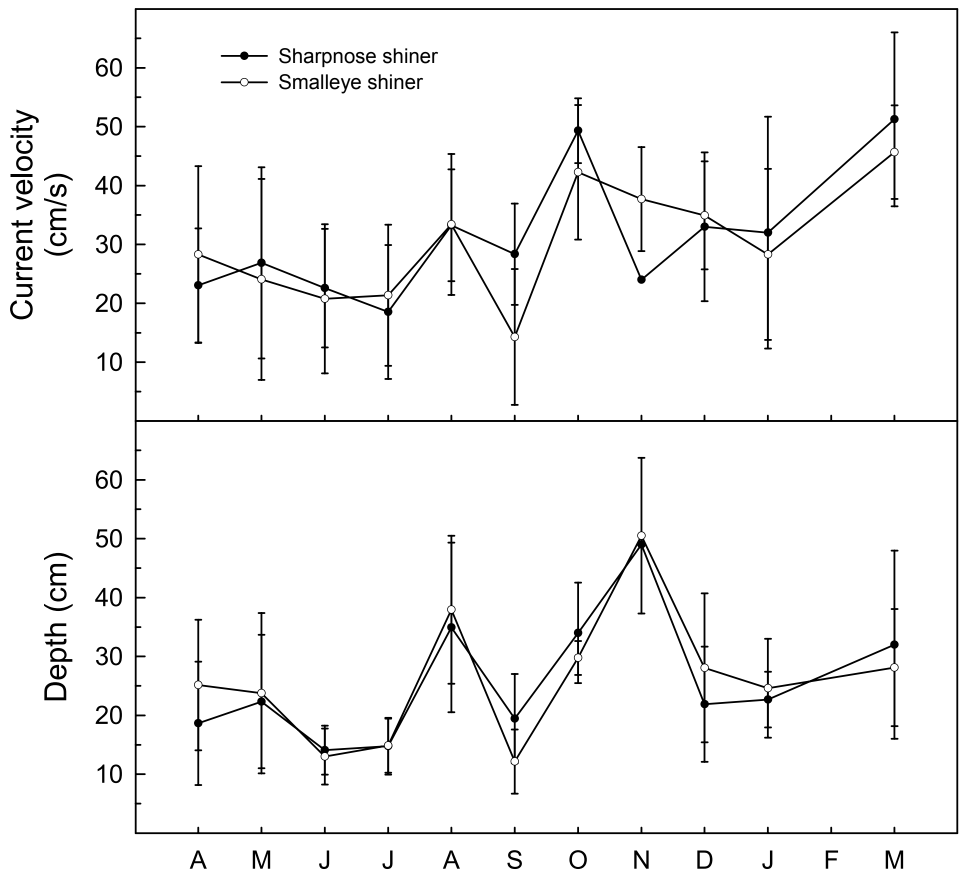


Figure 7. Mean current velocity and depth of samples that contained sharpnose shiner (closed circles) compared with those that contained smalleye shiner (open circles) in the Brazos River, Texas, from April 2004 to March 2005.

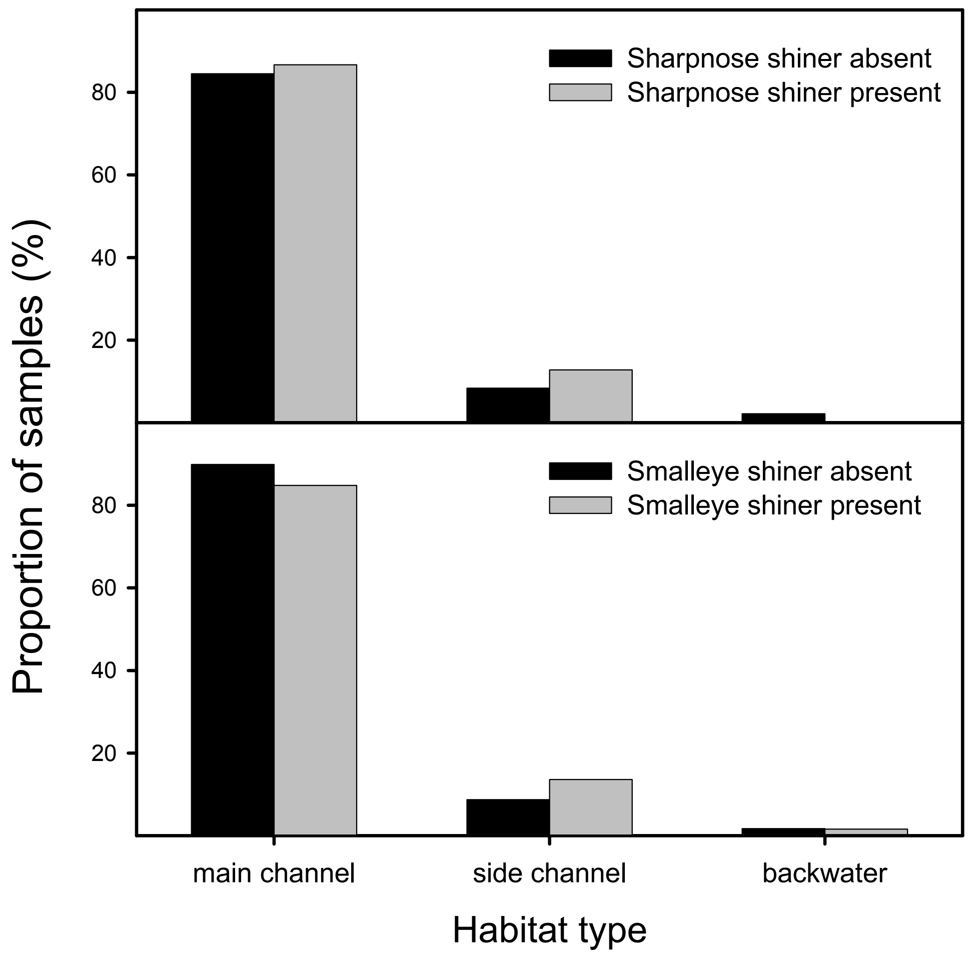


Figure 8. Channel habitat-type of samples that contained sharpnose shiner (top panel) or smalleye shiner (lower panel) compared with the channel habitat-type of samples that did not contain either species in the Brazos River, Texas, from April 2004 to March 2005.

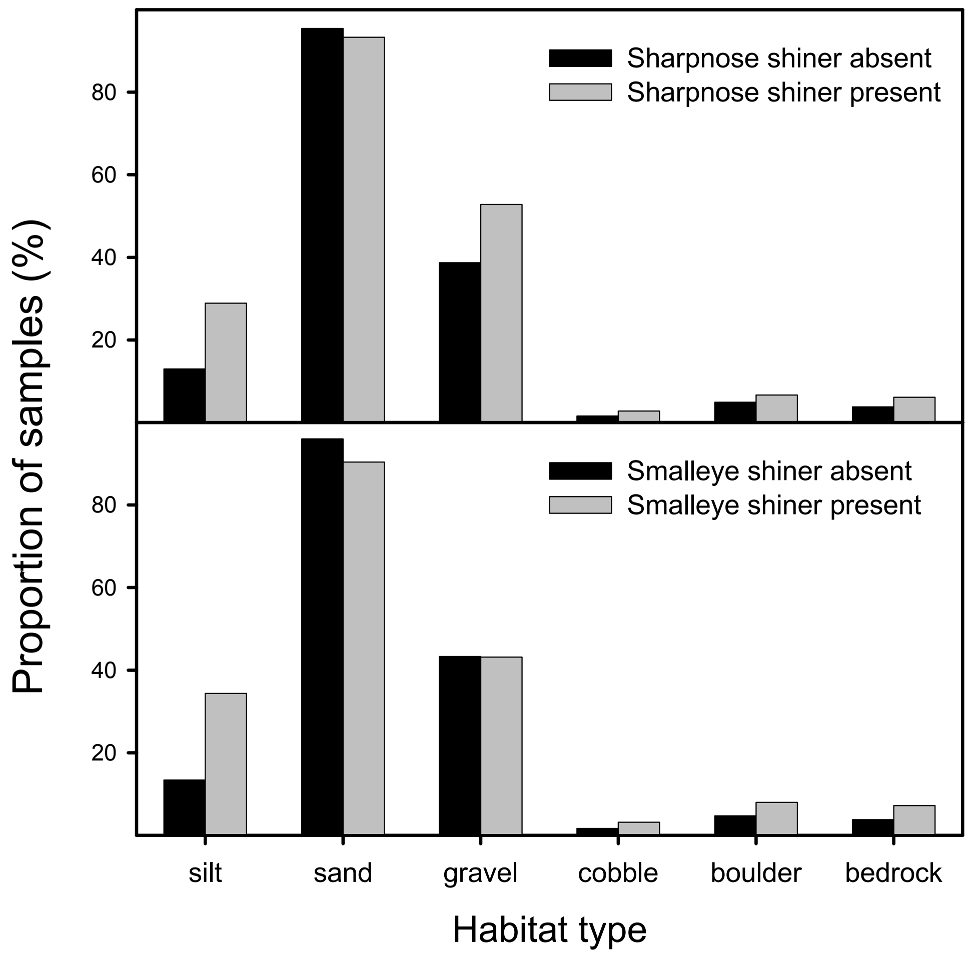


Figure 9. Substrate composition of samples that contained sharpnose shiner (top panel) or smalleye shiner (lower panel) compared with the substrate in samples that did not contain either species in the Brazos River, Texas, from April 2004 to March 2005.

over sand less frequently than expected (X^2 = 6.0646, 1 df, P < 0.0138). Smalleye shiner showed no other positive or negative associations with other substrate types (P > 0.05).

Population Size-structure of Sharpnose Shiner

Lengths of fish collected ranged from seven mm to 95 mm, but most specimens were less than 50-mm SL. Length-frequency histograms indicated that sharpnose shiner populations in the upper Brazos River primarily consist of two age groups: age-0 and age-1. A small number of specimens > 60-mm SL was collected, which likely represent a third age group (age 2) (Figure 10). Age-1 individuals made up the majority of the population during the study period. Age-0 individuals were collected beginning on the May II sampling date in 2004.

Mean lengths differed significantly among sampling dates (X^2 = 29.28; df = 1; P = < 0.0001) and sites (X^2 = 57.11; df = 2; P < 0.0001). Pair-wise contrasts between the three sites indicated that the only significant difference was between sites 1 and 4, with fish at site 1 being significantly smaller than fish at site 4. Normal probability distribution functions constructed using the mean and two standard deviations superimposed over the length-frequency distributions did not reveal a consistent temporal or spatial pattern to the differences in lengths of fish among sites or sampling dates (Figure 10).

Population Size-structure of Smalleye Shiner

Length-frequency histograms indicated that smalleye shiner populations consisted primarily of age-0 and age-1 individuals (Figure 11). Lengths ranged from four-mm to

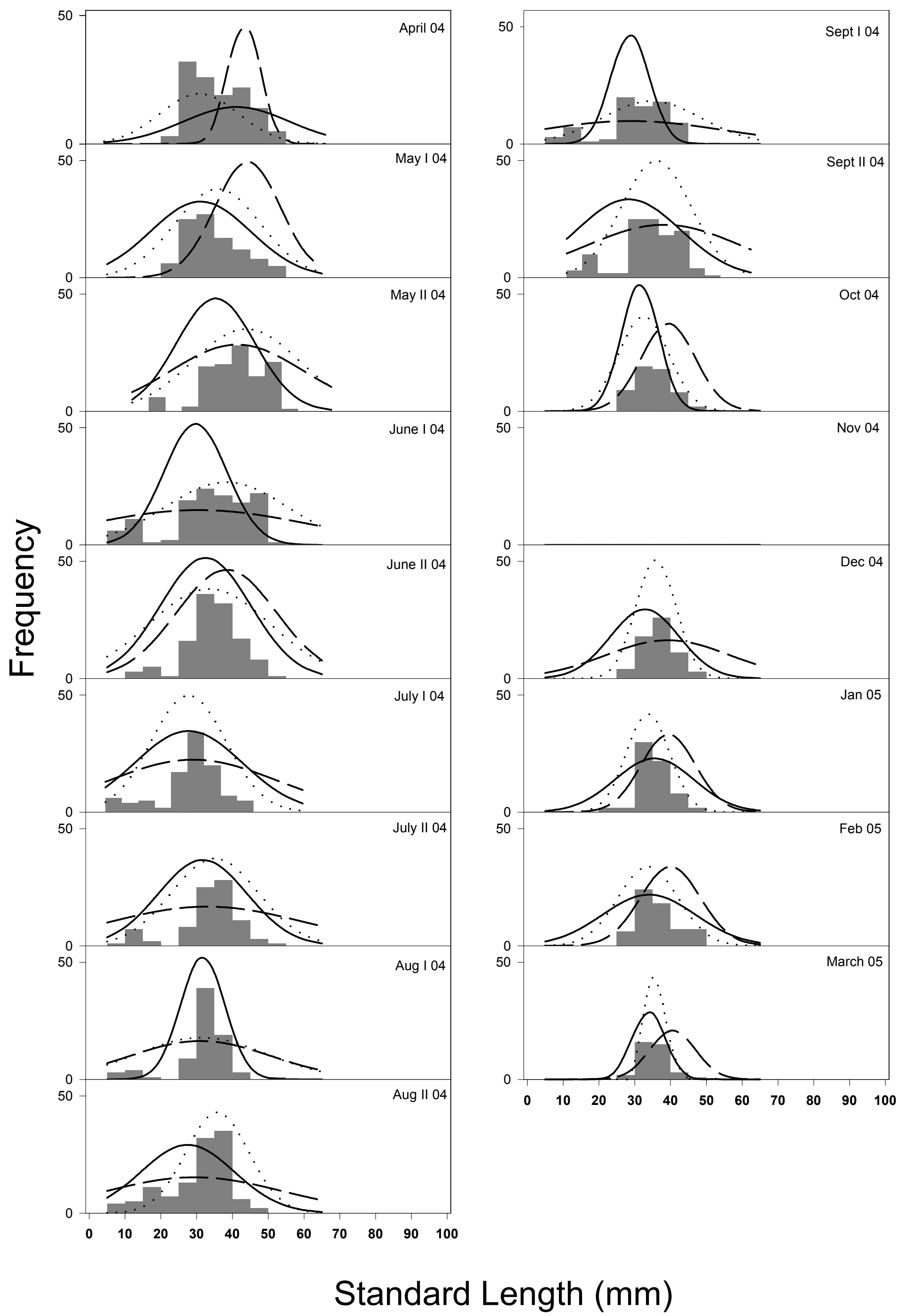


Figure 10. Length-frequency histograms for sharpnose shiner during April 2004 through March 2005 with normal probability distribution functions described by the mean length and two standard deviations of fish collected at each site.

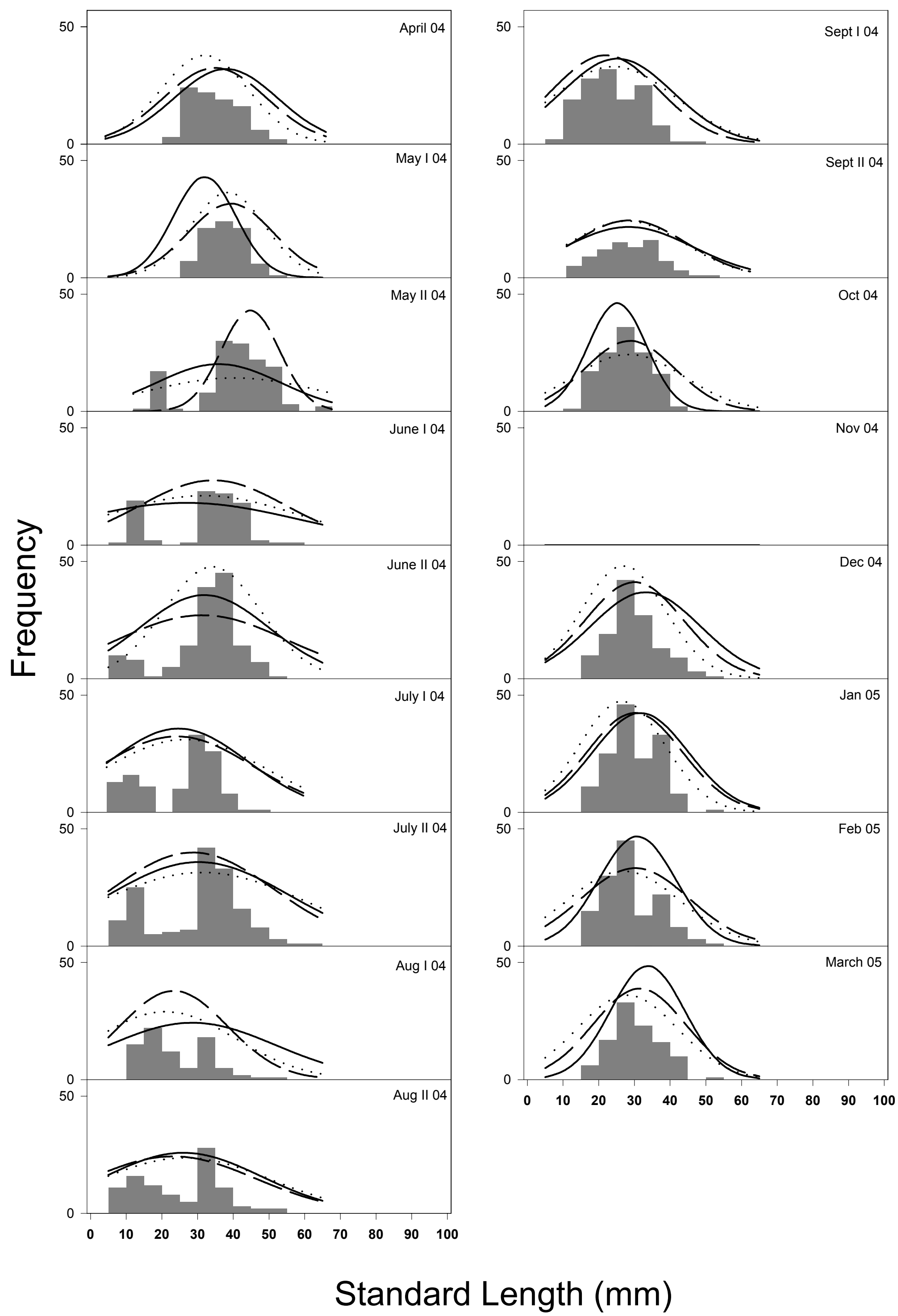


Figure 11. Length-frequency histograms for smalleye shiner during April 2004 through March 2005 with normal probability distribution functions described by the mean length and two standard deviations of fish collected at each site.

83-mm SL; however, a small number of specimens > 60-mm SL was collected. These larger individuals possibly represent a third age-group (age-2). Age-0 smalleye shiner were collected beginning on the May II sampling date in 2004 (Figure 11).

Mean standard lengths of smalleye shiner differed between sampling dates (X^2 = 88.0; *df* = 1 *P* = < 0.0001) and sites (X^2 = 14.24; *df* = 2; *P* = 0.0009). Pair-wise contrasts between the three sites indicated that fish were significantly larger at sites 1 and 2 than at site 4. Lengths of fish were not significantly different between sites 1 and 2. However, normal probability distribution functions superimposed over the length-frequency distributions failed to reveal any consistent temporal or spatial pattern in length among sites (Figure 11).

Ovarian Development of Sharpnose Shiner

Developing ovaries (Stage II) were observed in sharpnose shiner females beginning in April, indicating the onset of gonadal recrudescence (Figure 12). Sharpnose shiner ovaries developed rapidly and by the May II sampling date all ovaries were classified as mature (Stage III). Females contained mature ovaries for a six-month period, from April through September. Between May and July nearly all female sharpnose shiner ovaries were classified as mature. Spent ovaries (Stage IV) began to appear at the beginning of July and the proportion of Stage IV ovaries increased until October, after which time ovaries returned to a resting state (Stage I) that lasted from approximately October-March. Thus, sharpnose shiner has an extended reproductive period that lasts from April through September. In general, ovarian development was

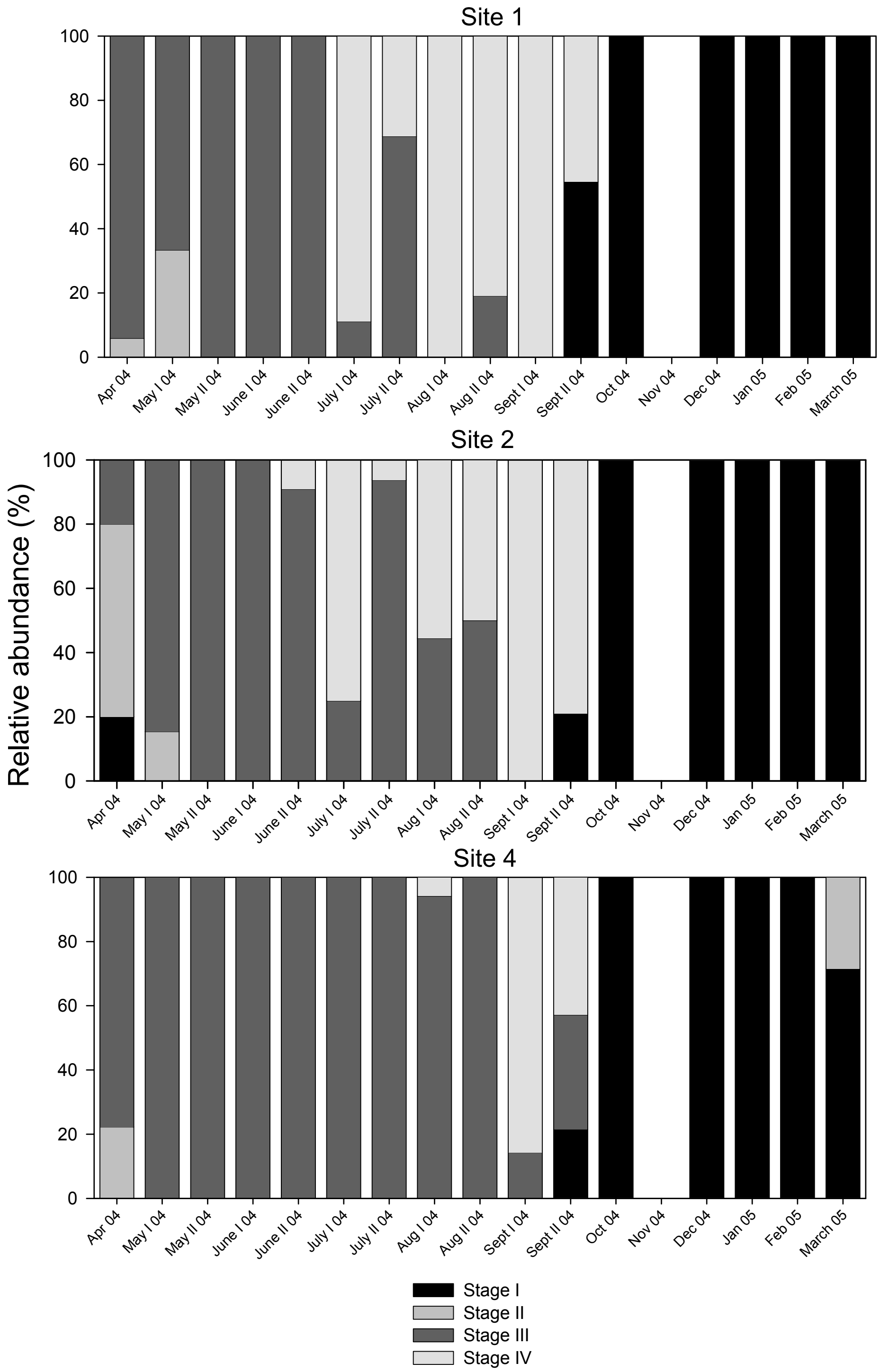


Figure 12. Relative abundance of female sharpnose shiner classified as having Stage I, II, III and, IV ovaries collected from each site on each sampling date, April 2004 through March 2005.

similar at all three sites, although there was some minor variation in the occurrence and proportion of females containing the different ovarian stages.

Mean GSI of female sharpnose shiner in 2004 ranged from 0.67% to 18.0% (Figure 13). Mean GSI at all three sites increased in early May, peaked in May or July, and generally remained elevated through August. GSI remained high and peaked multiple times before rapidly declining in September. Mean GSI in 2004 were significantly different among sampling dates (X^2 = 17.14; df = 1; P = < 0.0001) and sites (X^2 = 14.34; df = 2; P = 0.0008). Pair-wise contrasts between the three sites indicated that the only significant difference was between sites 1 and 4, with female GSI being greater at site 4.

Mean GSI of male sharpnose shiner in 2004 ranged from 0.39 to 1.99% (Figure 14). Male GSI generally increased in April and May and remained elevated through September in both years of the study. Mean GSI for male sharpnose shiner did not statistically different among sampling dates (X^2 = 2.44; df = 1; P = 0.12) or sites (X^2 = 2.43; df = 2; P = 0.30).

Ovarian Development of Smalleye Shiner

Developing ovaries (Stage II) in female smalleye shiner typically appeared in March, but were observed as early as February at site 4 in 2004 (Figure 15). Sharpnose shiner ovaries developed rapidly and mature ovaries (Stage III) were the most common ovarian stage from April to August in 2004. However, mature ovaries were observed as late as September in samples collected in 2003 that are not part of the present study. Smalleye shiner appear to be capable of spawning over month period, between April and

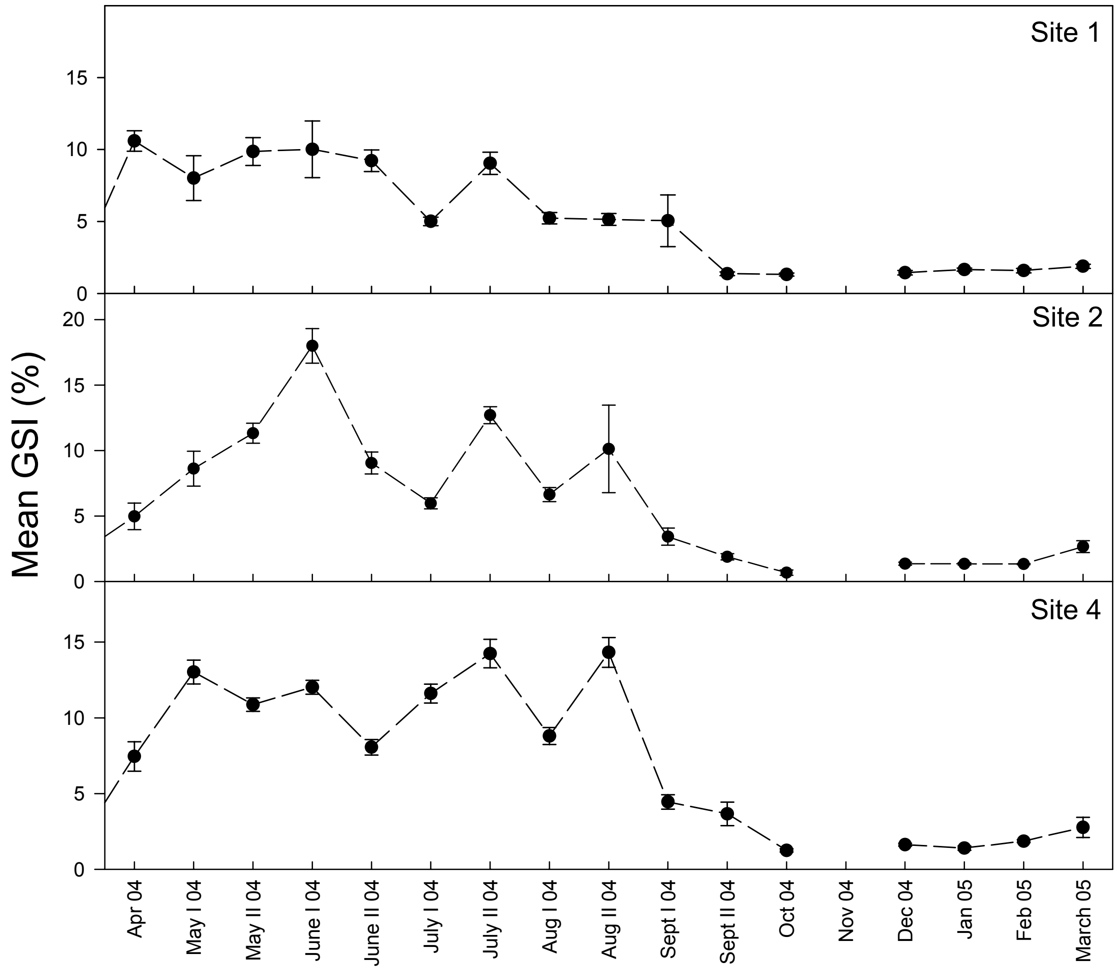


Figure 13. Mean gonadosomatic index (GSI) ± SE for female sharpnose shiner at each site on each sampling date, April 2004 through March 2005.

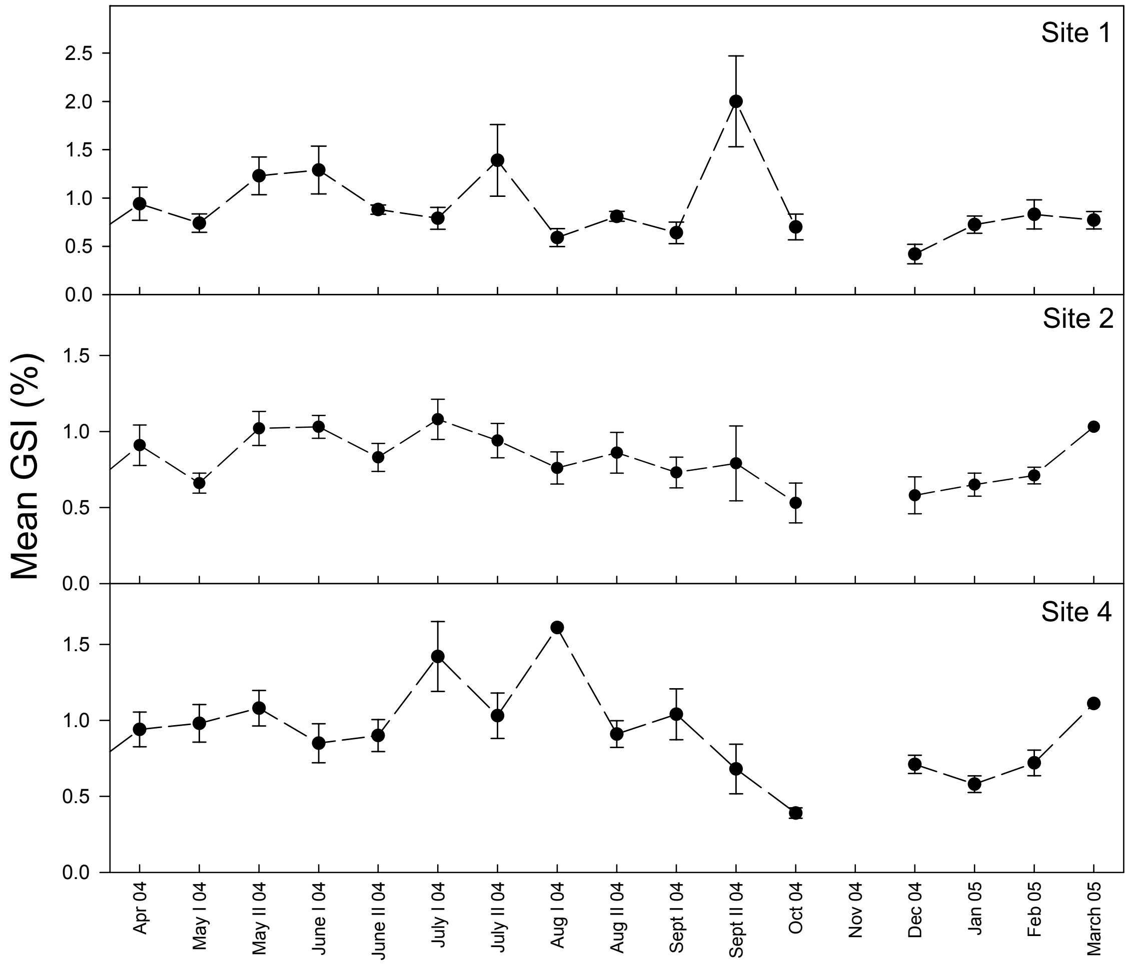


Figure 14. Mean gonadosomatic index (GSI) ± SE for male sharpnose shiner at each site on each sampling date, April 2004 through March 2005.

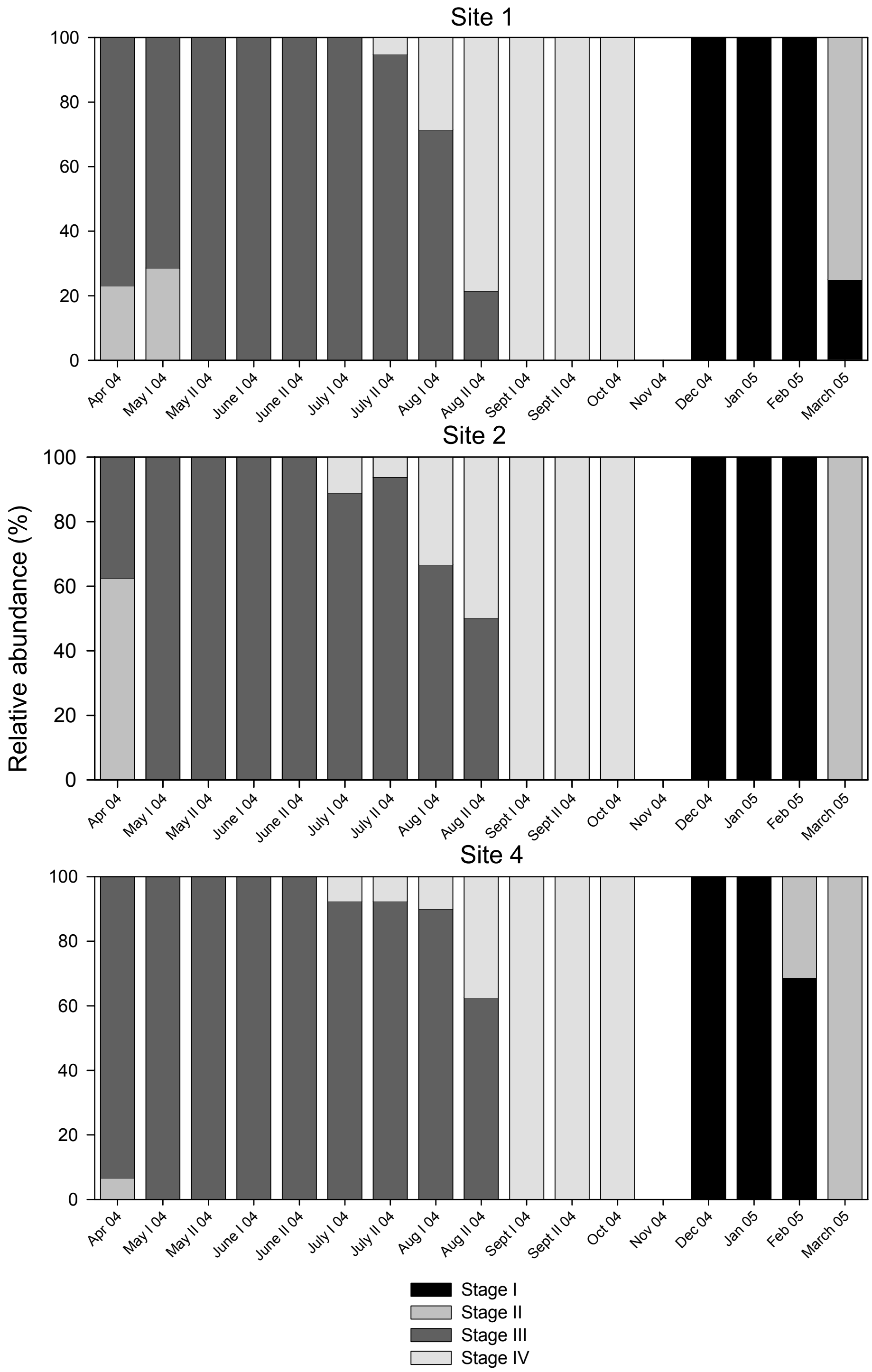


Figure 15. Relative abundance of female smalleye shiner classified as having Stage I, II, III or, IV ovaries collected from each site on each sampling date, April 2004 through March 2005.

September. Spent ovaries began to appear in July, 2004 and increased in frequency in until October, when the ovaries of most fish had returned to a resting state (Stage I).

Mean GSI of female smalleye shiner ranged from 0.71% to 18.49% in 2004 (Figure 16). Mean GSI at all three sites, increased in early May, peaked in late May, and generally remained elevated through the month of August. In 2004, GSI remained elevated and peaked multiple times before rapidly decreasing in August. GSI were differed significantly among sampling dates (X^2 = 7.36; *df* = 1; *P* = < 0.0067) but not sites (X^2 = 1.62; *df* = 2; *P* = 0.44).

Mean GSI of male smalleye shiner from 0.40% to 2.26% (Figure 17). Male GSI generally increased in April and May and remained elevated through September in both years of the study. In 2004, mean GSI were differed significantly among sampling dates (X^2 = 8.68; *df* = 1; *P* = < 0.0032) and sites (X^2 = 10.71; *df* = 2; *P* = 0.0047). Pair-wise contrasts between the three sites indicated that the only significant difference was between sites 2 and 4 with GSI being larger at site 4.

Oocyte Development of Sharpnose Shiner

Histopathological analyses were conducted for 125 females with mature ovaries in 2004. All ovaries examined contained oocytes in multiple stages of development (Figures 18-20), which indicates that oocytes develop asynchronously within the ovaries of sharpnose shiner. Direct evidence of ovulation and spawning of oocytes was confirmed by the presence of oocytes undergoing germinal vesicle breakdown as well as by the presence of spent follicles (remnants of recently ovulated oocytes) within ovaries. In 2004, these two stages were first observed in April at all sites (Figures 18-20) and

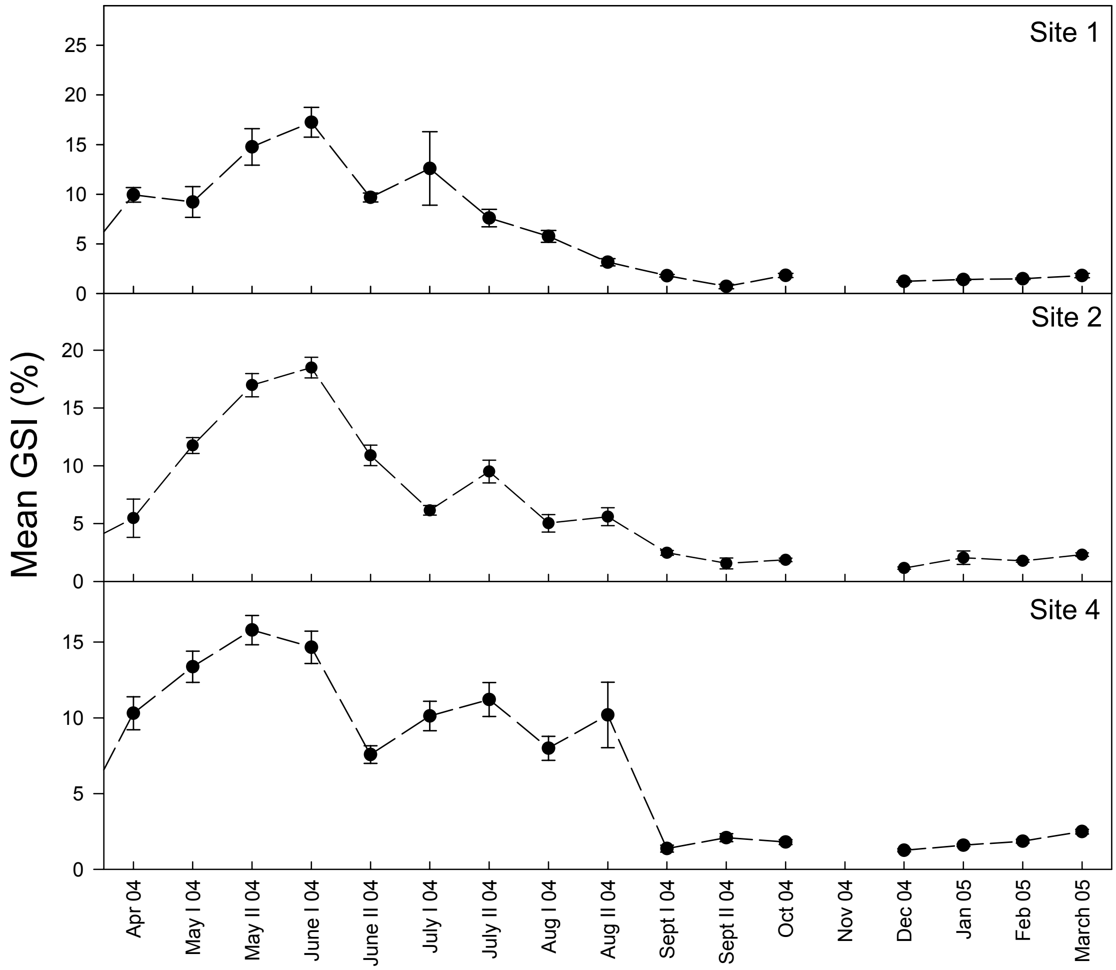


Figure 16. Mean gonadosomatic index (GSI) ± SE for female smalleye shiner at each site on each sampling date, April 2004 through March 2005.

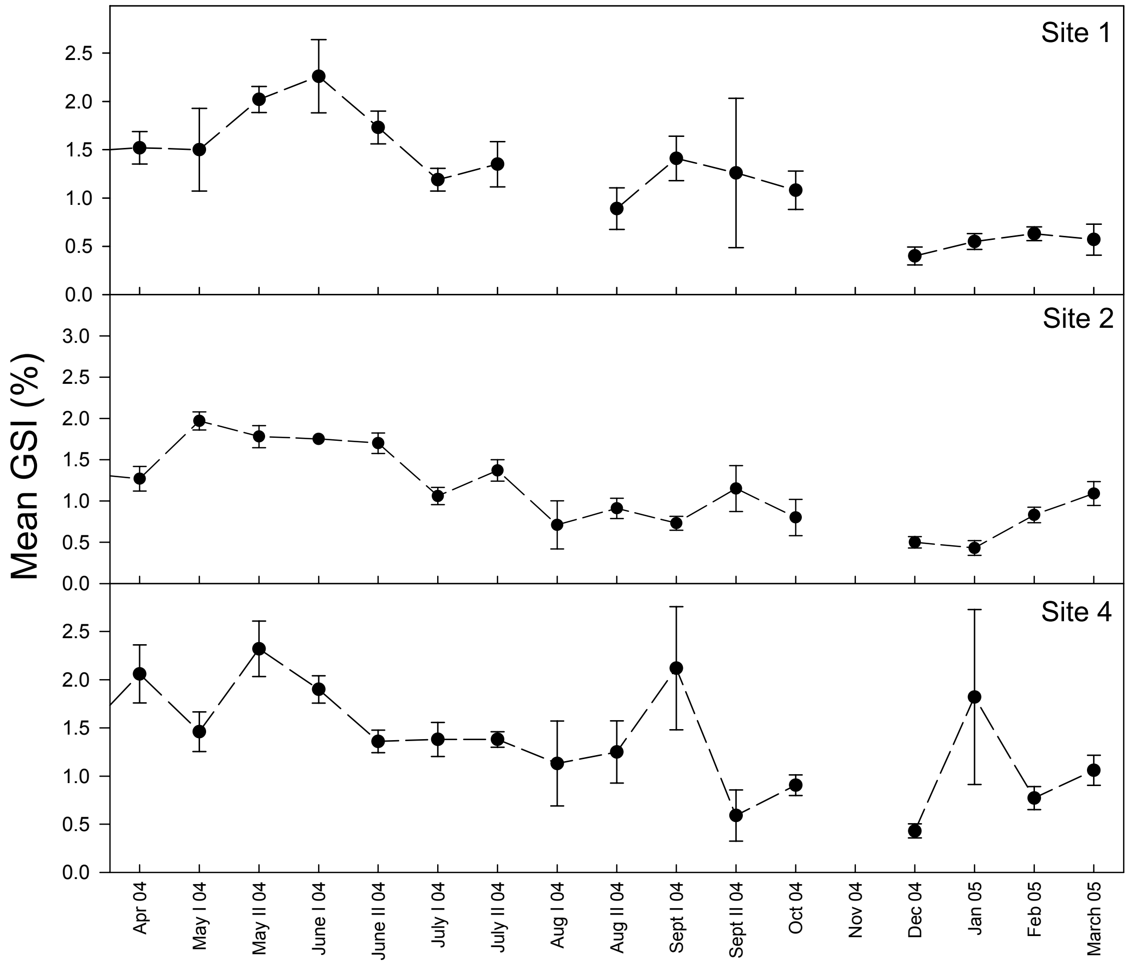


Figure 17. Mean gonadosomatic index ± SE for male sharpnose shiner at each site on each sampling date, April 2004 through March 2005.

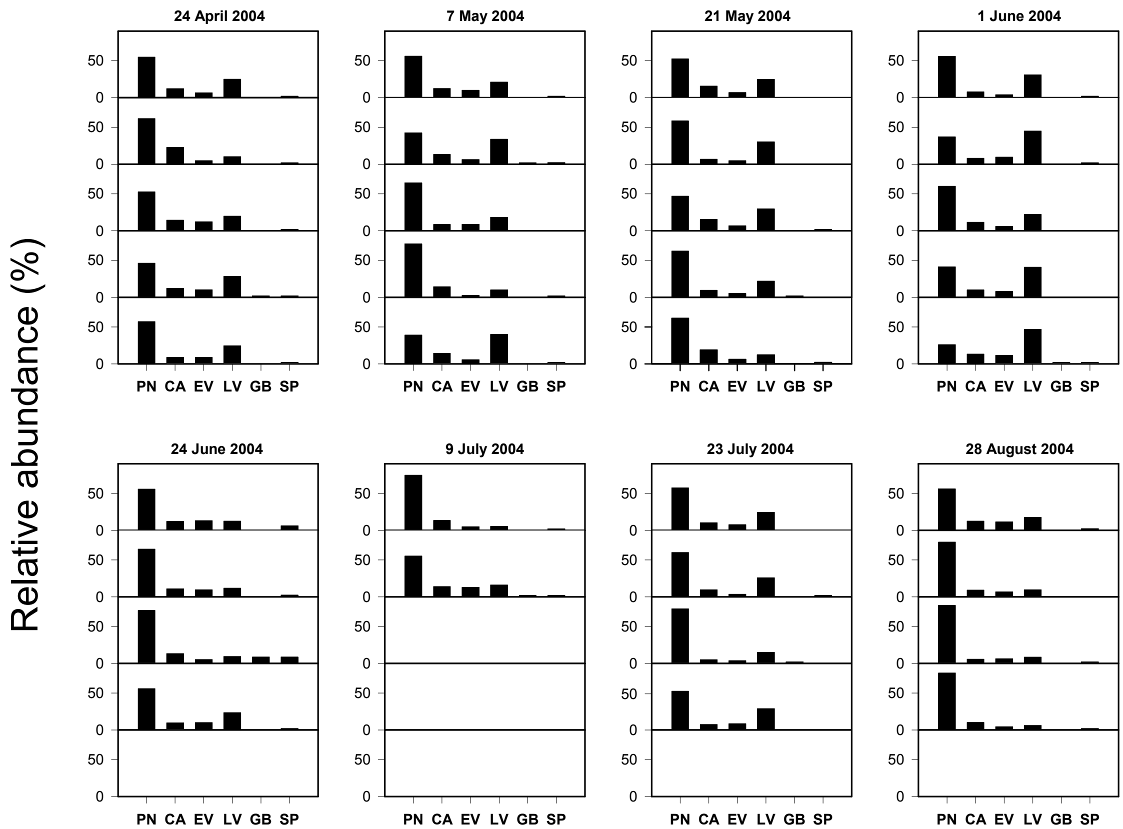


Figure 18. Relative abundance of oocytes classified as perinucleolar (PN), cortical alveoli (CA), early vitellogenic (EV), late vitellogenic (LV), germinal vesicle breakdown (GB), or spent follicles (SP) for female sharpnose shiner collected on each sampling date during the 2004 reproductive season at site 1.

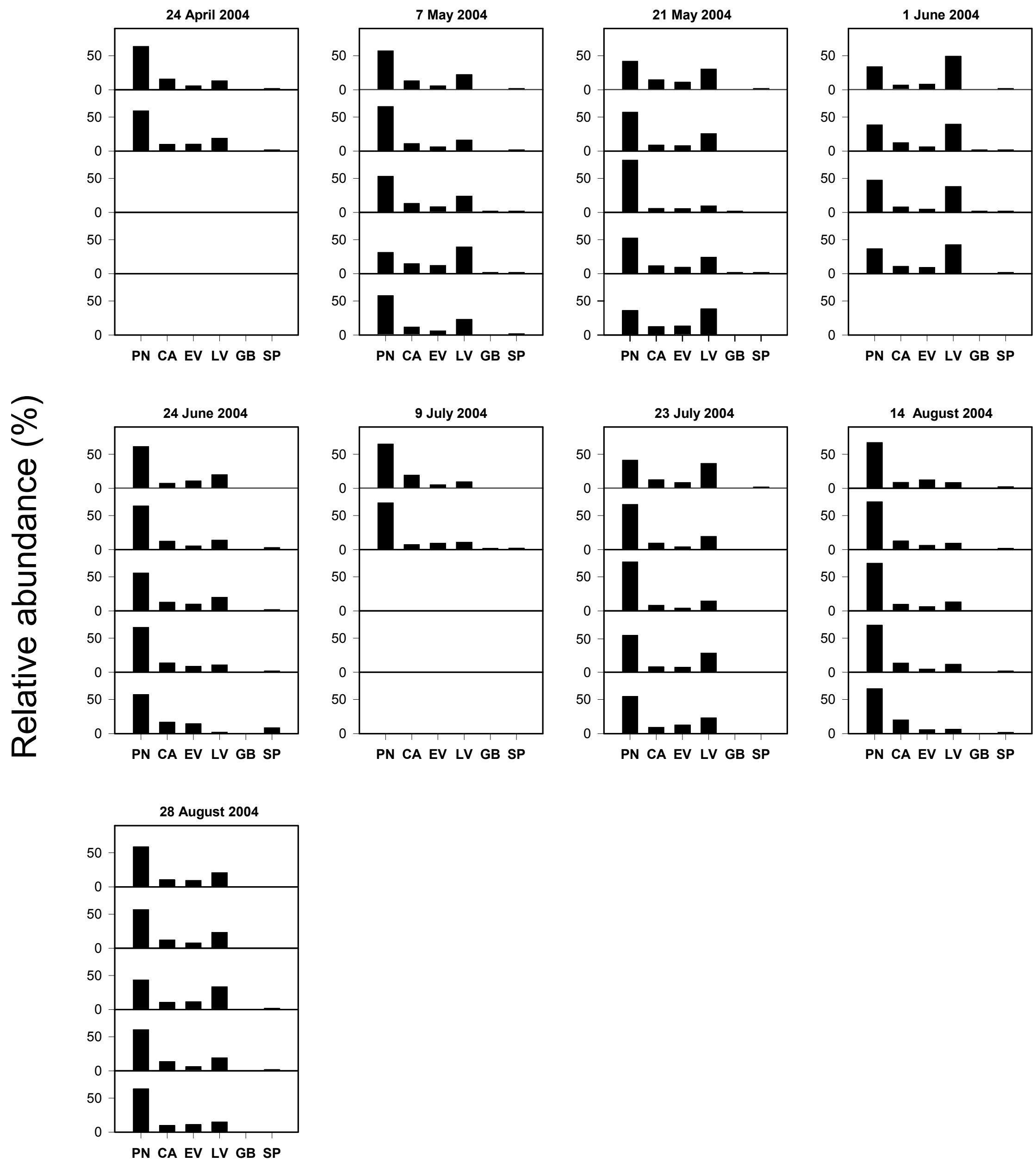


Figure 19. Relative abundance of oocytes classified as perinucleolar (PN), cortical alveoli (CA), early vitellogenic (EV), late vitellogenic (LV), germinal vesicle breakdown (GB), or spent follicles (SP) for female sharpnose shiner collected on each sampling date during the 2004 reproductive season at site 2.

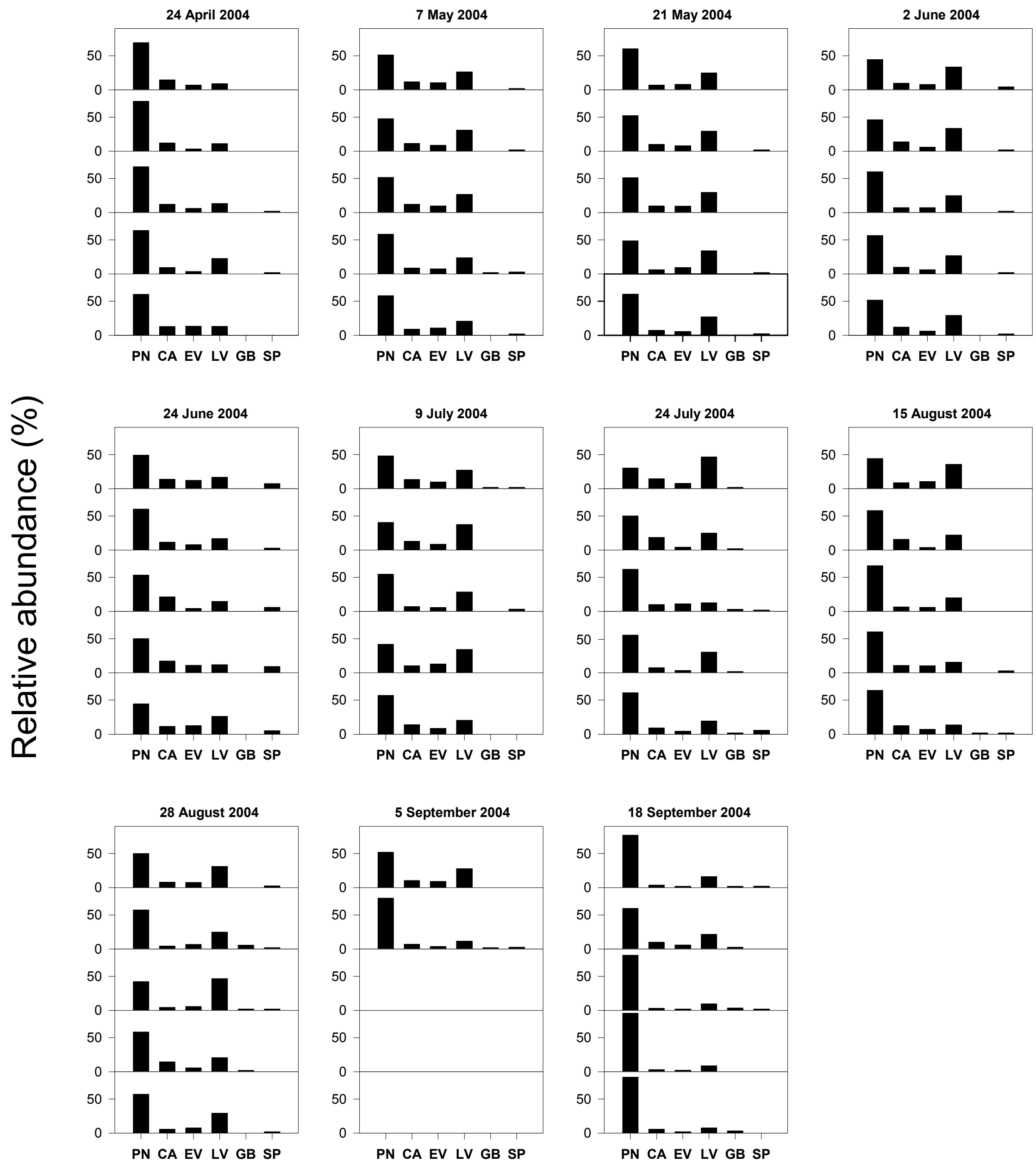


Figure 20. Relative abundance of oocytes classified as perinucleolar (PN), cortical alveoli (CA), early vitellogenic (EV), late vitellogenic (LV), germinal vesicle breakdown (GB), or spent follicles (SP) for female sharpnose shiner collected on each sampling date during the 2004 reproductive season at site 4.

In 2004, these two stages were first observed in April at all sites (Figures 18-20) and spent follicles were observed as late as the 18 September sampling date at site 4 (Figure 20). After their first occurrence, oocytes undergoing germinal vesicle breakdown and spent follicles were present in the ovaries of at least one fish at each sampling site on all but a few sampling dates, indicating that multiple cohorts of ova were developing concurrently within in the ovary. Thus, spawning by sharpnose shiner appears to occur continuously from April through September.

Oocyte Development of Smalleye Shiner

Histopathological analyses were conducted for 126 females with mature ovaries in 2004. All ovaries examined contained oocytes in multiple stages of development (Figures 21-23), which indicates that oocytes develop asynchronously within the ovaries of smalleye shiner. Direct evidence of spawning was confirmed by the presence of spent follicles within the ovaries. In 2004, spent follicles were first observed in April at sites 2 (Figure 22) and 4 (Figure 23) and spent follicles were observed as late as the 28 August sampling date at site 4 (Figure 23). After their first occurrence oocytes undergoing germinal vesicle breakdown as well as spent follicles were present in the ovaries of at least one fish at each sampling site on all but a few sampling dates, indicating that multiple cohorts of ova were developing concurrently within in the ovary. Thus, spawning by smalleye shiner appears to occur continuously from April through August.

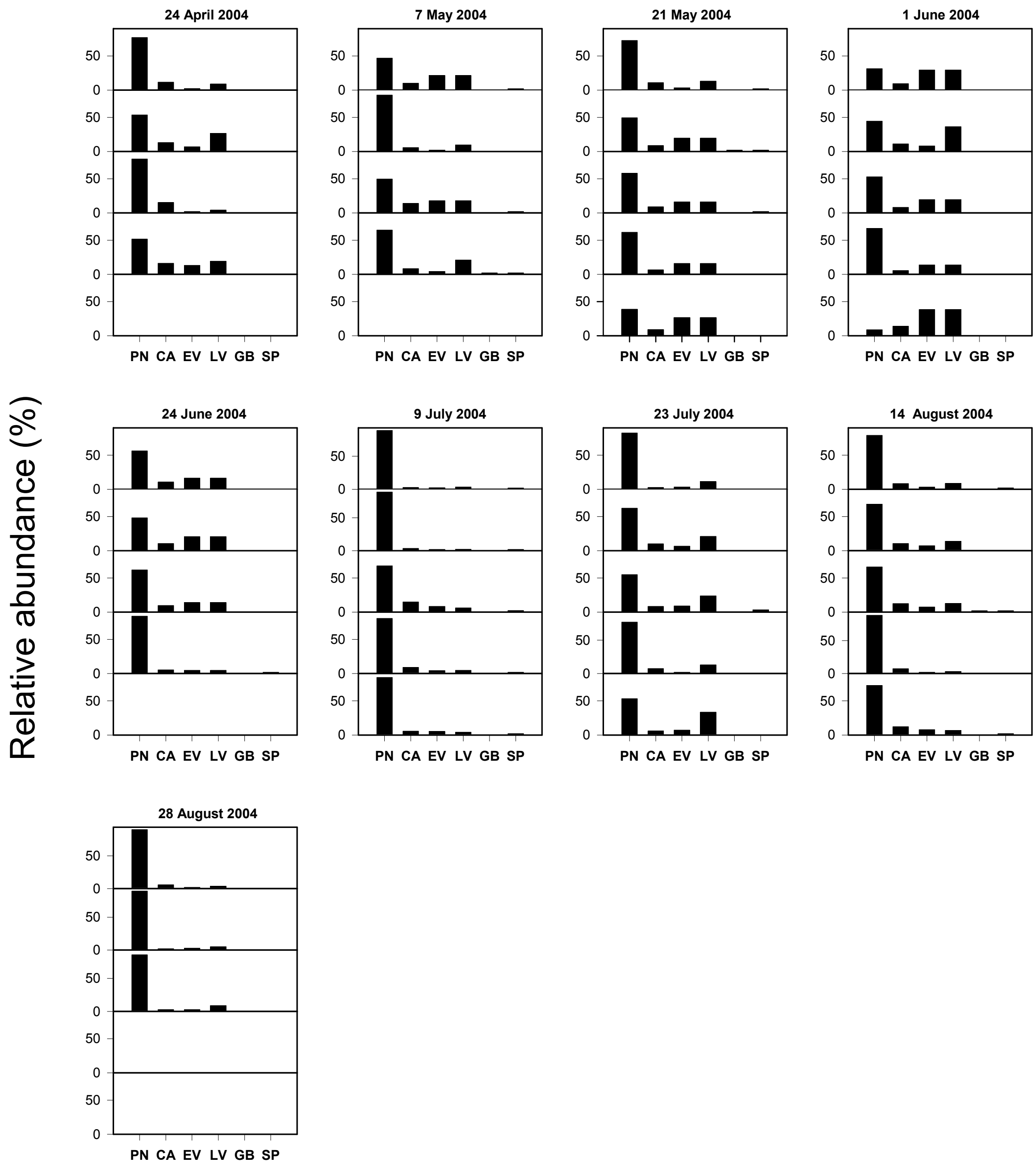


Figure 21. Relative abundance of oocytes classified as perinucleolar (PN), cortical alveoli (CA), early vitellogenic (EV), late vitellogenic (LV), germinal vesicle breakdown (GB), or spent follicles (SP) for female smalleye shiner collected on each sampling date during the 2004 reproductive season at site 1.

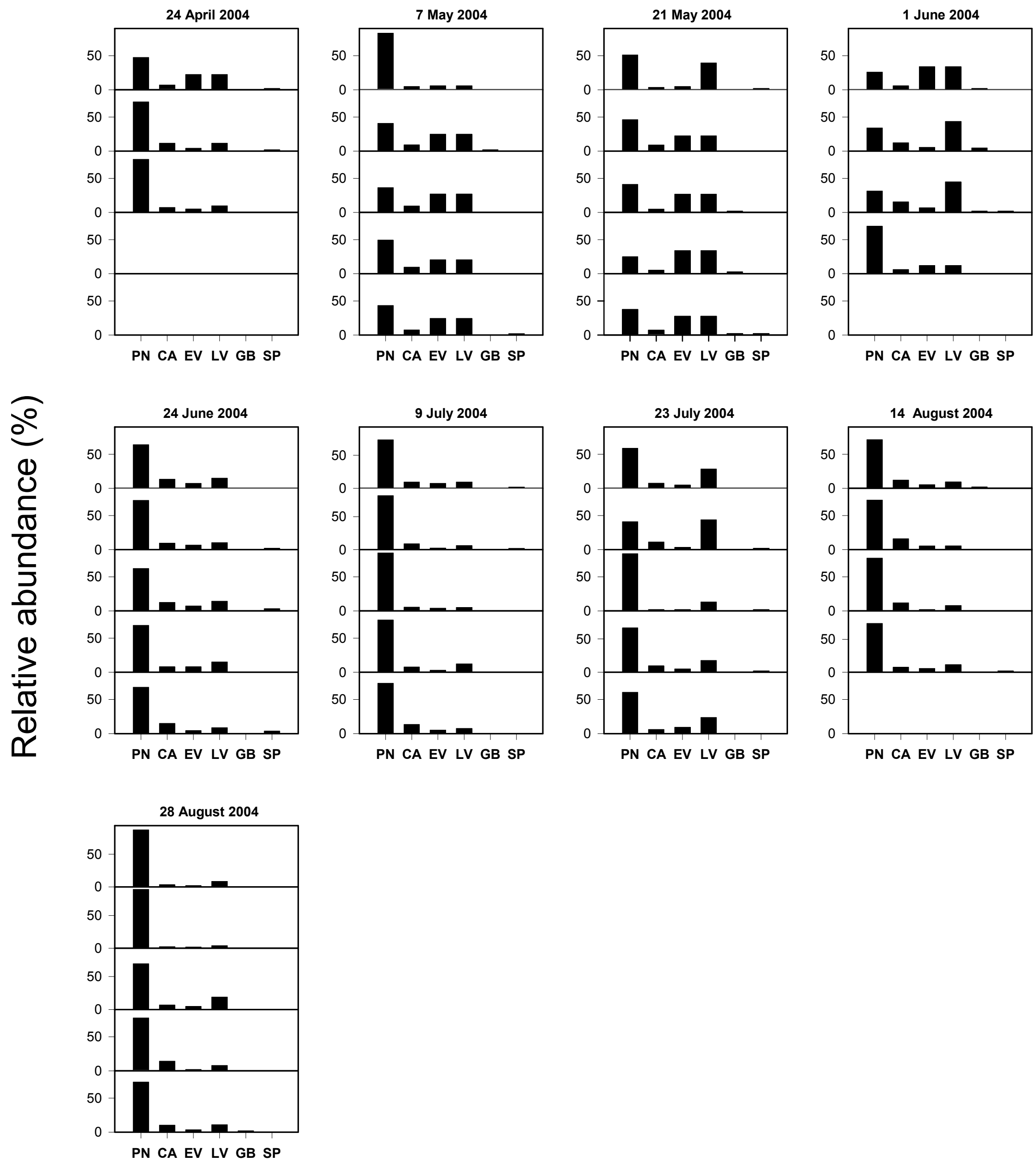


Figure 22. Relative abundance of oocytes classified as perinucleolar (PN), cortical alveoli (CA), early vitellogenic (EV), late vitellogenic (LV), germinal vesicle breakdown (GB), or spent follicles (SP) for female smalleye shiner collected on each sampling date during the 2004 reproductive season at site 2.

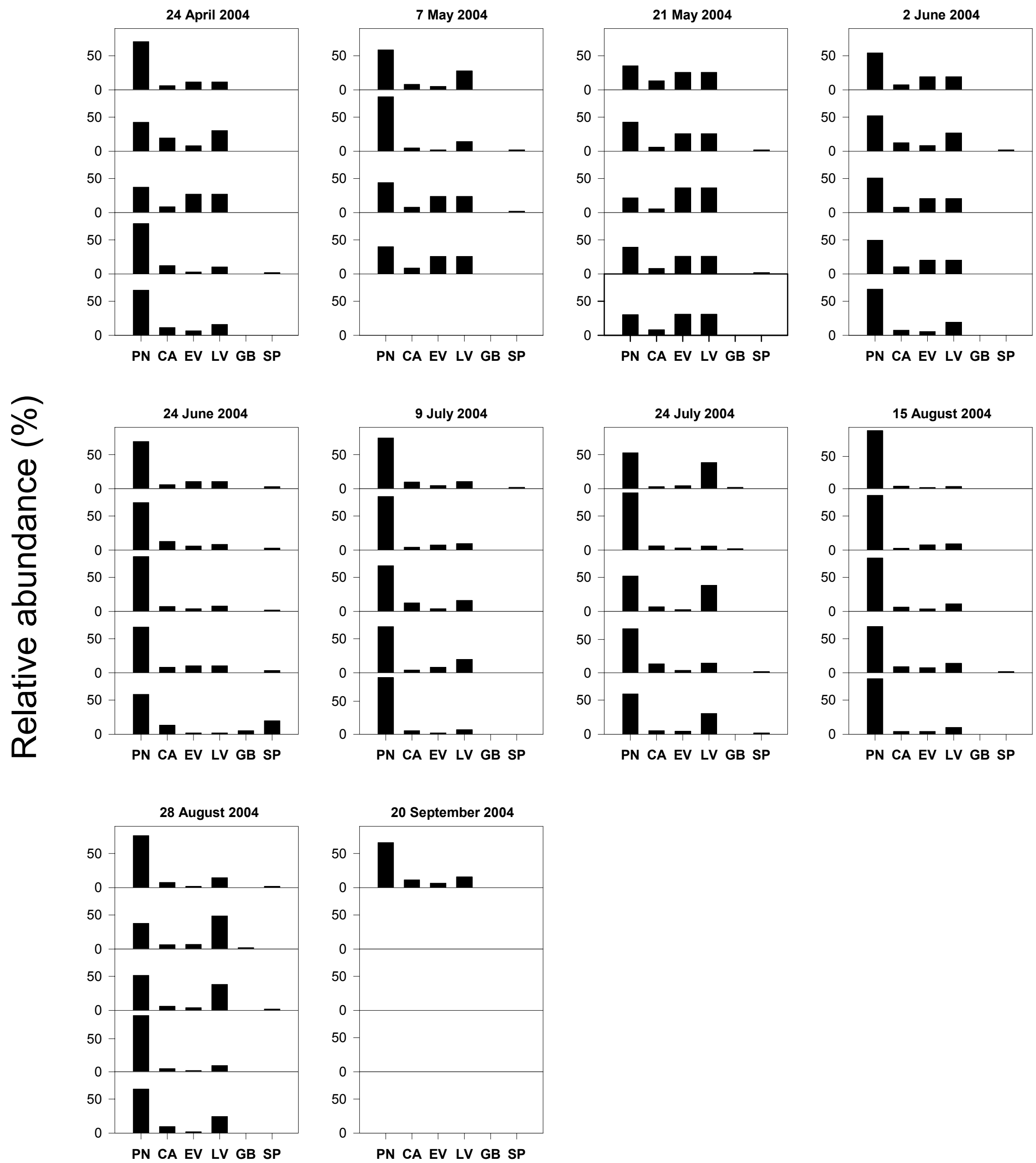


Figure 23. Relative abundance of oocytes classified as perinucleolar (PN), cortical alveoli (CA), early vitellogenic (EV), late vitellogenic (LV), germinal vesicle breakdown (GB), or spent follicles (SP) for female smalleye shiner collected on each sampling date during the 2004 reproductive season at site 4.

Ovum Diameter and Fecundity of Sharpnose Shiner

Vitellogenic ova of sharpnose shiner ranged in diameter from 0.4 mm to 1.1 mm (Figure 24). Histograms of ovum diameter showed evidence of several distinct spawning events. In 2004, shifts in ovum diameter were observed between the two June samples and between the July II sampling date and the August I sampling date. Although subtle, there was a correspondence between peaks in female GSI (Figure 16) and changes in ovum diameter on these dates.

The mean number of vitellogenic ova for sharpnose shiner in 2004 was 303.4 (range = 40 to 1235). These values represent ova counts made from only half of the ovary. Assuming that no systematic differences exist between the number of ova contained in each half of the ovary, these counts can be doubled to obtain a point estimate of mean fecundity. However, these values do not represent mean annual fecundity because results of the histology analyses (this study) demonstrate that sharpnose shiner are multiple spawners and vitellogenic ova develop within the ovary throughout the reproductive season.

Ovum Diameter and Fecundity of Smalleye Shiner

Vitellogenic ova of smalleye shiner ranged in diameter from 0.4 mm to 1.2 mm (Figure 25). Histograms of ovum diameter showed evidence of several distinct spawning events. In 2004, shifts in ovum diameter were observed between the two June samples and between the 24 July sampling date and the 14 August sampling date. Although subtle, there was some correspondence between peaks in female GSI (Figure 19) and changes in ovum diameter on these dates.

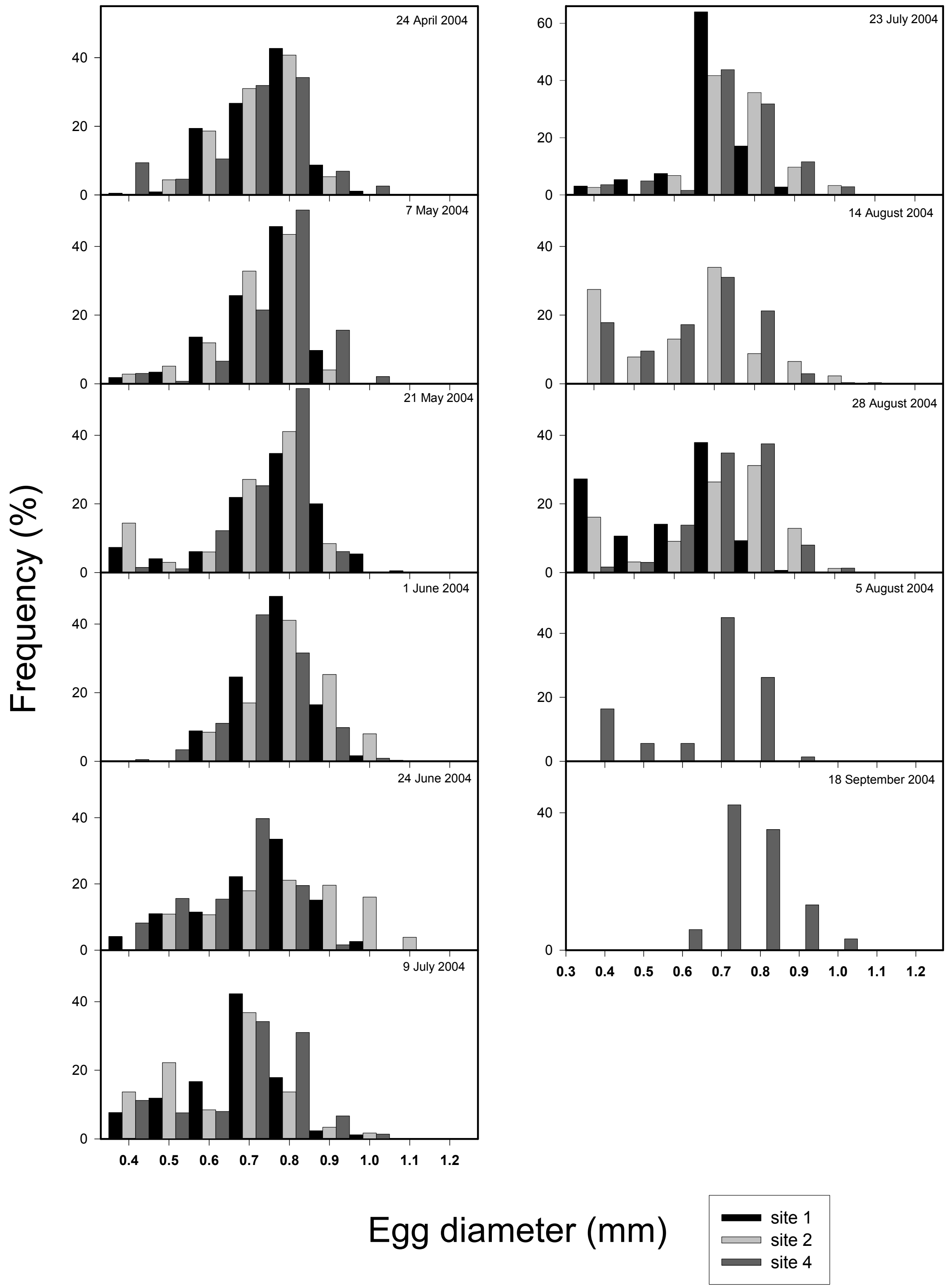


Figure 24. Size-frequency distributions of vitellogenic ova from female sharpnose shiner collected at each site during the April to September 2004 reproductive season.

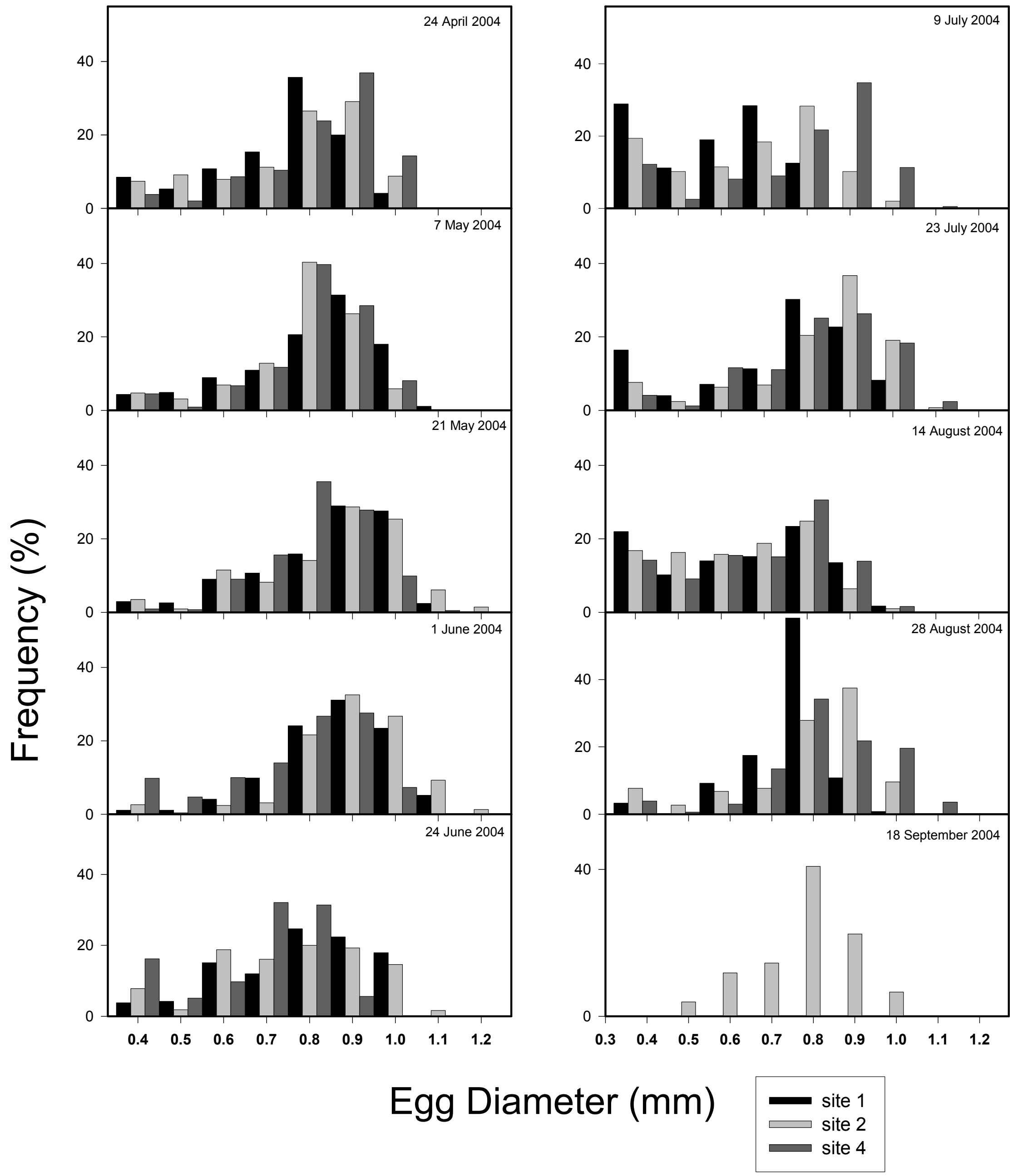


Figure 25. Size-frequency distributions of vitellogenic ova from female smalleye shiner collected at each site during the April to September 2004 reproductive season.

The mean number of vitellogenic ova for smalleye shiner in 2004 was 300 (range = 18 to 1326). Assuming that no systematic differences exist between the number of ova contained in each half of the ovary, these counts can be doubled to obtain a point estimate of mean fecundity. However, values do not represent mean annual fecundity because results of the histology analyses (this study) demonstrate that vitellogenic ova develop within the ovary and are spawned throughout the reproductive season.

Population Dynamics Models

We used various segments, in particular our analyses of otoliths and ovarian development, to estimate parameters for a Leslie matrix population dynamics model for sharpnose shiner and smalleye shiner. Age-specific survival rates for sharpnose shiner were 0.001818 for age 0 and 0.1218 for age 1. For smalleye shiner, survival rates were estimated to be 0.001479 for age 0 and 0.107 for age 1 (Table 5). Age-specific fecundities for sharpnose shiner were 379.3 for age 1 and 1379.9 for age 2. For smalleye shiner, fecundity was estimated to be 443.3 for age 1 and 2175.4 for age 2 (Table 5).

Elasticity and loop analyses indicated that population dynamics for both species is most influenced by age-0 survival (Table 6; Figure 26), which accounted for 43% of the variation in population growth for both species. Age-1 survival was also an important factor and accounted for approximately 30% of variation in population growth rate. Age-1 survival and age-2 fecundity were less influential to population growth and together accounted for less than 15% of variation in population growth rate for both species. Sensitivity simulations ($N = 1000$) showed that, although a substantial range in elasticities for each parameter could be observed, in most cases elasticities were similar

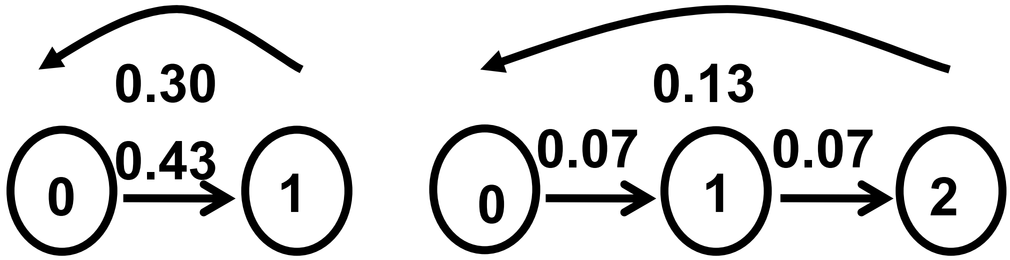
Table 5. Age-specific fecundity and survival estimates used in development of Leslie matrix population dynamics models for sharpnose shiner and smalleye shiner in the Brazos River, Texas.

	Age 0	Age 1	Age 2
Sharpnose shiner			
Survival	0.001818	0.1218	0.0
Fecundity	0.0	379.3	1397.9
Smalleye shiner			
Survival	0.001479	0.107	0.0
Fecundity	0.0	443.3	2175.4

Table 6. Age-specific elasticities for sharpnose shiner and smalleye shiner populations in the Brazos River, Texas.

	Age 0	Age 1	Age 2
Sharpnose shiner			
Survival	0.4330	0.1340	0.0
Fecundity	0.0	0.2989	0.1340
Smalleye shiner			
Survival	0.4265	0.1469	0.0
Fecundity	0.0	0.2797	0.1469

Sharpnose shiner



Smalleye shiner

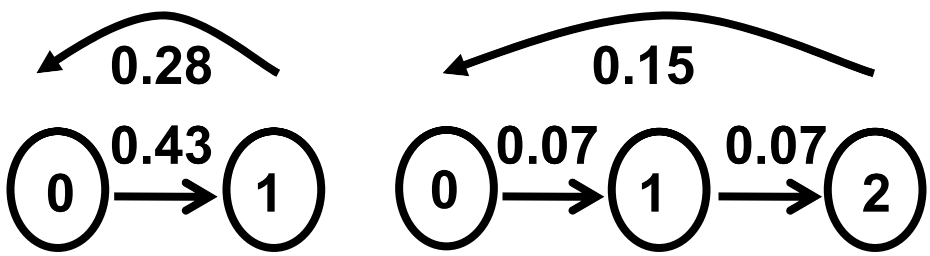


Figure 26. Loop diagrams for sharpnose shiner and smalleye shiner projection matrices.

to those obtained from the initial projection matrix parameterization (Figures 27 and 28). For sharpnose shiner, simulation elasticities ranged from 0.36 to 0.48 for age-0 survival, but most (91%) were greater than 0.40. Simulation elasticities for age-1 fecundity ranged from 0.13 to 0.45, with most (79%) greater than 0.25. Estimates were variable for age-1 survival and age-2 fecundity with most simulations resulting in elasticities of less than 0.10 and none was greater than 0.25. For smalleye shiner, simulation elasticities ranged from 0.34 to 0.46 for age-0 survival, but most (86%) were greater than 0.40. For age-1 fecundity, elasticities ranged from 0.11 to 0.41, with 62% greater than 0.2500. Elasticity values for age-1 survival and age-2 fecundity ranged from 0.06 to 0.23 but were generally less than 0.10. Results of the simulations provide evidence that elasticities obtained from the initial matrix parameterization are robust with respect to uncertainty in parameter estimates.

Among the three alternative models evaluated for sharpnose shiner, the two null parameterizations were significantly better predictors of sharpnose shiner abundance than the discharge model (Table 7). The constant lambda model was the best predictor followed by the static model. The discharge model had the greatest AICc. The discharge model closely predicted observed abundance in each year except for the last year when it overestimated the abundance of sharpnose shiner (Figure 30). Overall, performance of all three models for sharpnose shiner appeared to be mainly separated by the predicted abundance of fish in the last year modeled.

Of the three alternative models evaluated for smalleye shiner, the discharge model had the lowest AICc, indicating that it was the best predictor of observed smalleye shiner abundance (Table 7). The discharge model predicted smalleye shiner abundance very

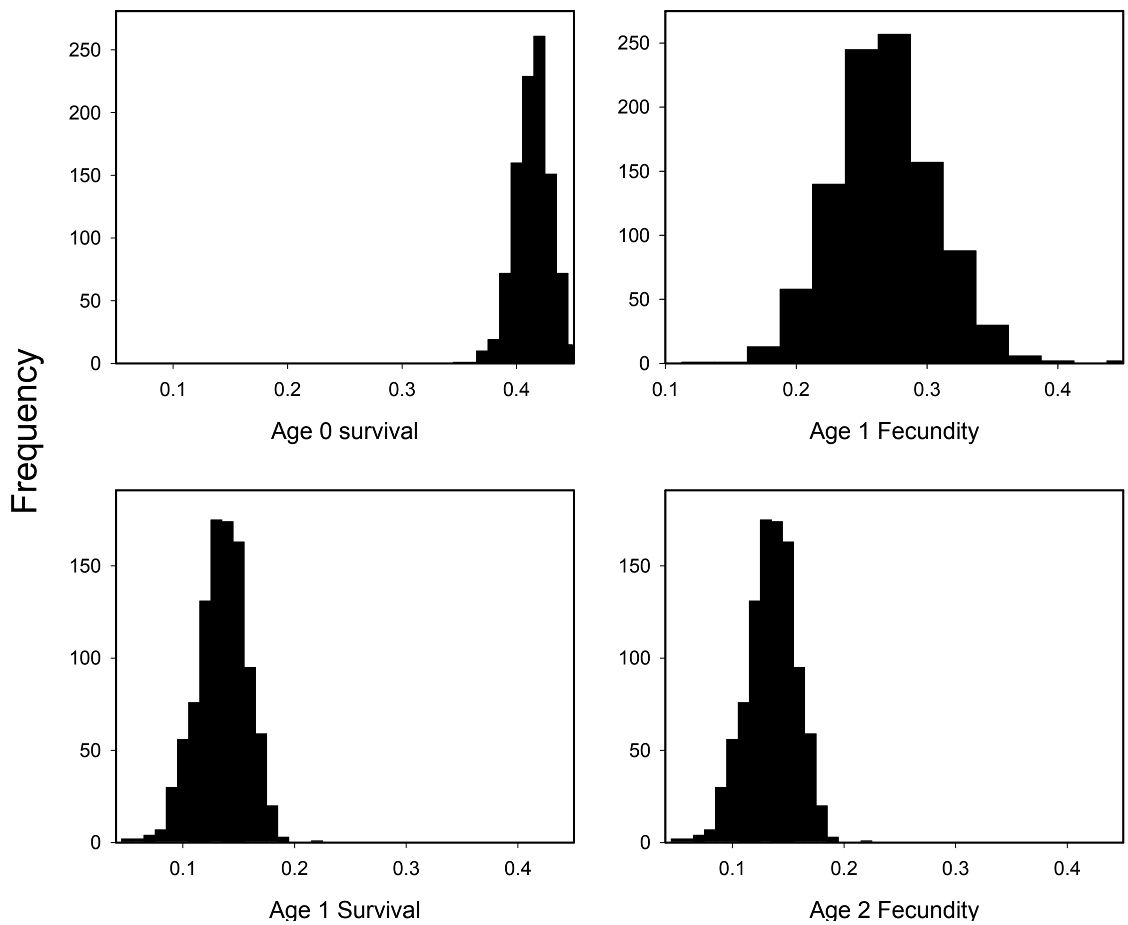


Figure 27. Frequency distributions of simulated projection matrix elasticities ($N = 1000$ iterations) for sharpnose shiner in the upper Brazos River, Texas.

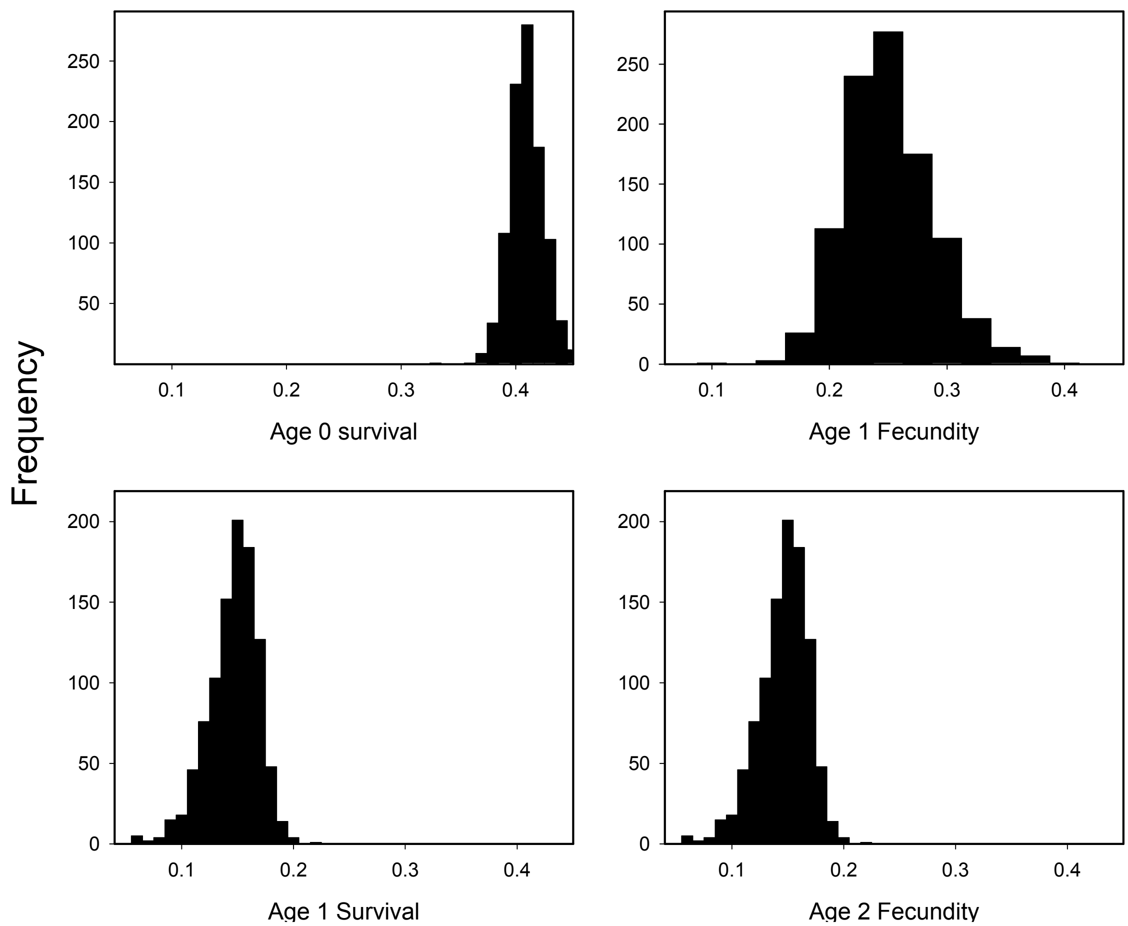


Figure 28. Frequency distributions of simulated projection matrix elasticities ($N = 1000$ iterations) for smalleye shiner in the upper Brazos River, Texas.

Table 7. Second order Akaike Information Criteria (AICc) values for three alternative models that predict abundance of sharpnose shiner and smalleye shiner in the upper Brazos River, Texas.

Species	Model	K	AICc	ΔAICc
Sharpnose shiner	Discharge	3	48.2	12.1
	Constant lambda	3	36.1	0.0
	Static	3	39.2	3.1
Smalleye shiner				
	Discharge	3	25.5	0.0
	Constant lambda	3	33.3	7.7
	Static	3	38.2	12.7

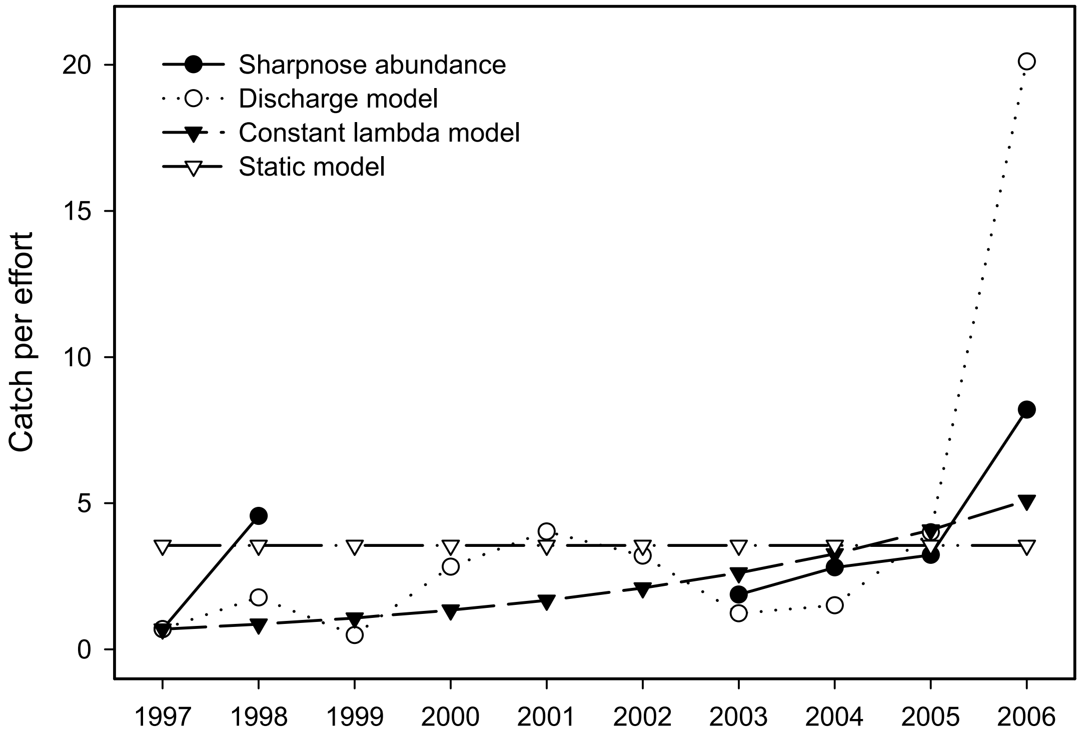


Figure 29. Observed abundance of sharpnose shiner in the upper Brazos River, Texas, and abundance of smalleye shiner predicted by three alternative population models.

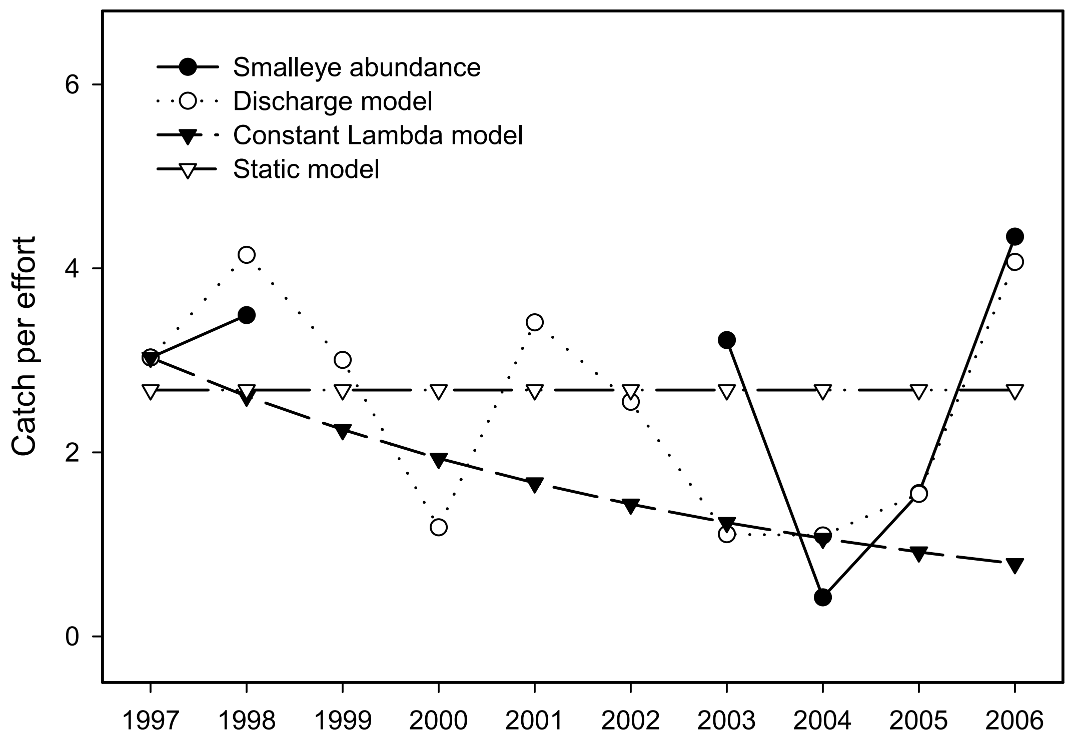


Figure 30. Observed abundance of smalleye shiner in the upper Brazos River, Texas, and abundance of sharpnose shiner predicted by three alternative population models.

closely (Figure 30). The discharge model was a significantly better predictor of abundance than the two null parameterizations because AICc for the constant lambda and static models were > 2.0 more than the AICc for the discharge model (Burnham and Anderson 2002).

The discharge factor (DEST) fitted to the observed abundance in the discharge model provides an estimate of the minimum discharge necessary during the reproductive season to keep population growth rate above 1.0. The DEST value for sharpnose shiner was 2.61 $m^3 \cdot s^{-1}$ and for smalleye shiner was 5.52 $m^3 \cdot s^{-1}$. Prior to the impoundment of Lake Alan Henry (1964-1992), the only major reservoir in the upper Brazos River, summer discharge was greater than DEST in 26 of 28 (93%) years for sharpnose shiner and 22 of 28 (79%) years for smalleye shiner. Since the impoundment of Lake Alan Henry (1993-2006), summer discharge exceeded DEST 12 of 14 (85%) years for sharpnose shiner and 8 of 14 (57%) years for smalleye shiner.

Based on stream-discharge data from USGS gaging stations in the upper Brazos River, mean summer (May-September) discharge has been 39.4 $m^3 \cdot s^{-1}$ downstream from Lake Alan Henry in the 14 years since its impoundment in 1993. This represents about a 14% reduction in mean summer discharge. Currently, there are plans to construct an additional large reservoir just downstream from the confluence of the Salt Fork of the Brazos River and Double Mountain Fork of the Brazos River. If these plans are realized, we estimate that summer discharge downstream from the new reservoir would be reduced from, current levels, by approximately 55%. If stream discharge had actually been reduced by this amount between 1993 and 2006, summer discharge below the proposed reservoir site would not have exceeded DEST values predicted by the discharge model for either species in any of those years, indicating a perpetual decrease in population growth. To further assess the effects of these alternative discharge regimes, we used the discharge-based model to compare the abundance of smalleye shiner and sharpnose shiner between 1993 and 2006 predicted by the observed mean summer discharge with the abundance predicted by a 14% increase in mean summer discharge (discharge prior to impoundment of Lake Alan Henry) and a 55% decrease in mean summer discharge (Figure 31). This comparison shows that even the fairly modest reduction of 14% can have a substantial negative effect on abundance. Our models also indicate that neither species would persist if current discharge levels were reduced by the 55% expected from impounding the Salt Fork of the Brazos River and Double Mountain Fork of the Brazos River. Population size predicted in the final few years modeled is not likely to be realistic because the model does not account for other limiting factors such as food, habitat availability, etc. However, the model output does allow an assessment of the potential effects of altered discharge on population dynamics of sharpnose shiner and smalleye shiner.

Temporal Patterns

We assembled available information on abundance and distribution of sharpnose shiner and smalleye shiner in the Brazos River. Much of this information is presented in Moss and Mayes (1993) and has been updated by Tim Bonner (Texas State University, personal communication) for the lower Brazos River. Additional information on the distribution and abundance of sharpnose shiner and smalleye shiner in the upper Brazos River are presented in Ostrand (2000), Durham (2007), and this study.

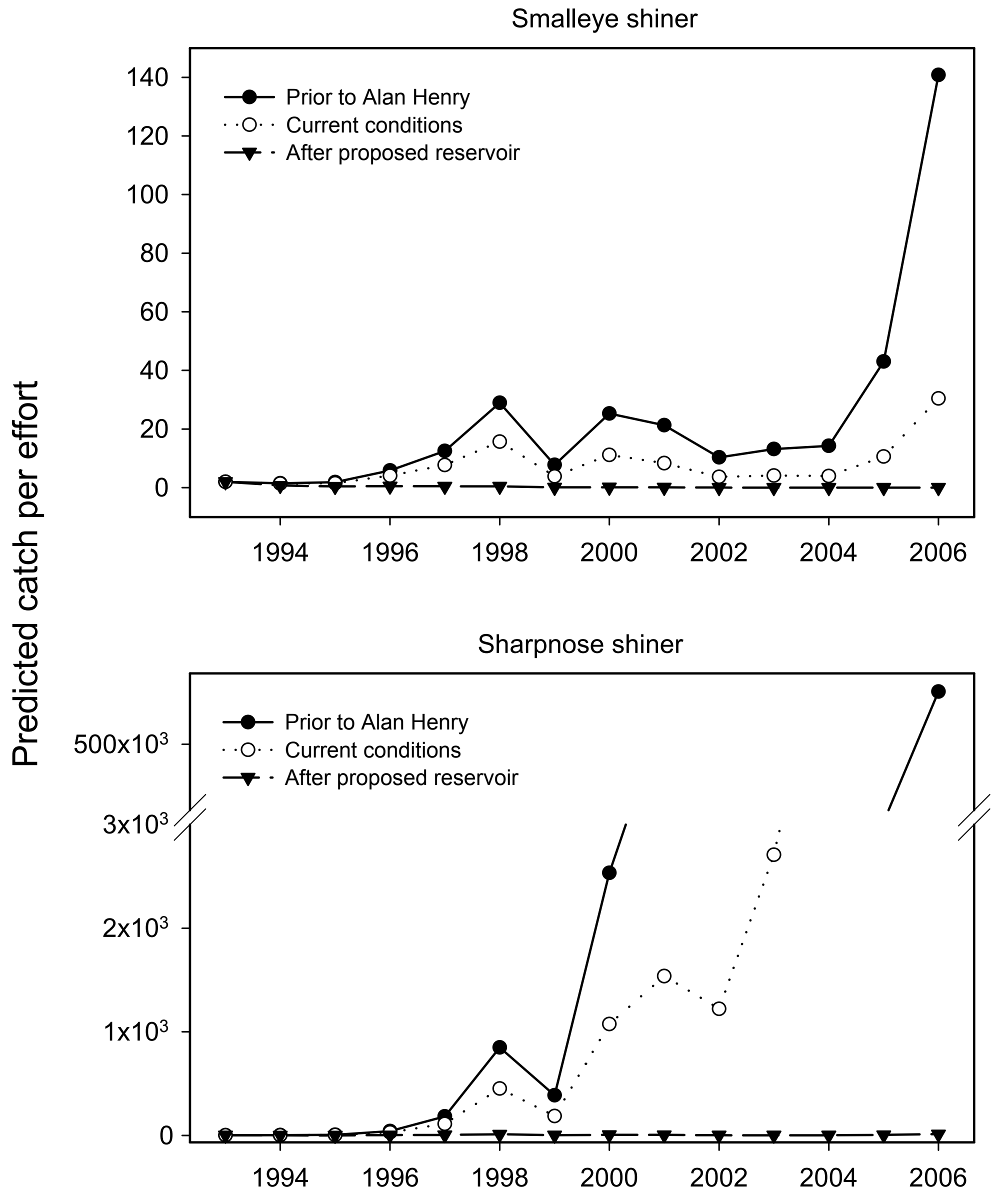


Figure 31. Effects of alternative discharge regimes on abundance of smalleye shiner and sharpnose shiner in the Brazos River, Texas. Solid circles represent predicted catch per effort based on discharge conditions prior to the construction of Alan Henry. Open circles represent predicted catch per effort based on discharge since the impoundment of Alan Henry. Triangles represent predicted catch per effort based on the estimated reduction in discharge that would result if a planned reservoir were constructed.

Because the Brazos River has been so infrequently sampled over the years, we pooled records for the upper and lower Brazos River sites, which permits at least a preliminary analysis of historic trends (Figure 33). There was no significant ($P = 0.8530$) temporal trend in sharpnose shiner catches in the upper Brazos River, but there was evidence of a significant ($P = 0.0070$) decrease in the lower Brazos River. For smalleye shiner, there was no evidence of a significant temporal trend in catches in either the upper ($P = 0.2172$) or lower Brazos River ($P = 0.3029$). The available data do not allow us to adapt our present population dynamics models for sharpnose shiner and smalleye shiner to explore changes in abundance of either species in the lower Brazos River.

DISCUSSION

Current Status of Sharpnose Shiner and Smalleye Shiner

We collected sharpnose shiner and smalleye shiner commonly in the upper Brazos River, upstream from Possum Kingdom Reservoir. In the upper Brazos River, sharpnose shiner was the most common species in our collections and represented about 21% of fishes collected. Smalleye shiner was the third most common species in this area and represented about 12% of the assemblage. Our results show no evident change in the distribution of either species in the upper Brazos River since the surveys conducted by Moss and Mayes (1993), Ostrand (2000), and Ostrand and Wilde (2002, 2004). Our results do suggest a change in relative abundance of sharpnose shiner and smalleye shiner since the collections of Ostrand (2000), and Ostrand and Wilde (2002, 2004) who reported that sharpnose shiner and smalleye shiner represented 7 and 17%, respectively,

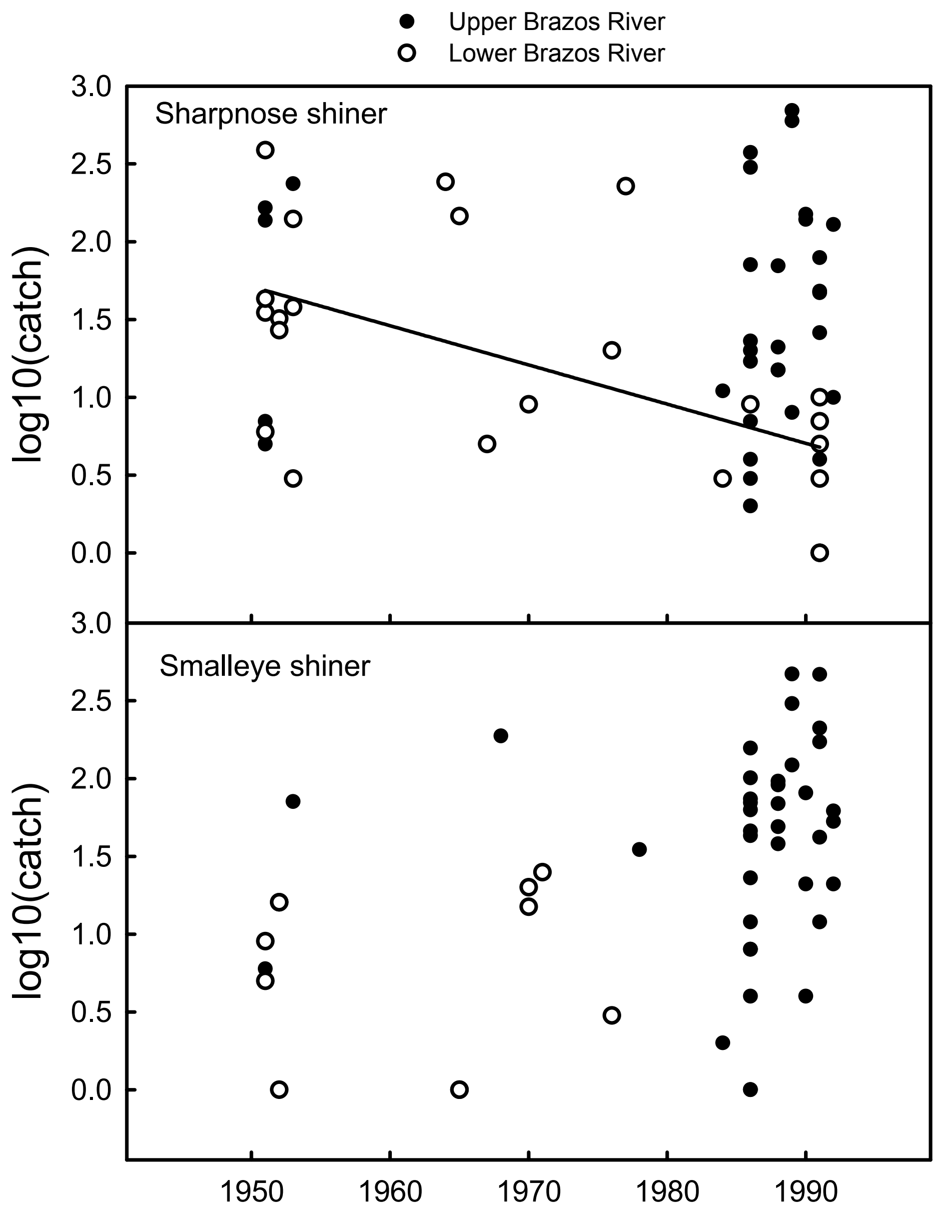


Figure 32. Trends in historic catches of sharpnose shiner (upper panel) and smalleye shiner (lower panel). Sites from the upper Brazos River, upstream from Possum Kingdom Reservoir are denoted by solid circles, sites from the lower Brazos River are denoted by open circles. There was a significant temporal trend only in abundance of sharpnose shiner in the lower Brazos River (showed by the solid line in the upper panel).

of the assemblage in 1997 and 1998. Thus, although populations of both species are large, there is evidence that they are temporally variable.

Despite making large collections at several sites in the lower river at which sharpnose shiner and smalleye shiner historically were common, we collected no specimens of either species. Although both species historically inhabited the lower Brazos River, they represented only a small proportion of the assemblage (Moss and Mayes 1993). Although we failed to collect either species, specimens of sharpnose shiner occasionally are collected at the confluence of Allens Creek and the Brazos River (Gelwick and Li 2002) where they are extremely rare. More recently, Zeug et al. (2005) reported collection of three specimens of smalleye shiner from oxbow lakes along the lower Brazos River. These specimens constitute the first reported collections of smalleye shiner from the lower Brazos River since the 1950s.

Microhabitat Selection

Sharpnose shiner and smalleye shiner occurred in microhabitats characterized by a wide range of physical and chemical conditions. There was no obvious habitat selection by either species based on water temperature, dissolved oxygen concentration, pH, or conductivity. Sharpnose shiner and smalleye shiner do appear to select microhabitat based on depth and current velocity. Both species were most common in currents between 20 and 40 cm s^{-1} and depths between 20 and 40 cm. Given the availability of suitable depth and current velocity, both species then may refine their microhabitat selection based on temperature, pH, conductivity, and possibly other factors. However, the presence of these associations, even if they represent selection for specific conditions, does not necessarily imply that such conditions are required for maintenance of either species (Rosenfeld 2003).

Selection of microhabitats based on depth and current velocity may explain the lack of obvious selection of specific habitat types or substrates by sharpnose shiner and smalleye shiner. Both species select specific microhabitats defined by depth and current combinations, which typically occur in the main channel and side channels and which have silt and gravel substrates. However, both sharpnose shiner and smalleye shiner also occur in backwater habitats. Utilization of these habitats may be important under very specific conditions, but they were used very infrequently.

Based on limited sampling Moss and Mayes (1993) reported that sharpnose shiner and smalleye shiner selected microhabitats based on depth and current velocity and that both species avoided shallow water at the edge of the river. During the course of our study, we found only weak evidence that sharpnose shiner and smalleye shiner selected specific habitat features. We believe that both species select habitat based on what is available, thus, from sampling period to sampling period, preferences may change. A further obstacle to understanding the habitat utilization and needs of both species is the tendency of Brazos River fishes to move between sites (Ostrand and Wilde 2002). If sharpnose shiner and smalleye shiner move between sites to locate optimum or preferred physicochemical conditions, they might not show any evidence of preference at a single site, as studied here.

Reproductive Ecology

Sharpnose shiner and smalleye shiner populations in the upper Brazos River undergo asynchronous oocyte development and spawn repeatedly during a protracted reproductive period. Mean GSI for both species abruptly increased in April and remained elevated for approximately six months until September, after which time GSI remained consistently low until the following April, when rapid development again occurs. This seasonal pattern in GSI observed for sharpnose shiner and smalleye shiner in the Brazos River closely resembles that of other cyprinids known to be multiple spawners (Taylor and Miller 1990; Rinchard and Kestemont 1996; Bonner 2000). In contrast, single spawning species typically have GSIs characterized by an extended period of recrudescence that may last up to nine months during which time GSI gradually increases before reaching a single peak and rapidly decreasing after a single spawning bout (Malison et al.1994; Rinchard and Kestemont 1996). Further definitive evidence of asynchronous ovarian development and multiple spawning by sharpnose shiner and smalleye shiner was provided by the histological analysis of ovarian tissues, which revealed that oocytes in all stages of development were present on nearly every sampling date between April and September. In contrast, for most single spawning species, ovarian development is synchronous among individuals and oocytes progress through the different developmental stages together (Blazer 2002).

Several distinct shifts in ova diameter from predominantly large ova on one sampling date to smaller ova on the following sampling date were observed during our study. These shifts in ova diameter corresponded with peaks in female GSI that were followed by declines on the next sampling date in 2004. Thus, patterns in GSI and ova size appear to indicate that sharpnose shiner and smalleye shiner populations batch-spawn ova in distinct episodes during the reproductive season (Scott 1987; Tyler and Sumpter 1996). However, spent follicles were observed in the ovaries of sharpnose shiner and smalleye shiner on nearly all of the sampling dates, indicating that in addition to batch-spawning, some baseline level of spawning within the populations occurs on a daily basis. The benefits of spawning daily versus batch-spawning are not clear; however, daily spawning may simply be related to the rate of growth among the different stages of oocytes within the ovaries (Wallace and Selman 1981) or may have an adaptive significance for persistence in a highly variable lotic environment.

In the Canadian River, New Mexico and Texas, Arkansas River shiner exhibit seasonal variation in length and reproductive condition in which larger, more mature fish are consistently found at upstream locations during the reproductive season (Bonner 2000), suggests that adults migrate to upstream areas each year prior to spawning. Despite some subtle differences among sites in the upper Brazos River, length-frequencies, GSI, and ovarian development of sharpnose shiner and smalleye shiner did not reveal any systematic spatial or temporal variation in fish length or reproductive condition. It is possible that seasonal migrations do occur among fishes in the Brazos River, but the locations of our sampling sites did not allow us to detect them. Indeed, the upper Brazos River is much more complex morphologically (greater distance of un-impounded river and presence of large tributaries) and chemically (e.g., variable salt content between the Salt Fork and Double Mountain Fork) than is the Canadian River in which Bonner (2000) made his observations.

Female GSI showed multiple peaks during the 2004 reproductive season that were possibly related to variation in stream discharge. Stream discharge during the 2004 reproductive season was variable but the river flowed continuously during the reproductive season instead of becoming intermittent as it commonly does (Ostrand and Wilde 2002, 2004). During periods of intermittent discharge, fish are confined in pools where physical and chemical conditions become increasingly extreme (Huntsman 1942; Bailey 1955; Barlow 1958; Rutledge and Beitinger 1989; Mundahl 1990). Durham (2007) found evidence that survival of young-of-year sharpnose shiner and smalleye shiner was reduced when the river became intermittent. He also found evidence of reduced reproductive condition in fishes restricted to pools. Effects of harsh conditions within pools, or between wet years and those in which the river is intermittent, could be manifested in a redirection of energy resources to somatic maintenance and away from reproductive pathways as conditions become increasingly extreme. If this occurs for sharpnose shiner and smalleye shiner in the Brazos River, it would affect GSI and reproductive success.

In fishes, extreme stress can result in oocytes being broken down and reabsorbed by the ovary in a process called oocyte atresia (Tyler and Sumpter 1996). Overall, the fewer that 2% of the oocytes in both sharpnose shiner and smalleye shiner were atretic. Thus, it does not appear that oocyte development is impacted by variation in discharge or environmental conditions in the upper Brazos River.

There is little evidence that spawning by sharpnose shiner and smalleye shiner was affected by environmental conditions, particularly discharge, because spent follicles were observed in the ovaries of both species during periods of high and low discharge.

Early investigations of the reproductive ecology of Great Plains cyprinids reported an apparent relationship between spawning and spring and summer flood events. For example, Moore (1944) and Sliger (1967) collected Arkansas River shiner and plains minnow ova, respectively, only during flooding conditions. Taylor and Miller (1990) and Lehtinen and Layzer (1988) suggested the same thing for plains minnow based on GSI and length-frequency data. However, these conclusions are suspect because more definitive histological evidence for Arkansas River shiner and peppered chub (Bonner 2000) and for sharpnose shiner and smalleye shiner (this study) clearly demonstrates that spawning occurred regardless of the magnitude or presence of discharge. It is more likely that higher discharge at the time of spawning aids the survival rate of the semi-buoyant ova and young larvae of these fishes rather than acting to initiate spawning of these species (Durham and Wilde 2006). Thus, discharge is a critical component of reproductive success, but probably is not an ultimate cue for the initiation of spawning.

The reproductive strategy of the sharpnose shiner and smalleye shiner appears to be well suited to the extremely variable and unpredictable environmental conditions that prevail in the upper Brazos River, Texas. Multiple spawning is a classic bet hedging reproductive strategy commonly observed in short-lived species and those that inhabit harsh environments (Starrett 1951; Lambert and Ware 1984; Weddle and Burr 1991; Rinchard and Kestemont 1996; Lowerre-Barbieri et al. 1998). Length-frequency histograms of sharpnose shiner and smalleye shiner indicate that they live no longer than three years (ages 0, 1, and 2) with only a few individuals reaching age-2. Therefore, most individuals have only one reproductive season during their life. Such short-lived organisms have a very narrow window for reproduction and, if the population is to persist, must have strategies such as asynchronous oocyte development, multiple spawning (daily and batch-spawning), and a protracted reproductive season to ensure that at least some offspring are successfully produced each season.

Population Dynamics

Elasticity analysis and sensitivity simulations of population dynamics models for both sharpnose shiner and smalleye shiner indicate that age-0 survival and age-1 fecundity have the greatest effect on overall population growth. Our results are consistent with those of Vélez-Espino et al. (2006) who analyzed elasticity patterns for North American freshwater fishes and found that among species with life histories characterized by early maturity and short life and reproductive spans, juvenile survivorship and fecundity were the most influential factors for population dynamics. Sharpnose shiner and smalleye shiner are classic opportunistic species (Winemiller and Rose 1992) that exhibit life history characteristics similar to those above. These insights suggest that conservation efforts for both sharpnose shiner and smalleye shiner should be focused on strategies that protect or enhance survival of age-0 individuals and age-1 fish, which represent the majority of reproductive output.

A common use of elasticity analysis is to identify the life-history stages that have the greatest effect on population dynamics because, it is believed, these stages will be the stages that are most sensitive to management intervention (Benton and Grant 1999; Vélez-Espino et al. 2006). Although Benton and Grant (1999) and Mills et al. (1999) caution against an uncritical use of elasticities to direct management actions, our results and those of Durham and Wilde (2006) suggest that peppered chub population dynamics can be readily manipulated by altering the discharge regime, which would result in an increase in early survival. Our results and observations constitute a major paradigm change for studying and managing fishes in the upper Brazos River when contrasted with the historic emphasis on habitat requirements of these fish, which is based almost exclusively on studies of adult fish (Matthews and Hill 1979; 1980; Bratten and Guy 1999; Polivka 1999; Luttrell et al. 1999; Scheurer et al. 2003; Dieterman and Galat 2004; Everett et al. 2004; Welker and Scarnecchia 2004).

Recent studies of recruitment by prairie stream fishes including sharpnose shiner and smalleye shiner have shown that successful production of young is precluded during periods when the river is not flowing (Durham and Wilde 2006; Durham 2007). We, therefore, modeled age-0 survival as a function of stream discharge. The resulting discharge model predicted the observed abundance of smalleye shiner extremely well and predicted sharpnose shiner abundance closely except for 2006, when the discharge model overestimated observed sharpnose shiner abundance. Although the discharge model correctly predicted general trends in observed abundance of sharpnose shiner, it failed to accurately predict the magnitude of the observed increases and decreases in abundance, particularly in 2006. The failure of the discharge model in 2006 is likely a reflection of the multiplicative relationship between discharge and survival of age-0 fish that is assumed by the model. Mean summer discharge during 2004 was 523 $m^3 \cdot s^{-1}$ and mean discharge during 2005 was 568 $m^3 \cdot s^{-1}$. Summer discharge during these two years was greater than for any other consecutive years. The model predicts greater survival of young during these years, resulting in the multiplicative population increase observed between 2005 and 2006. Biotic and abiotic factors (i.e., carrying capacity) not accounted for by the model may have prevented the actual abundance of sharpnose shiner from reaching abundances predicted by the model in 2006. Despite this limitation, the results of the model suggest that discharge and, potentially, other environmental variables, can be used to predict population dynamics of sharpnose shiner and smalleye shiner in the Brazos River.

Sensitivity simulations of the projection matrix for sharpnose shiner and smalleye shiner indicate that variation in estimates of survival and fecundity used to parameterize the model would not change the relative importance of individual parameter elasticities. Although we derived parameter estimates directly from the inspection of ovaries and otoliths, some reasonable variation about my sample estimates are expected to exist in nature. The simulations provide a measure of confidence that variation in fecundity or survival rates would not fundamentally alter conclusions about sharpnose shiner and smalleye shiner population dynamics derived from the model (Mills et al. 1999). Although not the ideal situation, the robust nature of the model with respect to variation in parameter estimates also suggests that surrogate life-history information of a closely related species could be used to model population dynamics of another species when survival and fecundity estimates are not available or cannot reasonably be obtained. For example, Durham and Wilde (*In Press*) used fecundity data for Arkansas River shiner to model population dynamics of the imperiled Pecos bluntnose shiner *Notropis simus pecosensis*, for which no fecundity information is available. The validity of this strategy is further supported by the conclusions of Vélez-Espino et al. (2006) who found that elasticities are highly conserved among genera within the same family.

There is an increasing recognition of the need for models that relate the population dynamics of fishes, especially imperiled species, to specific aspects of their environments (Oakes et al. 2005; Anderson et al. 2006). In particular, there is a need for models that include feedbacks between physical and chemical aspects of the river environment that can describe how population or community viability will respond to changes in the discharge regime (Anderson et al. 2006). Because sharpnose shiner and smalleye shiner are broadcast spawners and because first-year survival rates of fishes are strongly, and often non-linearly, related to stream discharge (Emlen et al. 1983; Capra et al. 2003; Lobon-Cervia 2004), we directly modeled the effects of stream discharge on first-year survival. Our models allows us to identify the life-history stages that have the greatest impact on sharpnose shiner and smalleye shiner population dynamics and to predict the potential effects of altered flow regimes on abundance and persistence of these species.

The modeling approach used in this study provides an alternative to the more commonly used instream flow models for predicting population dynamics of fishes in prairie streams. Instream flow models are based on extensive measurements of channel morphology (Annear 2004), consequently, these techniques may face their greatest limitations in prairie streams and rivers because of the variable nature of the environment and the rapidity with which changes in physical structure of the channel can occur. Accurate model predictions from instream flow models in prairie streams would require that morphological measurements of the stream channel be made frequently in response to changing conditions. Such frequent measurements would be labor and cost intensive. Furthermore, instream flow models assumes that fish abundance is a function of habitat availability; whereas, our model predicts abundance of fish directly from fecundity and survival (Orth and Maughan 1982; Mathur et al. 1985; Rosenfeld 2003).

The models presented herein represent a simple, mechanistic approach for predicting population dynamics and abundance of prairie stream fishes. The basic model requires minimal data inputs but can be modified to predict abundance based on key environmental factors such as discharge. With the model and associated elasticity analysis and sensitivity simulations, we were able to identify the life-history stages most critical to population dynamics of the sharpnose shiner and smalleye shiner and show that population dynamics can be reasonably modeled as a function of summer discharge in the Brazos River. Such information may help guide conservation and management efforts for the sharpnose shiner, smalleye shiner, and other imperiled prairie stream fish species. For example, with the model we were able to quantitatively assess the potential effects of alternative discharge regimes (i.e., impacts of reservoir construction) on fish population dynamics.

CONSERVATION IMPLICATIONS

Although occasional collections of sharpnose shiner, and more recently smalleye shiner are made in the lower Brazos River, these collections consist of only a few specimens. In contrast, both species are common in the upper Brazos River, although our results suggest the relative abundance of both species has changed since the last comphrensive surveys were made in 1997 and 1998.

Our models suggest that population dynamics of both sharpnose shiner and smalleye shiner are affected by the magnitude and, possibly variation in, Brazos River discharge. Both species spawn over a protracted reproductive season, but survival of ova and young fish appears to be directly related to discharge. Our models should be useful in assessing the effects of past and future modifications to the upper Brazos River on populations of sharpnose shiner and smalleye shiner. For example, impoundment of Lake Alan Henry in 1993 resulted in a 14% reduction in mean summer discharge. Our model (see Figure 32) indicates that this might have resulted in as much as a 49% decrease in abundance of sharpnose shiner and a 48% decrease in abundance of smalleye shiner. Nevertheless, populations of both species appear to be large. If a proposed reservoir on the upper Brazos River, immediately downstream from the confluence of the Double Mountain Fork of the Brazos River and the Salt Fork of the Brazos River, is constructed discharge at downstream sites will decrease by about 55% during the summer reproductive period. Our models predict that, over a 13-year period the average abundance of sharpnose shiner and smalleye shiner will decease 87%; however, our model also suggests that neither species will persist for more than a few years. At best, both species are likely to persist as only a few scattered individuals as they do now in the lower Brazos River.

The main limitation of our models is due to the limited availability of standardized catch data for sharpnose shiner and smalleye shiner in the Brazos River. Our model explicitly assumes that age-0 survival is related to discharge and then uses historic population data to estimate the exact form of the survival-discharge relationship. Thus, our current estimate of the discharge factor DEST are based on five years of data, including two years of data collected by Ostrand (2000), two years collected by Durham (2007), and data for one year collected in this study. Continued sampling, or monitoring, of the sharpnose shiner and smalleye shiner abundance in the upper Brazos River should be given a high priority, to insure the health of populations of both species, to better understand the change in relative abundance of both species that has occurred in the past 10 years, and to allow further improvement of the models presented herein. As continued modifications of the upper Brazos River appear likely, the models developed herein will be critically important in assessing the potential affects on sharpnose shiner and smalleye shiner populations.

SIGNIFICANT DEVIATIONS

There was only one deviation from the proposed research plan. We proposed to conduct two surveys of the Brazos River in both 2005 and 2006. However, due to high water levels in the river in 2005, we were unable to conduct surveys. We were able to conduct other, monthly, sampling in the upper portions of the river. We plan to conduct two surveys in the spring and summer of 2007.

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