

**Zooplankton, Gizzard Shad, and Freshwater Drum: Interactions
in a Great Plains Irrigation Reservoir**

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ABSTRACT

Harlan County Reservoir is an irrigation impoundment located in south-central Nebraska that provides an important sport fishery to the state. My study was aimed at gaining an understanding of the mid-level trophic interactions within the reservoir, specifically those occurring between larval fish and zooplankton. I had three objectives: 1) identify spatial patterns and relationships between larval gizzard shad and zooplankton; 2) examine the food habits of larval gizzard shad; 3) examine the food habits of freshwater drum and model the annual abundance of larval drum based on abiotic and biotic conditions within the reservoir. For the first objective, I sampled larval shad and zooplankton for 8 weeks during 2005-2009. For the second objective, I examined the diets of age-0 shad weekly from June-October in 2008 and 2009. For the third objective, I examined the diets from larval freshwater drum collected during 2008 and 2009, and modeled drum abundance based on abiotic and biotic factors.

The relationships between gizzard shad and zooplankton were examined through spatial correlation analysis. Gizzard shad and zooplankton were correlated during portions of all years but no clear pattern was detected. Water levels were low during 2005 and 2006, but in 2007-2009, the reservoir reached normal levels. This reduced the spatial resolution of the prediction layers and increased prediction error in the west-end of the reservoir.

Examination of the gut contents of age-0 gizzard shad showed that gizzard shad < 30 mm consume large amounts of zooplankton from different groups, and after

growing to 30 mm consume more algae and detritus than zooplankton. Larval shad also showed preferences for specific zooplankton species and avoided others.

Few investigations have examined larval drum diet, and my investigation revealed that drum consume numerous zooplankton taxa. Larval drum consume more and larger zooplankton as they grow and show preferences for certain species. The larval drum abundance model that was developed failed to predict larval drum abundance in 2009, but future work may lead to a more accurate model.

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Chapter 1. Introduction and Literature Review

Reservoir Limnology and Water Quality

Reservoirs are human-formed bodies of water created by the construction of a dam that impedes the flow of a river or irrigation channel. Reservoirs vary widely in size, physical, chemical, and biological parameters (Geraldine and Boavida 2005). Reservoirs receive inflow from rivers during portions of the year, and water levels are managed within them by releasing water through the dam (Cooke et al. 2005). Thus, water levels in reservoirs can experience large annual fluctuations, especially from spring through the fall. Spring precipitation and snowmelt increase water levels early in the year, and long draw-down periods occur throughout the summer and fall when evaporation losses, irrigation, and hydropower needs decrease water levels (Richter et al. 2003). These fluctuations can have effects on the fauna present because habitat availability changes as a result of the rising and falling water levels. For instance, during periods of prolonged water shortages, spawning habitat for many fish may be inaccessible and fish production within the reservoir can be reduced as a result (Naselli-Flores and Barone 1997).

Reservoirs support diverse aquatic communities, but are unnatural aquatic systems and often displace or eliminate native fauna. Dams and reservoirs have been shown to influence many species by changing the flow regime from lotic to lentic (Neves et al. 1997), and by impeding natural migration routes of native fish species (Kareiva et al. 2000). Additionally, by allowing introductions of lentic species to a once riverine

system, competition between introduced and existing species is common (Gido 2001). Dams and reservoirs also influence downstream channel morphology and have been shown to reduce channel braiding, as well as meandering, both of which are characteristic of natural river systems in the Great Plains (Friedman et al. 1998).

Although there are negative impacts following the establishment of dams and reservoirs, there are positive outcomes as well. Reservoirs provide many benefits to communities such as flood control, irrigation water supply, economic inputs, hydroelectric power, and recreational opportunities (Baxter 1977).

Aging and Trophic Level

Reservoirs go through dynamic changes over time. Changes to physical, chemical, and biological components occur on different spatial and temporal scales (Jorgensen 1995). Both natural and anthropogenic factors impact reservoirs to different extents, and ultimately have some effect on the chemical and community composition (Adams et al. 1983).

Most North American lakes and reservoirs are dimictic, which affects the chemical composition of the water column (Gerald and Boavida 2005), and all reservoirs are susceptible to limnological changes from wind or large precipitation events. The properties of water influence these changes as freshwater is most dense at 4° C.

Stratification is common in temperate climates when reservoirs are large and deep. During the spring, cold, melting ice-water at the surface warms to near 4° C,

increases in density, and sinks. Uniform temperatures and wind result in a mixing event that allows the chemical composition of the water column to become uniform (Lampert and Sommer 2007). During the summer months, less dense, warm water accumulates at the surface where it rests on top of the cold layer near the bottom. This creates a thermal gradient where mixing does not normally occur. Between the warm upper and cold bottom layers is a boundary known as the thermocline, where water temperature decreases rapidly with increasing depth (Hutchinson 1957). As fall approaches, cooler air temperatures cause the surface water to decrease in temperature and increase in density, resulting in another mixing event. “Turnover” is the term applied to these mixing events, which cause water to be cycled throughout the water column (Lampert and Sommer 2007).

Lakes, and reservoirs age at different rates depending on the system, and are influenced by watershed size and reservoir storage capacity. Reservoirs typically age more quickly than natural lakes because they are lentic storage areas within flowing systems. Because the flow dynamics change when water reaches a reservoir, particles which were entrained in the flowing waters are deposited when they reach the reservoir, increasing sedimentation and accelerating the aging process (Holz et al. 1997).

The aging process in reservoirs has been characterized into different stages. Kimmel and Groeger (1986) designated two stages in reservoir aging known as ‘trophic upsurge’ and ‘trophic depression’. Trophic upsurge occurs soon after reservoir filling and is characterized by high nutrient loading, and increases in plankton and fish

productivity. During this phase, there is high productivity within the reservoir because of the release of nutrients from the newly flooded soil and vegetation (Grimard and Jones 1982). Eventually the nutrients from these sources are depleted and production rates begin to decline, leading to trophic depression. For example, Popp and Hoagland (1995) documented a ten-fold decrease in benthic macroinvertebrate biomass during trophic depression compared to trophic upsurge levels.

The trophic state of lakes is related to aging processes, and generally follows a predictable pattern of progression from oligotrophic to mesotrophic and finally to a eutrophic state. Oligotrophic lakes are usually young, deep, and have low nutrient availability, and primary productivity. As lakes age and nutrients and sediment are added to the system, they become more eutrophic, meaning primary productivity and algal biomass increase (Lampert and Sommer 2007). Aging in reservoirs occurs more quickly than in lakes because of the addition of nutrients and sediments from inflow and surrounding shoreline (Holz et al. 1997).

Rapid changes in the trophic state of reservoirs are commonly a result of anthropogenic effects relating to land use. When reservoirs are built for purposes such as irrigation, land use practices throughout the reservoir watershed can impact water quality, accelerating the aging process by increasing sedimentation and eutrophication (Kimmel and Groeger 1983).

Changes in the trophic state of a water body can impact the biotic community. Pace (1986) showed that in some Quebec lakes, microzooplankton biomass increased

with trophic state, and similar results were found by Bays and Crisman (1983) in Florida lakes. In addition, Pinto-Coelho and colleagues (2005) found zooplankton, specifically cyclopoid copepods and cladocerans were at least twice as abundant in eutrophic lakes and reservoirs than in oligotrophic systems.

Abiotic Components

Trophic state is often the result of nitrogen and phosphorous availability in the water column which support phytoplankton growth. As part of monitoring aquatic system health, abiotic components are also measured including depth, temperature, pH, dissolved oxygen, turbidity, secchi depth, chlorophyll *a*, and conductivity.

Depth plays an important role in influencing aquatic communities, especially in reservoirs where seasonal and annual fluctuations are common. Low water levels in the spring can result in decreased spawning habitat, egg and juvenile mortality, and nest abandonment when drawdown is rapid (Kohler et al. 1993). Meals and Miranda (1991) showed the abundance of age-0 centrarchids in irrigation reservoirs increased when water levels were high and fish had access to littoral habitats. Rising reservoir levels were also linked to increased production of gizzard shad, *Dorosoma cepedianum*, in Missouri reservoirs (Michaletz 1997).

Temperature is another water quality parameter which affects reservoir communities and the chemical composition of the water column. Larval fish growth rates and survival increased with water temperature for many species including gizzard shad (Michaletz 1997), freshwater drum, *Aplodinotus grunniens* (Butler 1965), crappies,

Pomoxis spp., and sunfish, *Lepomis* spp. (Claramunt and Wahl 2000). Water temperature affects feeding rate of digestion, metabolism (Persson 1979), and frequency of feeding (Brandt 1993). Increases in water temperature has also been linked to spawning time in many species including gizzard shad (Paller and Saul 1996) which begin spawning when water temperatures reach 15.0° C (Bodola 1965). Increased water temperatures in Canadian lakes led to higher zooplankton productivity for some species (Shuter and Ing 1997).

In addition to the biotic effects which temperature influences, temperature affects water chemistry as well. Dissolved oxygen saturation is inversely correlated with water temperature (Lampert and Sommer 2007) and can impact fish distribution. This is especially true for coldwater fish such as trout which are highly dependent on sufficient dissolved oxygen levels to minimize stress (Matthews and Berg 1997).

Although reservoirs are considered lentic environments, flow regimes within them can affect abiotic parameters. Slow moving water within reservoirs travels from the point of inflow toward the point of discharge, and the chemical composition changes along its path (Thornton et al. 1990). Because reservoirs are usually long, narrow, and have a single hydrologic input which is often far from the point of discharge, a nutrient gradient can exist across the reservoir. This gradient is influenced by both basin morphology and flow regime, where long, deep reservoirs retain water longer than shallow, shorter reservoirs. Retention time can also be influenced by both inflow and outflow, and periods of high inflow and outflow can reduce the nutrient

gradient along the reservoir length because water moves more quickly through the system (Thornton et al. 1990).

Zooplankton and Larval Fish

Zooplankton are microscopic animals which inhabit both freshwater and marine habitats and play an important role in the food web. As primary consumers, zooplankton are the link between primary producers and higher trophic levels, and are often sensitive indicators of aquatic ecosystem health (Lampert and Sommer 2007).

Zooplankton are comprised of several groups of small, free-floating organisms including copepods, cladocerans, ostracods, rotifers, jellyfish, some insect larvae, and the larval stages of some fish. Several factors including predation by fish can influence zooplankton populations, so an understanding of community structure in fishless lakes can provide insight to natural zooplankton density patterns. In fishless lakes, large copepods and cladocerans are much more abundant than small zooplankton (Donald et al. 2001). Parker and colleagues (2001) suggest this tendency toward larger zooplankton in fishless lakes is a result of reduced predation by fish.

Zooplankton usually constitute a large portion of the biomass within an aquatic system, and changes in their community structure can influence ecosystem dynamics (Pace et al. 1999). Zooplankton communities change throughout the year based on several abiotic and biotic factors, as well as natural population cycles. The resulting effects on other members of the aquatic community are collectively referred to as the trophic cascade hypothesis (Brett and Goldman 1996). This model describes changes in

community composition as either being controlled by top-down or bottom-up effects based on which members of the community are most strongly influencing the interactions. Although large fish such as northern pike, *Esox lucius* can exert top-down control effects on communities by reducing numbers of smaller fish, it is often the interactions at lower trophic levels, or bottom-up controls which influence ecosystems most heavily (Vander Zanden and Vadeboncoeur 2002). Producers are generally regarded as bottom-up controllers, but zooplankton, which occupy an intermediate position in the food web, can also have bottom-up effects (Fredericksen et al. 2006).

Because zooplankton act as the link between primary producers and most fish, they can exhibit bottom-up control of fish communities. Juvenile and adult fish feed on a variety of prey, but larval fish are restricted to smaller food items (Siefert 1972). Larval fish are gape-limited predators, making zooplankton one of the few food items available in lakes and reservoirs for young life stages (Schael et al. 1991). Because many larval fish species rely on zooplankton as their primary food source, they can be influenced by changes in zooplankton community composition. Low zooplankton abundance has been shown to reduce survival and growth of larval bluegill, *Lepomis macrochirus*, (Welker et al. 1994), and abundance of gizzard shad (Michaletz 1997). Because of these factors, zooplankton may have impacts on initial year class strength, and fish recruitment (Bremigan and Stein 1994).

Another important component of zooplankton and larval fish interactions is the impact which fish have on the zooplankton community. Larval fish have the potential to

shape zooplankton communities by electing to consume certain types or sizes of prey (Yako et al. 1996). In high densities, larval fish such as gizzard shad have been shown to nearly eliminate portions of the zooplankton population which may affect other species of larval fish (Stein et al. 1995). These changes can influence larval fish communities, and foraging strategies among different fish.

One factor which influences larval fish growth and survival is timing of appearance, and earlier emergence can be an advantage for some fish (Garvey and Stein 1998). Earlier emerging fish have a competitive advantage over other larval fish because there is less competition between species for resources, allowing them to attain larger sizes more quickly (Dettmers and Stein 1992). Not only are late emerging fish smaller than others already present in the system, but they are also at a disadvantage because zooplankton resources can be lower later in the year because of predation by other members of the fish community (Stein et al. 1995) and natural decreases in zooplankton populations (Stenseth et al. 2002). Gizzard shad are fish which spawn in the late spring and early summer, reach high densities, and can deplete zooplankton in lakes and reservoirs (Dettmers and Stein 1992), creating a competitive bottleneck for late emerging sport fish which can reduce recruitment of these species (Werner and Gilliam 1984). Because of this influence on both zooplankton and larval fish, it has been suggested that gizzard shad can act as middle-out consumers, impacting species both above and below their trophic level (Miranda and Gu 1998).

The native range of the gizzard shad in the U.S. extends from the east coast to the Gulf of Mexico and up to the Great Lakes (NatureServe 2003). They have also been introduced widely as a forage fish in many systems across the country. Gizzard shad prefer water with high phytoplankton production, and the young generally occupy the littoral and limnetic areas of lakes and reservoirs (Matthews 1984). Spawning occurs in the late spring and early summer, when females broadcast their pelagic eggs in shallow, littoral habitat (Bodola 1966). Females mature at age one or two (Bodola 1966) and can expel between 20,000 and 170,000 eggs depending on their size (Kilambi and Baglin 1969). The average life span of gizzard shad is about six years (Kilambi and Baglin 1969). As adults, gizzard shad are filter feeders which use specialized gill rakers to concentrate food particles such as zooplankton, microcrustaceans, phytoplankton, and detritus (Bodola 1966). The primary food of adults is detritus, and Baker et al. (1971) found adult fish will graze the bottom of lakes and reservoirs ingesting detritus and other organic matter.

Larval gizzard shad are unusual because they feed omnivorously on zooplankton, algae, and detritus, while most other larval fish are restricted to zooplankton for food (Yako et al. 1996). In the laboratory (Mundahl and Wissing 1988) and natural systems (Yako et al. 1996), gizzard shad have been shown to consume zooplankton when available, but switch to algae and detritus when densities of zooplankton are absent or in low abundance. This capability allows shad to survive periods of low zooplankton availability which other fish cannot (DeVries and Stein 1992). Shad are filter feeders as

adults and late juveniles (Dettmers and Stein 1996), and consume their prey by pumping water past their gill rakers which collect zooplankton and organic matter (Drenner et al. 1982). Because detritus is abundant in nearly all systems, shad are provided with a constant food source and allowed competition-free foraging (Dettmers and Stein 1996).

Larval Fish Diet Analysis

Knowing the food requirements of fish is crucial to the understanding of competition, growth, and survival. There are different methods used to evaluate diet components in fish including gastric lavage, visual observations of feeding in a laboratory setting, and dissection of the digestive tract. Dissection and direct visual observation are the only practical means of assessing the diets of larval fish because of their small, fragile bodies. Mooij (1996) suggests there is variation among larval fish species and their preferred prey. Larval bluegill have been shown to consume mostly zooplankton and other small invertebrates, while gizzard shad can consume zooplankton, invertebrates, and detritus (Garvey and Stein 1998).

There are preference differences in species and prey sizes consumed by different larval fish. Mathias and Li (1982) found larval walleye in field and laboratory settings consumed 1.0 to 2.0 mm zooplankton almost exclusively with prey length averaging 1.2 mm. In contrast, larval gizzard shad in Kokosing Lake consumed smaller zooplankton averaging less than 0.5 mm, and larval white crappie consumed prey which was between 0.25 and 0.75 mm (DeVries et al. 1998).

Gizzard shad change their diet based on their size and food availability, consuming zooplankton during early larval stages and eventually switching to a diet which consists primarily of detritus (Miranda and Gu 1998). When shad are abundant and consume large amounts of zooplankton, they can limit the food availability for other larval fish.

Spatial Analysis

Many ecological questions can be answered by the use of spatial-temporal analyses (Turner 1990). Geostatistical analysis and geographical information systems (GIS) software have aided ecologists in answering questions regarding the timing and distributional patterns of organisms in their environments (Kushwaha and Roy 2002). GIS software is capable of organizing, analyzing, and displaying spatial data, and has advantages over other methods of evaluation in the form of speed, accuracy, and the ability to handle large datasets (Isaak and Hubert 1997). In addition, GIS software is capable of allowing analyses of the relationship of parameters in multiple layers which vary in space and time. GIS has gained in popularity as a research tool of fisheries scientists (Isaak and Hubert 1997) where it has been used in many applications including mapping distribution and movement of northern squawfish, *Ptychocheilus oregonensis*, in river systems (Isaak and Bjorn 1996), and comparing trout abundance and density with thermal regimes in the North Platte River in Wyoming (Rahel et al. 1996). Additionally, Arbuckle and Downing (2002) used GIS to analyze the relationship between zebra mussel, *Dreissena polymorpha*, densities and specific habitat types within a watershed.

Spatial relationships between water quality parameters, zooplankton and gizzard shad distribution are important for understanding interactions among species. Other studies have shown changes in the composition of minnow populations after the introduction of smallmouth bass, *Micropterus dolomieu*, and have described the changes on a spatial and temporal scale (Schofield and Driscoll 1987). Haines (1981) determined fish populations changed spatially because of different physiological tolerances of pH levels. Another study by Sabates and Olivar (1996) evaluated the changes in distribution of larval marine fish in relation to the slope of offshore benthic habitat. The spatial distribution of Cutthroat trout, *Oncorhynchus clarki*, in the streams and rivers of Oregon was analyzed using geostatistical tools and GIS by Torgersen et al. (2004).

Repetitive sampling at georeferenced sites can provide the data necessary to detect patterns in the distribution of organisms on a spatial and temporal scale (Torgersen et al. 2004). Before reaching conclusions about spatial relationships between abiotic and biotic parameters in an aquatic system, several years of data need to be collected to reduce the variability of experimental error. Olds (2007) examined spatial-temporal relationships between water quality, zooplankton, and gizzard shad abundance at Harlan County Reservoir during and after a period of drought. By adding more years to this dataset, a better understanding of the spatial-temporal patterns in the reservoir can be developed. Once the data are obtained and if patterns are detected, managers can use the information to improve management decisions.

Biology of Freshwater Drum

The freshwater drum is the only non-marine representative of the Sciaenidae family. Marine Sciaenidae are abundant in the Gulf of Mexico and there is evidence that freshwater drum originated from this area (Barney 1926). Drum are believed to have transitioned into the brackish water of Louisiana before eventually becoming tolerant of freshwater and moving inland. The freshwater drum began to spread northward up the Mississippi River, then east and west into other river systems and tributaries (Barney 1926). The distribution of drum in North America is widespread, existing in aquatic systems from as far north as Lake Winnipeg, Canada, and south to river systems in Guatemala (Barney 1926). Freshwater drum inhabit 31 states and 3 Canadian provinces (NatureServe 2005) and it has the largest latitudinal range of any freshwater fish found in North America (Rypel 2007). They are found in a variety of systems including tropical rivers, limestone streams, inland seas in the U.S., glacial lakes and rivers, and temperate lakes and rivers. The mountainous regions of the eastern and western United States have blocked the spread of drum to the coasts (Barney 1926).

Although drum are important components of the aquatic food web, they are not regarded as economically valuable (Edsall 1967). There are a few places where freshwater drum play a role economically, including Lake Erie which has a commercial harvest for use in the production of animal food (Johnson and Metcalf 1982). Although they are classified as a commercial fish in Nebraska (NGPC 2009), in most states they are not targeted heavily by anglers.

Adult drum are one of the most fecund freshwater fish, with mature females producing several hundred thousand eggs per season (Rypel 2007). They are also long-lived, with records of fish reaching age 72 in the Red Lakes of Minnesota (Pereira et al. 1992). Although they exhibit episodic annual recruitment (Winemiller and Rose 1992), freshwater drum abundance generally remains stable in aquatic systems. In some reservoirs such as those in Alabama, drum account for the largest percentage of biomass of any local species (Rypel 2007). Drum are broadcast spawners which begin spawning in the spring when water temperatures are between 18 and 25 °C. In South Dakota reservoirs, the spawning period can last for up to 7 weeks (Swedburg and Walburg 1970). Drum produce a semi buoyant egg, and hatch into larvae 1 to 2 days after fertilization. They are pelagic during the early larval stage, but move to deeper water after growing to a size greater than 20 mm (Swedburg and Walburg 1970).

Larval drum begin actively feeding within a few days of hatching and have been shown to consume a variety of zooplankton and small invertebrates (Swedburg and Walburg 1970). Larval fish are gape limited predators, and freshwater drum have one of the largest gape to length ratios of all larval freshwater fish (Schael et al. 1991). Because of this, drum are less restricted in their diet, and can consume organisms which are too large for other larval fish. In Lewis and Clark Lake, South Dakota, Swedburg and Walburg (1970) found larval freshwater drum less than 15 mm consumed large amounts of *Daphnia* and *Cyclops* copepods which comprised 90% of the diet by volume. Chironomid larvae and zooplankton made up the majority of the diet of 20 – 40 mm

drum, and fish larger than 40 mm consumed *Hexegenia* mayfly nymphs and other invertebrates (Swedburg and Walburg 1970).

Adult drum are omnivorous and consume insect larvae, as well as mollusks and small fish (Cross and Collins 1995). Drum possess molariform teeth which they use to crush the shells of mollusks. In the Great Lakes, zebra mussels, *Dreissena polymorpha*, are abundant and can contribute up to two-thirds of the diets of adult drum (French and Bur 1996). In Lewis and Clark Lake, South Dakota, adult freshwater drum consumed aquatic invertebrates for most of the year, with burrowing *Hexegenia* mayflies, making up nearly three-fourths of the diet by volume (Swedburg 1968). Being opportunistic feeders, drum have also been shown to consume fish, and in Lake Erie are known to consume large numbers of larval gizzard shad (Griswold and Tubb 1977).

Abundance and Recruitment of Larval Fish

Butler (1965) suggests that the initial year class strength of fish such as drum, which have high fecundity but exhibit episodic recruitment, is affected most heavily by factors occurring early in the first year of life. Abiotic factors such as water temperature, surface acres, dissolved oxygen, pH, turbidity, mean depth, inflows to a system, and air temperature are linked to the dynamics of an aquatic system (Lampert and Sommer 2007). Additionally, biotic factors such as predation, inter- and intra-species competition, zooplankton density, and chlorophyll a concentrations, are also dynamic and can influence aquatic systems. In addition to individual effects, many of the factors are correlated with each other such as higher water temperatures and

increased zooplankton. Additionally, changes in some of these abiotic and biotic parameters affect the system at different trophic levels.

Drum are unusual because unlike gizzard shad, predatory sport fish do not regularly utilize them as a food source during the larval stage (Butler 1965). Because it is unlikely that drum numbers are being influenced by predation from other fish, there are other factors that must contribute to their changes in annual abundance (Butler 1965).

Even though drum abundance is not normally directly affected by the presence of other species through predation, competition between fish species for resources can play a role. Welker and colleagues (1994) showed high diet overlap between larval fish species and found that starvation is possible if zooplankton resources cannot support the fish biomass present in a system. Gizzard shad, a species present in Harlan County Reservoir at the same time as freshwater drum (Olds 2007), have been shown to significantly reduce zooplankton numbers in other systems, limiting the recruitment of other fish (Dettmers and Stein 1992).

Nearly all fish rely on crustacean zooplankton as their primary food source during the earliest stages of life (Schael et al. 1991), and high densities are necessary because fish are more prone to starvation during the larval stage than during adulthood (May 1974). Because of this, it is likely that changes in zooplankton community composition will affect larval fish growth and survival (Welker et al. 1994). Crecco and

Savoy (1985) showed higher survival rates of larval American shad, *Alosa sapidissima*, when zooplankton densities were high.

Intra- and inter-specific competition can also influence the initial survival of larval fish (Hall and Rudstam 1999). Because fish density and not growth or recruitment is used as a measure of year class strength, the effects of intra-specific competition on this parameter cannot be analyzed. Inter-specific competition among larval fish is usually associated with availability of zooplankton and the ability of different species to forage successfully. Devries and Stein (1992) showed gizzard shad grazed zooplankton to densities near zero, which reduced the survival and recruitment of other fishes in the system. It is possible that gizzard shad are having similar effects on the zooplankton in Harlan County reservoir, and thus, may be limiting drum success, as well as influencing other fish species.

Abiotic Factors Influencing Larval Fish Abundance

Abiotic factors can also play significant roles in shaping the aquatic community and are constantly changing. During spring months when spawning occurs, random, highly variable weather patterns occur in Nebraska in the form of warm and cold fronts (Brown and Brown 2000). These fronts can cause rapid changes in zooplankton availability and water quality parameters including temperature, pH, dissolved oxygen (Secor and Houde 1995).

Fluctuations in water temperature during spawning periods have been associated with year class strength of several fish species (Hall and Rudstam 1999). In

the Mississippi River, drum have been shown to experience higher hatches when surface water temperatures were above average during spawning periods (Butler 1965). Larval bluegill, crappie, and gizzard shad also experienced better growth and survival when surface water temperatures were higher than average (Claramunt and Wahl 2000). Cold fronts can also be detrimental to some pelagic larval fish. Houde (1989) found over 65% mortality of some marine fish eggs and young larvae when exposed to sub-optimal temperatures.

Other abiotic factors such as mean depth, inflow, and turbidity have been shown to influence larval fish growth and survival. Claramunt and Wahl (2000) found gizzard shad growth increased as mean depth decreased, because shallower water provided a larger littoral area which increased total productivity. In contrast, high inflows into reservoirs can cause high turbidity, impacting the ability of sight-feeding larvae to forage successfully, thereby reducing survival (Matthews 1984).

Study Site

In 1952, Harlan County Reservoir was constructed by the U.S. Army Corps of Engineers (USACE) for the purpose of flood control and irrigation. The reservoir is located in south-central Nebraska on the Republican River between Alma and Republican City and has a surface area of 5,261 hectares at conservation pool (USACE 1996). Unlike the majority of the other reservoirs in Nebraska which are controlled by the U.S. Bureau of Reclamation, the operations at Harlan County Reservoir are controlled by the USACE. Water rights within the basin are controlled by the Republican

River Water Conservation District which is composed of representatives from Colorado, Kansas, and Nebraska.

This body of water experiences inflow patterns typical of reservoirs in a temperate climate, with inputs of water during late fall through spring, followed by draw-down periods during the summer when irrigation needs are high. These patterns create a dynamic system which influences the aquatic community and water quality attributes. In addition, a prolonged drought in 2005 and 2006 nearly eliminated both inflows and irrigation releases, further changing the system.

Over 90% of the land area in the Republican River Basin is used for agricultural purposes, and runoff inputs are likely affecting the trophic state of Harlan reservoir (USACE 1996). The reservoir is classified as very eutrophic because of high total nitrogen (TN) and phosphorus (TP) amounts. From 1996 to 2006, the mean annual TN and TP measures ranged from 0.94 to 1.17 and 0.12 to 0.17, respectively. These values are much higher than the target values established by the Nebraska Department of Environmental Quality which are 0.57 mg/L for TN and 0.033 mg/L for TP (USACE 2006).

The reservoir supports a variety of non-game and sport fish which are managed by the Nebraska Game and Parks Commission (NGPC). Records show the following species have been collected in the reservoir: black bullhead, *Ameiurus melas*, channel catfish, *Ictalurus punctatus*, flathead catfish, *Pylodictus olivaris*, common carp, *Cyprinus carpio*, river carpsucker, *Carpionodes carpio*, bluegill, black and white crappies, freshwater drum, gizzard shad, golden shiner, *Alosa chrysochloris*, largemouth bass, *Micropterus*

salmoides, northern pike, white bass, *Morone chrysops*, striped bass, *Morone saxatilis*, and walleye, *Sander vitreus*. Anglers at Harlan primarily target white bass, walleye, and catfish, and provide significant revenue to the local towns (Chang et al. 2003). Stocking of sport fish by the NGPC has been a regular occurrence, and records indicate that walleye, white bass, largemouth bass, channel catfish, northern pike, and wiper have all been stocked in Harlan County Reservoir in the last 20 years.

Walleye stocking in Harlan County Reservoir is a regular occurrence but efforts have been variable. Walleye stocking treatments of fry, fingerling, and no walleye alternate based on availability from the hatcheries and the current year's management objectives.

Gizzard shad are an important forage species for sport fish in many impoundments, and can influence reservoir communities. Gizzard shad were stocked in Harlan County Reservoir as forage fish for walleye and white bass, and have reached high densities. During the last decade, there has been concern for the walleye fishery at Harlan, and the NGPC began an investigation of possible causes. Olsen et al. (2007) concluded that although adult walleye, white bass, and wiper had high diet overlap, they occupied different portions of the water column and therefore did not directly compete with one another. This led to the investigation by Olds (2007) which addressed larval shad and zooplankton dynamics in the reservoir. It is hypothesized that young of the year gizzard shad are consuming zooplankton limiting this resource for larval

walleye. While Olds (2007) found spatial and temporal patterns among zooplankton and larval gizzard shad, he did not assess the diet components of the shad sampled.

Study Objectives

The goals of this project were to gain an understanding of the complex processes and interactions relating to larval fish, zooplankton, and water quality in Harlan County Reservoir. This was done by: 1) Investigating the relationship between zooplankton and larval gizzard shad on a spatial and temporal scale; 2) Evaluating the diet composition of larval gizzard shad and its relationship to trends in zooplankton abundance and community composition; 3) Determining the diet of larval freshwater drum and creating a model of abiotic and biotic parameters that may predict their abundance.

By understanding the interactions taking place in lower trophic levels among zooplankton, gizzard shad, and drum, the changes occurring at other trophic levels may be better understood, perhaps explaining declines in walleye numbers. Knowing the processes which are affecting the forage fish community may also help NGPC personnel make more informed decisions relating to stocking and fish management.

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Chapter 2. The Spatial Relationship of Larval Gizzard Shad and Zooplankton in a Nebraska Irrigation Reservoir

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Abstract

Gizzard shad, *Dorosoma cepedianum*, consume zooplankton during the larval stage and have the potential to reduce zooplankton populations. Describing the spatial relationship between gizzard shad and zooplankton is important for understanding the interactions between these species. Conventional and geostatistical analysis techniques provide a means of evaluating these relationships. Gizzard shad and zooplankton communities were sampled weekly for 8 weeks in June and July at 24 stations in Harlan County Reservoir from 2005-2009. Zooplankton and gizzard shad densities were correlated in less than half of the weeks during the 5 year study. Gizzard shad were positively correlated with copepod nauplii most frequently and *Daphnia* spp. least frequently. The highest densities of gizzard shad and zooplankton occurred in 2005 and 2006 when the reservoir was under drought conditions. When the reservoir increased to full pool in 2007-2009, gizzard shad and zooplankton density dropped significantly, suggesting the fish and zooplankton were less aggregated, or conditions became unfavorable. In all 5 years, both zooplankton and gizzard shad densities were spatially autocorrelated and showed clustered distributions. Densities were especially high in the mid- and upper-reservoir, while lower production occurred near the dam. In 2007-2009 the reservoir expanded well beyond the previously established sampling points, leading to increased error on the prediction layers in the upper-reservoir. Sampling these locations in the future could lead to a better understanding of the zooplankton

and gizzard shad population structure in the upper-reservoir, and would provide better spatial resolution for the prediction layers.

Introduction

Determining spatial relationships allows for characterization of complex ecological processes across ecosystems; however, until recently, researchers were restricted to utilizing conventional statistical approaches when looking at abiotic and biotic processes within aquatic systems. Although the use of multivariate statistical methods in fisheries has become increasingly popular (Paukert and Wittig 2002), these methods have biases when used to evaluate spatial relationships among organisms and their environment (Rueda 2001). Multivariate statistical methods which have been used in the past lacked the ability to detect spatial autocorrelation between sites (Rueda 2001). Spatial autocorrelation is the tendency of values to be more similar at locations which are short distances from one another than at stations which are greater distances apart. By accounting for spatial autocorrelation, geostatistical techniques not only minimize pseudoreplication, but also allow effective visual representations of the data to be created (Kern and Coyle 2000). Thus, geostatistical methods have improved the ability of researchers and managers to describe spatially related processes and have provided a better understanding of fish distribution (Petitgas 1996).

Zooplankton are an important food source for many fish, and understanding the spatial distributions of fish and their zooplankton prey has only recently been explored using geostatistical analysis. Bulit and colleagues (2003) studied marine plankton

patchiness within a tropical coastal lagoon using geostatistical methods. In another study, kriging, a prediction technique, was applied to estimate zooplankton biomass on a large scale (Kern and Coyle 2000). Masson et al. (2001) studied small-scale spatial interactions between Eurasian perch, *Perca fluviatilis*, and zooplankton in a sub-alpine lake. Although these studies have examined the spatial distributions of zooplankton and fish species in other systems, none have used a geostatistical approach to investigate relationships between gizzard shad, *Dorosoma cepedianum*, and zooplankton populations within freshwater reservoirs.

Within an aquatic habitat, interactions take place between and among organisms from the same and different trophic levels. From a top-down ecological approach, predators such as fish are often considered the driving forces which have the greatest influence on the food web and trophic status of the system (Brett and Goldman 1997). In contrast, bottom-up control is influenced by nutrient availability and organisms which occupy lower trophic levels such as phytoplankton, zooplankton, and larval fish. The division between top-down and bottom-up control is often unclear, and some fish can influence control in both directions (Dettmers and Stein 1996). Gizzard shad are one of these species, because they have the ability to feed on food sources from different trophic levels (Schaus and Vanni 2000). Through this omnivorous feeding, shad can influence higher trophic levels by consuming zooplankton, limiting food availability for other larval fish (Welker et al. 1994), and alter nutrient availability

within a system by switching to a diet of algae and detritus when zooplankton is scarce (Stein et al. 1995).

Consideration of gizzard shad size is important because shad change their feeding preferences as they grow (Yako et al. 1996). Larval gizzard shad grow quickly and growth is estimated at 0.84 mm per day (Claramunt and Wahl 2000). This factor coupled with a prolonged spawning period, results in the simultaneous presence of several size classes of fish with potentially different feeding preferences. Other studies have documented that newly hatched gizzard shad less than 15 mm total length (TL) did not feed heavily on zooplankton (Bremigan and Stein 1997), fed heavily on zooplankton when 15-25 mm (TL) (Miranda and Gu 1988), and transition to a diet composed of algae and detritus between lengths of 25-30 mm (TL) (Yako et al. 1996).

Individual zooplankton groups and species are also important because larval gizzard shad have been shown to prefer specific zooplankton groups. Sullivan (unpublished data) showed larval gizzard shad < 30 mm preferred copepod nauplii and cyclopoid copepods. These results are similar to those documented by Miranda and Gu (1998), who found the diets of gizzard shad < 10 mm in length was composed of 90% copepod nauplii. Additionally, gizzard shad < 25 mm showed highest preference for cyclopoid copepods in a Kansas reservoir (Cramer and Marzolf 1970).

Because gizzard shad have high fecundity (Bodola 1966), there is potential for large hatches of larvae in mesotrophic and eutrophic systems such as Harlan County Reservoir in south central Nebraska. This can provide sport fish with abundant prey

while shad are juveniles, but can also lead to competition and limited recruitment of newly hatched sport fish that rely on the same zooplankton diet. At Harlan County Reservoir, the Nebraska Game and Parks Commission reported an increase of 653% in gizzard shad abundance and a 36% decrease in walleye, *Sander vitreus*, abundance from 1994-2001. These dramatic changes in abundance may suggest that high numbers of gizzard shad are impacting the recruitment of age-0 walleye in Harlan, since walleye have been shown to rely on zooplankton for food during the larval stage (Li and Mathias 1982). If gizzard shad are consuming zooplankton in Harlan County Reservoir, gizzard shad and zooplankton should exhibit similar distribution patterns throughout the reservoir.

Investigating the spatial relationship between gizzard shad and zooplankton will help to understand the effects that gizzard shad may have on sport fish. If a relationship between these organisms can be found, demonstrated, and described, further investigations may lead to a better understanding of the impacts of gizzard shad on other species.

Geostatistics can be used to examine spatial relationships within a dataset. Kriging is a geostatistical prediction technique which applies autocorrelation within a dataset to estimate values at unsampled locations. This technique uses variogram models that describe the spatial continuity or roughness of a dataset and have distinct components including the range, sill, and nugget. The range is the distance at which the variogram's curve becomes a constant and shows the maximum distance that spatial

data can be modeled. The sill is the value of the variogram for distances beyond the range of the variogram, and the nugget is the distance before which autocorrelation exists (Groenigen 2000). These values can be manipulated to create a best-fit model for a dataset.

Materials and Methods

Study Site

Harlan County Reservoir is an impoundment on the Republican River located in south-central Nebraska. With a maximum multipurpose pool of 9,348 ha, Harlan County Reservoir is the second largest reservoir in the state. Harlan County Reservoir is long and narrow, and wind regularly mixes the water column, preventing thermal stratification. As a eutrophic system, there are high amounts of available nutrients, algal biomass, and high turbidity.

Sampling Regime and Data Collection

Harlan County Reservoir was divided into three zones, each containing eight sampling stations for a total of 24 stations (Figure 1). Sampling started during the last week of May and continued for eight consecutive weeks from 2005-2009. During week three of all years, an additional 24 stations were sampled to provide more spatial resolution for analysis. Sampling was initiated near dusk and continued until all stations had been sampled. Weather conditions often dictated the starting point and route of travel from station to station and varied by week.

Both larval fish and zooplankton were sampled at each station. Zooplankton samples were collected using an 80 μm Wisconsin plankton net which was deployed to within 0.5 m of the bottom and pulled vertically to the surface. Samples were preserved in a 4% sucrose formalin solution until they could be processed in the lab. Gizzard shad were captured using two different sized push nets attached to a custom-made T-bar which allowed them to be raised and lowered into the water at the start and end of sampling at each station. The large, 1 m diameter net had a mesh size of 1.8 mm and a 0.75 mm cod-end cup, and the small, 0.5 m diameter net had a mesh size of 0.75 mm and a 0.75 mm cod-end cup. Each net was equipped with a flow-meter in the center of the opening to determine the amount of water sampled at each station. The boat was driven at a constant speed of 4 kph for 5 minutes in a direction which was dictated by weather and depth considerations. Upon completion of each station, contents from each net were preserved separately in ethyl alcohol and stored until they could be processed in the lab.

In the laboratory, zooplankton were identified and enumerated. Four subsamples were identified and counted for each station to determine densities of total zooplankton and individual groups. Zooplankton were separated into groups including copepods, cladocerans, and other. Copepods were separated into the orders Calanoida and Cyclopoida and the immature nauplii stages. Cladocerans were identified as *Daphnia pulicaria*, *D. retrocurva*, or *D. lumholtzi*. Other less common zooplankton which were identified included *Bosmina* spp., *Alona* spp., and *Diaphanosoma* spp. Larval shad

catches from both nets were combined to produce a single shad/m³ value. Gizzard shad densities were then calculated for four size classes: 5-30 mm (all larval shad), 5-14 mm, 15-30 mm, and >30 mm total length (TL).

Statistical Analysis

Sigma Stat 3.1 (SSI 2004) software was used to analyze gizzard shad and zooplankton density data. Because data were not normally distributed, a Kruskal-Wallis test was used to test for differences among years for zooplankton and gizzard shad densities. Differences between years was determined using a Dunn's post-hoc test at $\alpha=0.05$. Density differences between years among total gizzard shad, each gizzard shad size class, total zooplankton, and each zooplankton group were tested in the same manner. Spearman correlations were conducted at $\alpha=0.05$ using Sigma Stat software to test for correlations between gizzard shad size classes and each zooplankton group.

ArcGIS 9.2 with the Geostatistical Analyst plug-in (Johnson et al. 2001) was used for geostatistical analysis and mapping. To test for spatial autocorrelation in total zooplankton and gizzard shad densities, Moran's I statistic was computed for the intense sampling week during each year. Moran's I tests against the null hypothesis that for a given set of data there is no spatial dependence. This test produces a z-score which is a measure of standard deviation. Z-scores greater than +1.96 indicate clustering and lower than -1.96 indicate dispersion at $p < 0.05$. Because this test requires a minimum of 30 points, only data from the intense sampling week of each year, when 48 stations were sampled, were analyzed. Because shad and zooplankton densities were not

normally distributed, all densities were transformed using the following equation before

being tested with Moran's I: $x = \left| \ln \left(\frac{1}{\sqrt{\text{Density}}} \right) \right|$.

The dates which were used for spatial analysis included the second, third and fourth sampling weeks in each year and encompassed the peak of the gizzard shad hatch. Using the geostatistical analyst plug-in, ordinary kriging methods were used to create isotropic prediction maps for zooplankton and gizzard shad densities at unsampled locations throughout the reservoir. All kriged surfaces were created using a spherical covariance model. The best-fit model had a standardized root-mean squared value close to 1.0. Representative surfaces were created for the intense sampling week in two years, one year when zooplankton and gizzard shad densities were correlated and Moran's I statistic showed autocorrelation within each dataset, and one year when gizzard shad and zooplankton were not correlated but Moran's I statistic showed autocorrelation within each dataset.

To allow for better interpretations of the kriged surfaces and the potential prediction error, standard error maps were created using data from the intense, 48-station sampling weeks in 2005 and 2008 to represent the drought years (2005-2006) and the years when Harlan reservoir was near full-pool (2007-2009). These error maps represent the prediction error in drought years and years where Harlan County Reservoir was at full pool.

Results

The average densities of total shad and total zooplankton were highest in 2005 and 2006 (Table 1). Of the five years sampled, 2006 had the highest mean density of 5-30 mm shad at 4.32 ± 0.76 fish/m³. Zooplankton groups including Calanoida, Cyclopoida, and nauplii were also highest in 2006. Total *Daphnia* spp. was highest in 2005, and was significantly lower in all other years (Table 1).

Significant correlations between gizzard shad and zooplankton were observed in all years (Table 2). During the 15 weeks sampled from 2005-2009, significant correlations occurred between gizzard shad 5-30 mm in length and the following zooplankton groups in these proportions: total zooplankton in 46.6% of weeks, copepod nauplii (46.6%), *Daphnia* spp. (13.3%), and copepods (40%) (Table 2). Gizzard shad 5-14 mm in length were correlated with total zooplankton in 26.6% of the weeks, *Daphnia* spp. in 20% of the weeks, copepods in 26.6% of the weeks, and copepod nauplii in 26.6% of the weeks. Gizzard shad 15-30 mm in length were correlated with total zooplankton in 26.6% of the weeks, *Daphnia* spp. in 6.7% of the weeks, copepods in 20% of the weeks, and copepod nauplii in 40% of the weeks (Table 2).

The results from the Moran's I test showed that the densities of gizzard shad and zooplankton showed positive spatial dependence (clustering) or random distribution in all years, and densities were never negatively spatially dependent (dispersal). Gizzard shad 5-30 mm in length were spatially dependent in 1 of 5 years, and densities of shad 5-14 mm were spatially dependent in 3 of 5 years. Densities of gizzard shad 15-30 mm

in length were spatially dependent in 3 of 5 years. Total zooplankton and copepod densities were spatially dependent in 3 of 5 years, but nauplii were only in 2 of 5 years (Table 3).

The kriged surfaces created for the intense week in 2008 shows gizzard shad from 15-30 mm in length and total zooplankton densities had similar distributions (Figure 3). During the intense sampling week in 2009, densities of shad 5-30 mm in length and total zooplankton were not correlated with each other, and while gizzard shad were clustered in the reservoir, zooplankton densities increased toward the upper reservoir (Figure 4).

The range for all models was 3,155 meters and sill, and nugget values ranged from 0.1 to 364.5, and 0.1 to 0.5, respectively (Table 4).

Standard error maps can be used to determine areas within a kriged surface which have high and low prediction error. Two error maps were created, one for gizzard shad and one for zooplankton densities (Figure 2). Both maps show the highest error, represented by dark shading, near the shores and in the west end of the reservoir.

Discussion

The highest densities of shad were observed in 2005 and 2006 (Table 1). Several factors could have accounted for these observations including abundant forage, fluctuating water levels between years, or other abiotic and biotic factors. Larval gizzard shad prey on zooplankton when they are abundant (Yako et al. 1996), and high zooplankton densities have been linked to better survival of larval gizzard shad in many

systems (Dettmers and Stein 1996; Michaletz, 1996). Because total zooplankton were most abundant in 2005 and 2006 (Table 1), it is possible that this led to better survival and therefore higher densities of larval shad in the same years.

Another factor which could explain the differences in shad abundance is the drought which caused reservoir water levels to be near 40% of full pool in 2005 and 2006. Above average precipitation raised water levels to near full capacity in 2007-2009. It is possible that gizzard shad had dispersed throughout the reservoir in recent years, and the greater area occupied reduced the overall density of larval gizzard shad. Equally plausible is the possibility that high densities of shad were located in the extreme upper west end of the reservoir in 2007-2009, an area which was not sampled during this study. To replicate stations across all years, sample locations did not change when the reservoir area expanded, and this led to areas in the west end which were not investigated. If these areas had been sampled, the average shad density for 2007-2009 may have been higher, making them closer to those found in 2005 and 2006.

Significant correlations between gizzard shad and zooplankton were observed in less than half of the weeks sampled from 2005-2009. When gizzard shad were correlated with total zooplankton, they were also often correlated with total copepods and copepod nauplii. This was likely due to the fact that copepods and nauplii are the most numerous zooplankton in the reservoir, thus contributing the most to total zooplankton density.

Correlations occurred most frequently between shad and nauplii (Table 2). This is likely due to the feeding behavior of shad in Harlan. In a study which investigated the food habits of gizzard shad, Sullivan (unpublished data) observed 5-30 mm gizzard shad consumed more nauplii than any other zooplankton group. These findings were similar to those documented by Dettmers and Stein (1992), who found positive selection for copepod nauplii by larval gizzard shad.

While total zooplankton and most zooplankton groups were frequently correlated with shad abundance, *Daphnia* spp. were not. Although *Daphnia* spp. are preferred prey of larval gizzard shad in some lakes and reservoirs (Shepherd and Mills 1996; Schaus et al. 2002), they were only correlated with gizzard shad abundance in 13% of the weeks during this study (Table 2). In one week during 2008 and one week during 2009, gizzard shad and *Daphnia* spp. were positively correlated; however, *Daphnia* spp. have not been shown to be preferred prey of shad in Harlan (Sullivan unpublished data). Their spatial overlap and positive correlation was likely because of higher numbers of all zooplankton which were also found to be positively correlated with gizzard shad during the same periods. In week 4 of 2008, *Daphnia* spp. were highly negatively correlated with gizzard shad, yet no other zooplankton groups showed significant correlations. It is unlikely that *Daphnia* spp. abundance was low as a result of predation by gizzard shad, but they could have been eaten by other fish in the system. Larval freshwater drum, which are also present in Harlan during late spring, have been shown to consume *Daphnia* (Swedberg and Walburg 1970; Sullivan unpublished data)

and could have been responsible for their low numbers and the resulting negative correlation with larval gizzard shad.

Correlations between shad and zooplankton were not observed in all weeks. Several factors could lead to a lack of correlation between shad and groups of zooplankton. For instance, shad predation on zooplankton could be occurring on localized scales within the reservoir, but the once weekly sampling regime might not detect this pattern. Because sampling only captures moments in time, the observed results could be influenced by whether shad are moving to a group of zooplankton, are in the process of grazing on zooplankton, or have already consumed the majority of the zooplankton at a sample site.

The prediction surfaces which were created using kriging techniques provided a means of assessing shad and zooplankton abundances at locations across the reservoir. In general, gizzard shad abundance varied across the reservoir and from year to year. Overall shad density in 2007, 2008, and 2009 was significantly lower than in previous years (Table 1), and this could have explained the lower densities found in the upper reservoir during those years. Additionally, the far west end of the reservoir remained unsampled during 2007-2009, and data from 2005 and 2006 suggest high densities may occur in these areas of the upper reservoir. Had these locations been sampled, consistently high densities of shad and zooplankton may have been observed in zone three for all 5 years of the study.

Standard error maps were also created to determine the reliability of the kriged surfaces. Two maps were needed because the amount of predictive error was different between shad and zooplankton densities. To maintain consistency in this investigation through changes to the reservoir, the same stations were sampled throughout the duration of the study. Unfortunately, as the water rose and the area of the reservoir increased, approximately one third of the reservoir was not sampled and prediction error increased, especially along the shores and in the west end of the reservoir from 2007-2009 (Figure 2). Two stations were added in 2008 and 2009 to minimize areas that had high error in previous years, however due to the expanding reservoir, the error in these areas remained unchanged.

Calculating Moran's I for the distribution of gizzard shad and zooplankton showed that both were positively autocorrelated in about half of the years (Table 3). The sill and nugget values differed between weeks and between shad and zooplankton models. Nugget values showed that spatial dependence was present at short distances between sampling points, and the sill was much higher in models for zooplankton density than shad density. This is because densities of zooplankton were much higher than shad densities in the reservoir, resulting in a larger sill.

The lack of sampling in the west end of the reservoir could have had implications on the reliability of predictions and estimates of shad abundance. High numbers of shad were found in zone 3 in 2008 (Figure 3), and juvenile shad were very abundant in unsampled locations in the west end of the reservoir in 2009 (Sullivan personal

observation). These observations were consistent with those found by Bremigan and Stein (1999), who found highest production of shad in the upper, shallow ends of reservoirs. The juveniles could have moved to this location from other parts of the reservoir, but they also could have hatched in these areas earlier in the year. If high water levels persist, future studies should investigate the density of shad in the west end of the reservoir to better evaluate productivity.

From this five year study, I found that larval gizzard shad and zooplankton were correlated in about half of the weeks studied. The inconsistencies observed in the density of shad in different zones of the reservoir are likely a result of changing water levels and dispersed shad populations. Further research aimed at learning about shad and zooplankton production in the upper reservoir would help to answer these questions. It is possible that the greatest shad production has shifted to the unsampled areas in the west end of the reservoir, and densities in these areas are as high as those found in the low water years of 2005 and 2006.

I found that gizzard shad and zooplankton distributions in Harlan County Reservoir are predictable at times. As primary forage for other larval and juvenile fish, zooplankton and gizzard shad can be useful for fisheries managers looking to maximize stocking efforts. Knowledge of the distribution and concentration of the forage base (i.e. gizzard shad and zooplankton), could lead to stocking in areas with high forage, thus minimizing the initial mortality of newly stocked fish caused by starvation. Additionally, because shad populations are patchy and fluctuate in their distribution throughout the

reservoir, stocking success could be maximized by stocking sport fish in multiple locations throughout the reservoir.

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Table 1. Mean densities and standard errors for shad size groups (fish/m³), total zooplankton/L, and individual zooplankton groups/L collected at Harlan County Reservoir from 2005-2009. Significantly similar values between years are denoted by the same letter following the standard error.

Organism	2005	2006	2007	2008	2009
Shad 5-30 mm	2.86 ± 0.60 ^a	4.32 ± 0.76 ^a	0.69 ± 0.10 ^b	0.54 ± 0.11 ^c	0.97 ± 0.16 ^b
Shad 5-14 mm	0.27 ± 0.06 ^a	0.36 ± 0.08 ^a	0.06 ± 0.01 ^b	0.44 ± 0.09 ^a	0.29 ± 0.04 ^a
Shad 15-30 mm	2.43 ± 0.55 ^a	3.63 ± 0.72 ^a	0.56 ± 0.08 ^b	0.11 ± 0.03 ^c	0.69 ± 0.15 ^b
Total Zooplankton	69.17 ± 2.51 ^a	120.36 ± 8.49 ^b	47.48 ± 3.02 ^c	35.35 ± 2.35 ^d	44.37 ± 1.71 ^{cd}
Total Copepods	20.98 ± 0.97 ^a	45.91 ± 3.10 ^b	39.63 ± 2.56 ^b	28.35 ± 1.99 ^a	36.55 ± 1.48 ^b
Copepod Nauplii	28.57 ± 1.23 ^a	63.11 ± 5.82 ^b	16.25 ± 0.91 ^c	12.56 ± 1.07 ^d	13.74 ± 0.76 ^{cd}
Calanoid Copepod	14.38 ± 0.68 ^a	37.64 ± 2.78 ^b	13.18 ± 1.33 ^{ac}	10.73 ± 0.91 ^c	19.70 ± 0.79 ^d
Cyclopid Copepod	6.59 ± 0.53 ^a	8.28 ± 1.66 ^a	5.87 ± 0.81 ^a	2.83 ± 0.17 ^b	3.11 ± 0.23 ^b
Total Cladocerans	19.55 ± 1.05 ^a	8.38 ± 0.96 ^b	7.84 ± 0.87 ^b	7.00 ± 0.47 ^b	7.82 ± 0.37 ^b
<i>Daphnia pulex</i>	18.12 ± 1.01 ^a	3.73 ± 0.72 ^b	4.92 ± 0.62 ^c	4.24 ± 0.36 ^c	2.68 ± 0.17 ^{bc}
<i>Daphnia retrocurva</i>	0.64 ± 0.07 ^a	3.77 ± 0.49 ^b	2.69 ± 0.39 ^b	2.76 ± 0.30 ^b	5.14 ± 0.28 ^c

Table 2. Spearman's correlations between shad density by size groups and total zooplankton density, zooplankton groups, or copepod nauplii. Correlations were calculated for data collected during the three weeks surrounding the intense sampling week. Data were analyzed by week between individual shad size groups and individual zooplankton groups. Total Daphnia includes *D. pulicaria* and *D. retrocurva*, and total copepods include the orders *Calanoida* and *Copepoda*. The values reported are the Spearman's correlation test statistics. Significance was determined at $P < 0.10$ (*), $P < 0.05$ (**).

Date	Shad	Total Zooplankton	<i>Daphnia</i> spp.	Total Copepods	Nauplii
6/6/2005	5-30 mm	0.1266	-0.0444	-0.1027	0.3188
	5-14 mm	0.1049	-0.0544	-0.0527	0.0896
	15-30 mm	0.1148	0.0304	-0.1722	0.3643
6/14/2005	5-30 mm	0.0414	-0.1153	0.1467	0.0249
	5-14 mm	0.1349	0.0144	0.1688	0.1296
	15-30 mm	0.0278	-0.1082	0.1186	0.0165
6/21/2005	5-30 mm	0.4640**	-0.2835	0.4205**	0.6362**
	5-14 mm	0.3853	0.0758	0.2892	0.3386
	15-30 mm	0.1332	-0.2891	0.064	0.3909*
6/6/2006	5-30 mm	0.2478	0.2335	0.1557	0.3470*
	5-14 mm	0.0914	0.1317	-0.0052	0.2507
	15-30 mm	0.2965	0.3162	0.2235	0.3600*
6/12/2006	5-30 mm	0.2536*	0.0408	0.1264	0.3012**
	5-14 mm	0.1604	-0.2069	0.1288	0.2813*
	15-30 mm	0.2331	0.0867	0.105	0.2636*
6/19/2006	5-30 mm	0.4609**	0.0555	0.5670**	0.2939
	5-14 mm	-0.4071**	-0.0766	-0.3682*	-0.3877*
	15-30 mm	0.6875**	0.0448	0.7858**	0.5240**
6/4/2007	5-30 mm	-0.0802	-0.2402	-0.0763	-0.2509
	5-14 mm	-0.2909	-0.2609	-0.3408	-0.3980*
	15-30 mm	-0.0198	-0.1983	-0.0096	-0.1876
6/13/2007	5-30 mm	0.1364	0.096	0.1442	-0.1816
	5-14 mm	0.0193	0.0667	-0.0143	-0.1111
	15-30 mm	-0.0287	0.0271	-0.0253	-0.2552*
6/18/2007	5-30 mm	0.3748*	0.3248	0.2109	-0.0926
	5-14 mm	0.0455	0.2701	-0.1019	-0.1674
	15-30 mm	0.4233**	0.3693*	0.2369	0.1517
6/3/2008	5-30 mm	0.7361**	0.5085**	0.6900**	0.7303**
	5-14 mm	0.7619**	0.5313**	0.7165**	0.7465**
	15-30 mm	-0.1455	-0.2739	-0.1251	-0.0353
6/9/2008	5-30 mm	0.2243	-0.0343	0.2896**	0.2689*
	5-14 mm	0.1851	-0.0804	0.2524*	0.2342
	15-30 mm	0.3074**	0.161	0.3519**	0.3161**
6/18/2008	5-30 mm	-0.2675	-0.5176**	-0.229	-0.1903
	5-14 mm	-0.2409	-0.4491**	-0.2072	-0.1836
	15-30 mm	-0.2676	-0.5370**	-0.2184	-0.128
6/3/2009	5-30 mm	0.5640**	0.5093**	0.5486**	0.6044**
	5-14 mm	0.5464**	0.4991**	0.5430**	0.5924**
	15-30 mm	0.2907	0.276	0.2406	0.2042
6/8/2009	5-30 mm	-0.01368	0.0384	-0.0202	-0.043
	5-14 mm	-0.0182	0.033	-0.0328	-0.0514
	15-30 mm	-0.0303	0.0098	-0.0275	-0.0595
6/16/2009	5-30 mm	0.5731**	0.2981	0.5738**	0.6487**
	5-14 mm	0.6464**	0.4286**	0.6347**	0.7531**
	15-30 mm	0.4675**	0.2157	0.4716**	0.5363**

Table 3. Spatial autocorrelation of shad size groups, total zooplankton, copepod, and nauplii densities measured during the intense sampling week at Harlan County Reservoir from 2005-2009. The Z score is a calculated value used to determine statistical significance. Significance values from 0.05-0.01 indicate a clustered distribution for the given parameter, while not-significant (ns) indicates spatial randomness.

Year	Group	Moran's I	Z Score	Significance
2005	Shad 0-30 mm	0.03	1.9	ns
	Shad 5-14 mm	-0.01	0.6	ns
	Shad 15-30 mm	0	0.8	ns
	Total Zooplankton	0.04	2.3	0.05
	Copepods	0.04	2.1	0.05
	Nauplii	0.03	1.8	ns
2006	Shad 0-30 mm	0.02	1.6	ns
	Shad 5-14 mm	0.12	5.2	0.01
	Shad 15-30 mm	0.06	2.9	0.05
	Total Zooplankton	0.01	1.2	ns
	Copepods	-0.02	0.1	ns
	Nauplii	0.03	1.8	ns
2007	Shad 0-30 mm	0.04	2.3	ns
	Shad 5-14 mm	0.02	1.5	ns
	Shad 15-30 mm	0.02	1.6	ns
	Total Zooplankton	0.02	1.6	ns
	Copepods	0.01	1.3	ns
	Nauplii	0.02	1.6	ns
2008	Shad 0-30 mm	0.03	1.9	ns
	Shad 5-14 mm	0.03	2.2	0.05
	Shad 15-30 mm	0.04	2.1	0.05
	Total Zooplankton	0.07	3.3	0.5
	Copepods	0.05	2.9	0.05
	Nauplii	0.06	3.0	0.05
2009	Shad 0-30 mm	0.09	4.4	0.01
	Shad 5-14 mm	0.04	2.4	0.05
	Shad 15-30 mm	0.1	4.6	0.01
	Total Zooplankton	0.14	5.8	0.01
	Copepods	0.1	4.2	0.01
	Nauplii	0.06	3.0	0.05

Table 4. Variogram parameters from the weeks for which kriged surfaces were produced.

Date	Species	# Lags	Lag Size	Range (m)	Sill	Nugget
6/9/2008	15-30 mm Shad	10	157	3155	0.1	0.5
6/9/2008	Total Zoo	10	157	3155	364.5	0.3
6/8/2009	5-30 mm Shad	10	157	3155	0.7	0.1
6/8/2009	Total Zoo	10	157	3155	163.2	0.2

Figure Captions

Figure 1. Map showing borders, zone divisions, and sampling stations at Harlan County Reservoir. The dashed and solid lines represent the reservoir border in 2005-2006, and 2007-2009, respectively. Circles represent the standard 24 stations, and stars represent the additional 24 stations sampled during the intense week.

Figure 2. Standard prediction error maps for 5-30 mm gizzard shad and total zooplankton densities at Harlan County reservoir in 2008.

Figure 3. Ordinary prediction maps for gizzard shad 15-30 mm in length and total zooplankton densities on June 9, 2008.

Figure 4. Ordinary prediction map for gizzard shad 5-30 mm in length and total zooplankton on June 8, 2009.

Figure 1.

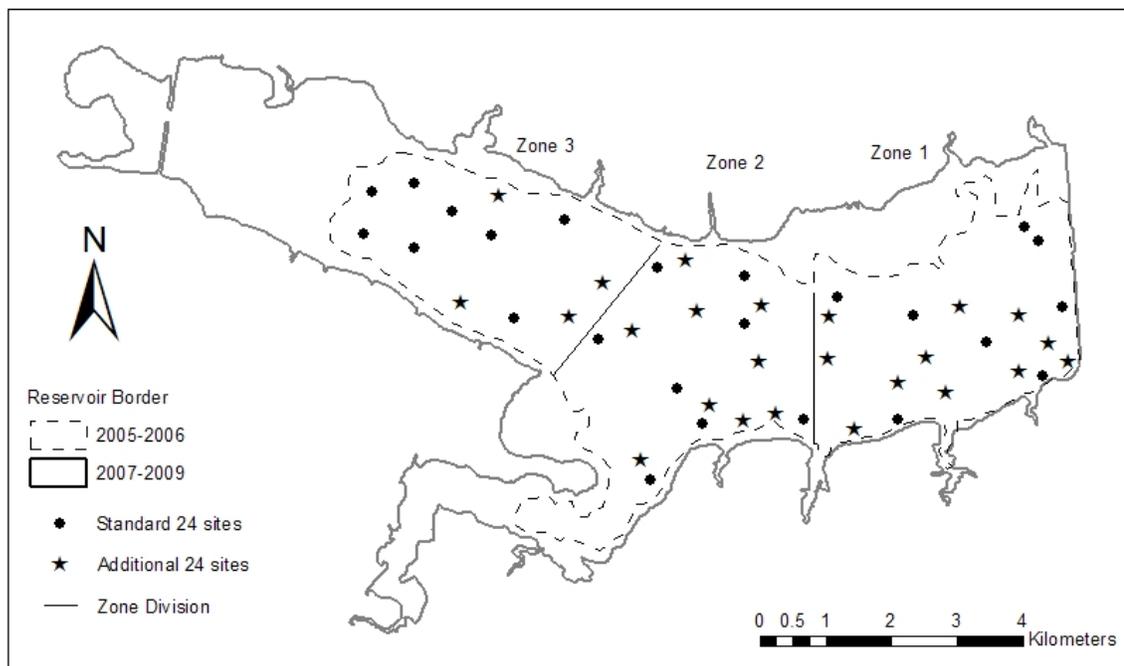


Figure 2.

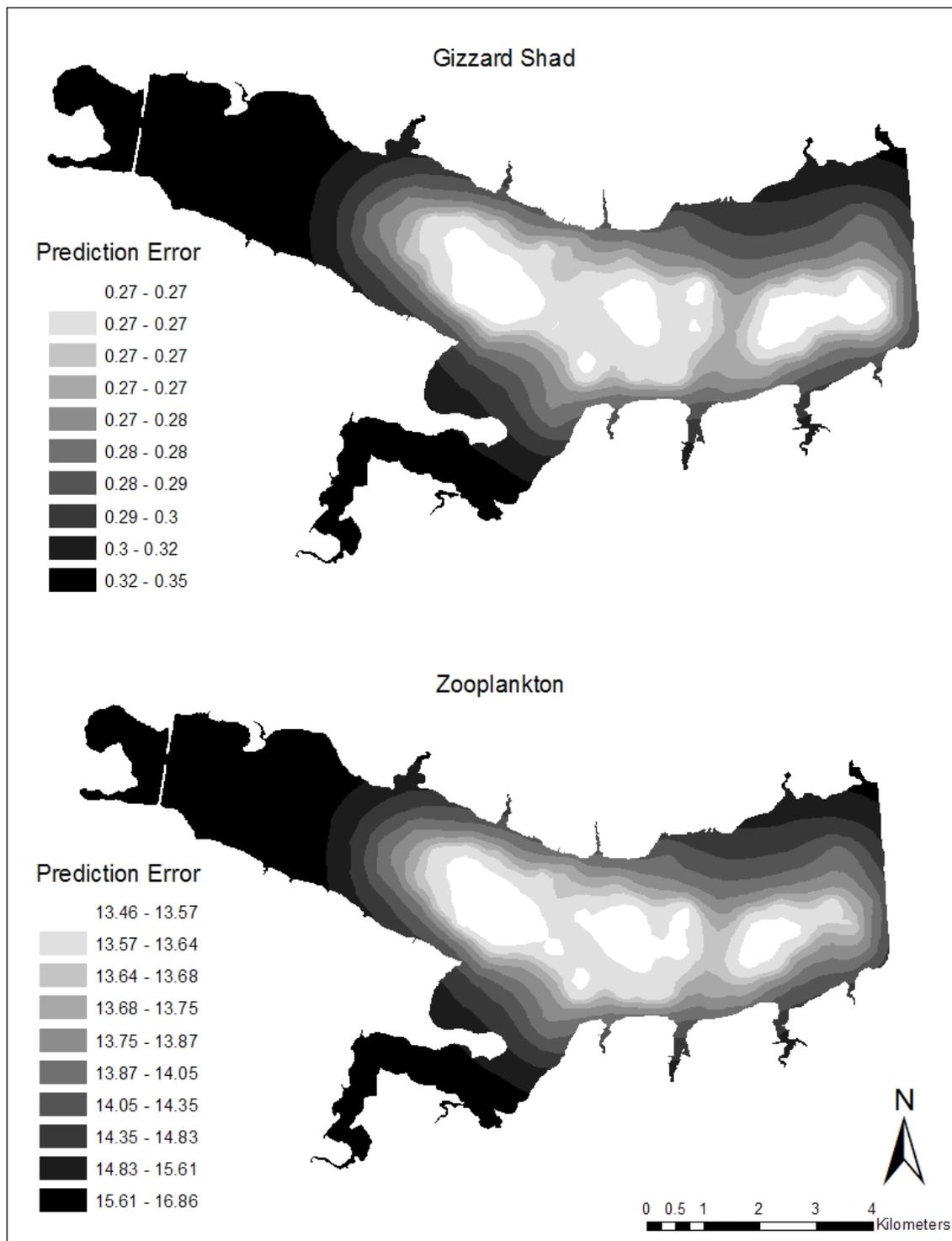


Figure 3.

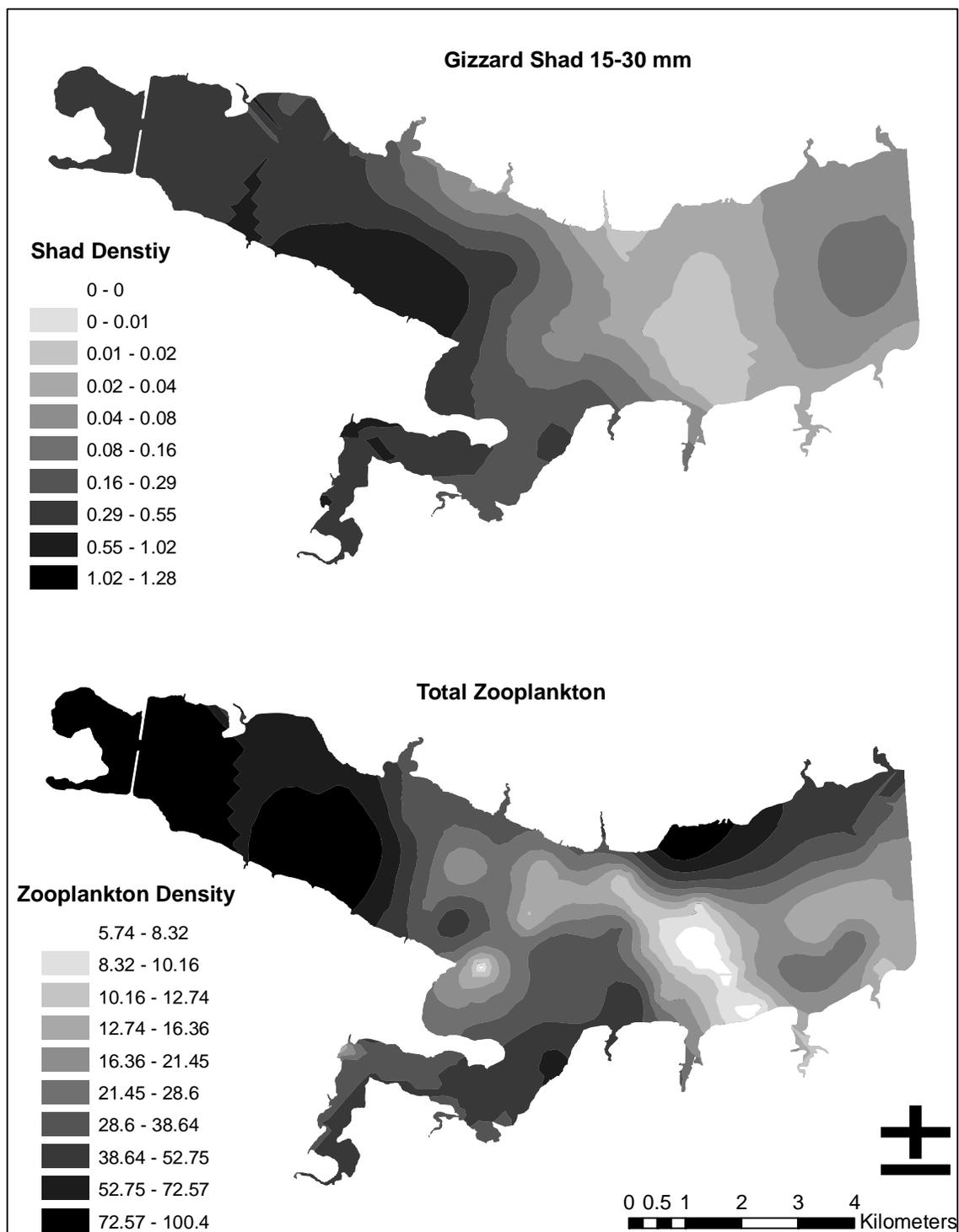
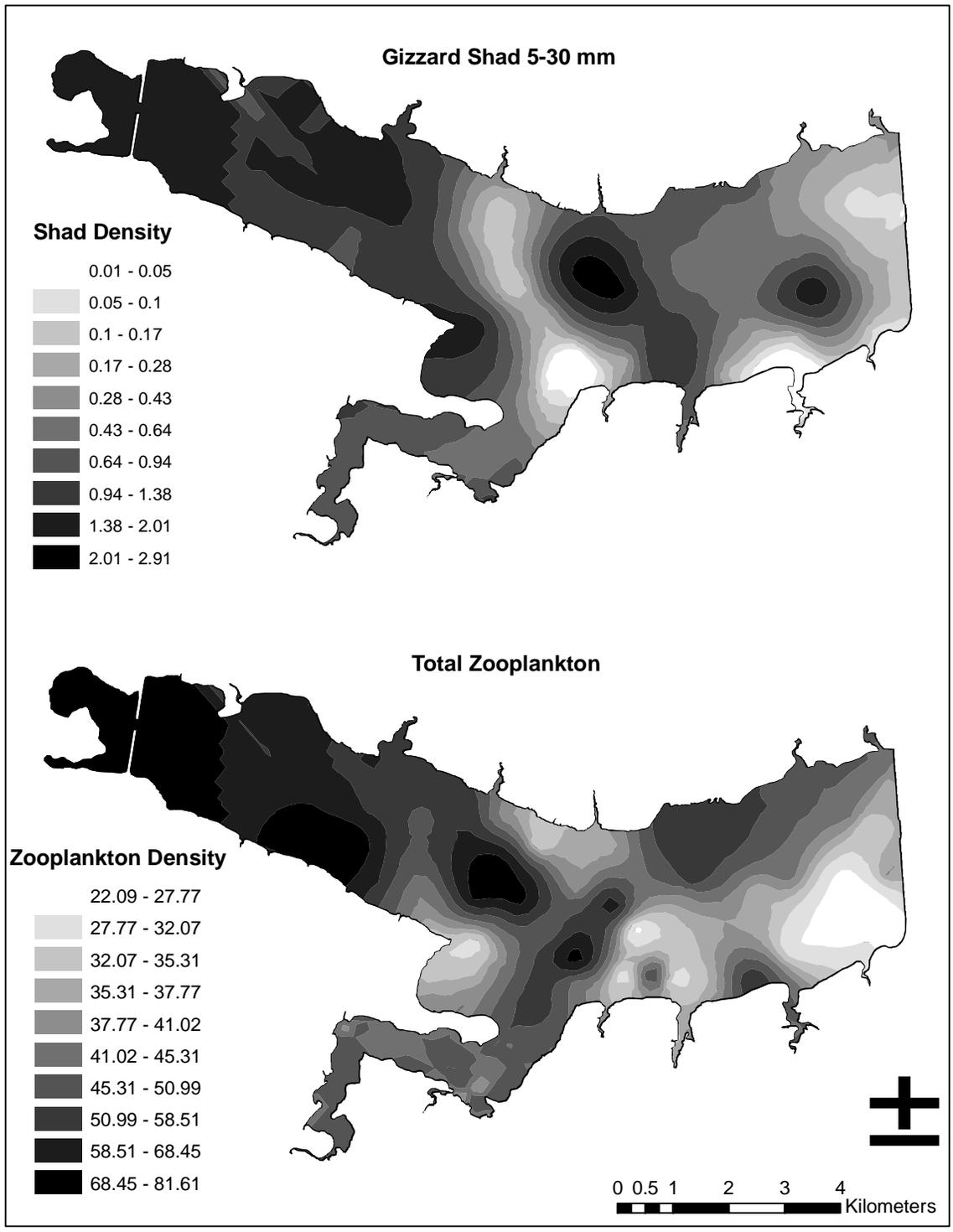


Figure 4.



Chapter 3. Diet Patterns of Age-0 Gizzard Shad in a Nebraska Irrigation Reservoir

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Abstract

Gizzard shad, *Dorosoma cepedianum*, are prolific spawners that can influence forage communities in reservoirs. The impact gizzard shad have on a community can be variable and it is essential to determine their diet to better understand their level of influence. This study examined weekly diet patterns and electivity of age-0 gizzard shad in Harlan County Reservoir between June and October in 2008 and 2009. Stomachs from 638 age-0 gizzard shad yielded a total of 7,338 zooplankton. Stomach contents were compared to zooplankton in the reservoir to calculate electivity. Spearman's correlations determined that gizzard shad < 30 mm demonstrated a significant positive correlation between total length and the number of zooplankton consumed in 2008 (0.3293;p<0.0001;n=224) and 2009 (0.8390;p<0.0001;nm=225). The number of zooplankton consumed was also positively correlated to the size of zooplankton consumed in 2008 (0.2530;p<0.0001;n=224) and 2009 (0.6346;p<0.0001;n=225). As in other studies, gizzard shad > 30 mm reduced their consumption of zooplankton. Small shad (5-14 mm) had a positive Strauss's electivity score for cyclopoid copepods in 2008 (0.33±0.05) and nauplii (0.51±0.06) in 2009, and selected against calanoid copepods in both 2008 (-0.26±0.06) and 2009 (-0.35±0.05). Medium shad (15-30 mm) showed positive electivity for cyclopoid copepods in 2008 (0.17±0.06) and 2009 (0.15±0.08), and positive selection for *Daphnia* spp. in 2008 (0.15±0.03). These results show that gizzard shad consume zooplankton as larvae and can assist managers in determining the level of impact gizzard shad can have on Harlan County Reservoir in the future.

Introduction

Aquatic systems offer less habitat heterogeneity than terrestrial ecosystems, (Chase 2000) which make predation and competition more influential on community structure (Kerfoot and Sih 1987). Diehl (1992) recognized several factors that impact community structure including predation, competition, and habitat complexity. In particular, impacts of piscivorous activity can cascade through multiple trophic levels including zooplankton (Dettmers and Stein 1992), macroinvertebrate (Williams et al. 2003), amphibian (Petranka 1983), fish communities (MacRae and Jackson 2001), and between fish species (Garvey and Stein 1994; Welker et al. 1994).

Gizzard shad, *Dorosoma cepedianum*, are a species which can impact other fish through both competition and by serving as prey (Garvey and Stein 1994; Dettmers and Stein 1992). Gizzard shad are abundant in many systems because of their high fecundity (Michaletz 1998), and young of the year gizzard shad often comprise the majority of predatory sportfish species' diets in Midwest reservoirs (Olsen et al. 2007). Gizzard shad can grow too large within their first year to be consumed by most predators (Buynak et al. 1992) and may compete for zooplankton at smaller sizes (Garvey and Stein 1994). Thus, the stocking of gizzard shad to improve sport fisheries has had unexpected negative consequences in many systems (DeVries and Stein 1990).

As omnivorous larvae, gizzard shad can feed on zooplankton, algae, and detritus (Yako et al. 1996), and have been shown to significantly reduce zooplankton populations in some systems (Dettmers and Stein 1992). Zooplankton are consumed most

frequently by gizzard shad larvae less than 30 mm in total length (Cramer and Marzolf 1970), but larger gizzard shad have also been shown to feed on zooplankton when prey are abundant (Schaus et al. 2002). Aday and colleagues (2003) showed bluegill growth and survival decreased in the presence of gizzard shad, and Miranda and Gu (1998) showed that young gizzard shad can reduce growth, survival, and abundance of other larval fish. Unlike many other fish species that also feed on zooplankton as larvae, gizzard shad have the ability to utilize algae and detritus as a food source, providing an alternative energy source when zooplankton resources become scarce (Stein et al. 1995).

The severity of impacts by gizzard shad on zooplankton and other fish is often associated with the density of these organisms (DeVries and Stein 1992). Predation on zooplankton increases with prey density, and the tendency of large individuals to switch to feeding on detritus was suppressed when zooplankton densities were high (Yako et al. 1996). The detrimental effects of gizzard shad on zooplankton populations also varies with fish density, and Dettmers and Stein (1996) found that fish densities of at least 12 shad/m³ were required to eliminate zooplankton in enclosure experiments.

Gizzard shad abundance in Harlan County Reservoir, Nebraska has increased dramatically in recent years. Originally stocked as a forage species for sport fish in the reservoir, the Nebraska Game and Parks Commission (NGPC) reported a 653% increase in gizzard shad abundance during 1991 to 2001 compared with surveys from 1980-1991 (Olds 2007). Determination of the food habits of age-0 gizzard shad within Harlan was

necessary to determine their effects on zooplankton and other species in Harlan County Reservoir, a mesotrophic/eutrophic irrigation reservoir in south-central Nebraska. I hypothesize that larval gizzard shad will consume more and larger zooplankton as they grow, and will show preference for certain zooplankton groups.

Materials and Methods

Study Site

Harlan County Reservoir is an irrigation impoundment located on the Republican River in south-central Nebraska. Its watershed extends into eastern Colorado, northern Kansas and southern Nebraska. The reservoir is the second largest in the state, covering over 9,000 hectares at full pool. As a recreational destination, the reservoir attracts, fisherman, boaters, campers, hikers, hunters, and birdwatchers. The reservoir provides an economic boost to the area, and is a popular fishery (USACE 2006).

Sampling Methods

To study the food habits of larval gizzard shad, Harlan County Reservoir was divided into three zones, and one station for fish collection was selected within each zone (Figure 1). The stations remained the same for both years of the study.

Age-0 gizzard shad were captured weekly from their first emergence in the reservoir through the end of September in 2008 and 2009. Sampling was conducted during the day because Dettmers and Stein (1992) showed that larval gizzard shad do not feed at night. Initially, larval fish were captured using push nets deployed near the bow of the boat. When gizzard shad reached a large enough size that they could not be

collected by the push nets, fish were collected using a 3.2 m diameter cast net with 0.95 cm bar-mesh or electrofishing gear. Fish of all sizes were immediately placed in zip-loc bags and frozen to await processing. Abundance of juvenile fish was low in 2008 resulting in some weeks where fish were only caught at one station within the reservoir.

In the laboratory, shad were divided into three total length size classes: 5-14 mm, 15-30 mm, and > 30 mm. These size classes were chosen because 14-15 mm is the length when gizzard shad have been shown to start feeding heavily on zooplankton (Bremigan and Stein 1997), and 30 mm is when shad have been shown to switch to a diet of detritus (Yako et al. 1996). To process larval shad 5-30 mm in length, 15 fish from each size class were thawed, measured for total length (TL), and the entire gut from the gill rakers to the anus was separated from the body. Contents of the gut tube were extracted and placed onto a microscope slide where individual zooplankton were identified to the lowest possible taxon, measured, and enumerated. For gizzard shad greater than 30 mm in length, only contents from the foregut were examined because differential rates of prey digestion can occur further down the digestive tract (Sutela and Huusko 2000).

In conjunction with shad sampling, a zooplankton sample was collected at each of the three stations to determine the available prey base. For the zooplankton samples, a 0.5 m diameter Wisconsin plankton net with 80 μ m mesh was deployed vertically to within 0.5 m of the substrate and was slowly towed to the surface. Contents of the tow were poured into collection bottles and preserved in a 4% buffered

formalin solution. When gizzard shad were collected at all three stations, zooplankton samples were analyzed individually, but later in the summer when shad were only caught at one station, only zooplankton from the corresponding location were considered for analysis.

In the laboratory, samples were processed and densities were calculated for different groups and species. *Daphnia pulicaria* and *D. retrocurva* were combined into the group “Daphnia”, and “nauplii” included all copepod naupliar stages. Densities of calanoid and cyclopoid copepods and *Bosmina* spp. were determined individually.

Statistical Analysis

A Kruskal-Wallis, non-parametric test ($P < 0.05$) was used to assess differences in the number and size of zooplankton consumed by different shad size groups within years and were followed by a Dunn’s post-hoc test.

Spearman’s correlations were calculated between gizzard shad length and the number and size of prey consumed within years using InStat software (2008). In addition, a Kruskal-Wallis non-parametric test was used to detect differences in the number and size of zooplankton consumed between groups in each year, and a Dunn’s post-hoc test was used to separate groups.

Prey electivity by gizzard shad was evaluated using the index developed by Strauss (1979):

$$L = r_i - p_i$$

where r_i and p_i represented the relative abundance of prey in the diet and environment, respectively. The relative abundance of prey in the diet of shad (r_i) was determined by dividing the number of each zooplankton species or group found in the stomachs of all shad processed from a site by the total number of zooplankton consumed by the group at the same site. Zooplankton proportions (p_i) were calculated by dividing the density of each zooplankton species or group by the total density of all zooplankton at each site. The index value (L) could range from -1 (total negative selectivity) to 1 (perfect positive selectivity) for a given prey species. A value of ± 0.15 was selected as the cutoff to determine selectivity or avoidance because others have used similar representative values in electivity studies (Dettmers and Stein 1992). An index value from 0.15 to -0.15 represented prey that were consumed in equal proportion to availability in the environment. Prey electivity was determined for each size class and zooplankton group each week, and averaged for each size class each year. Prey electivity by shad > 30 mm was not included in the analysis because of the low number of zooplankton consumed by this group.

Results

The diets from 298 and 340 gizzard shad were examined in 2008 and 2009, respectively. From the stomachs of these fish, 3,957 and 3,381 zooplankton were extracted, identified, and measured, respectively. The mean number of zooplankton consumed by each size class differed among all groups in both years (Table 1). Medium 15-30 mm shad consumed the most zooplankton per fish in both years, with an average

of 17.33 and 16.81 zooplankton per fish, respectively. The size of zooplankton consumed by each size class also differed among groups in both years (Table 1). The 5-14 mm gizzard shad consumed the smallest prey while shad greater than 30 mm consumed the largest prey (Table 1). Additionally, there were 21 shad in the 5-14 mm size class that had empty guts, while no shad 15-30 mm in length had empty guts. The number of zooplankton consumed by 5-30 mm gizzard shad was positively correlated with shad length in both years ($P < 0.0001$) and prey size was also positively correlated with shad length for 5-30 mm fish in both years ($P < 0.0001$) (Table 2.)

In 2008, the most abundant prey items found in the stomachs of 0-14 mm gizzard shad were copepod nauplii (48%) and immature cyclopoid copepods (41%), and 15-30 mm gizzard shad consumed the largest numbers of copepod nauplii (60%) (Figure 2). The zooplankton consumed by gizzard shad greater than 30 mm consisted of calanoid and cyclopoid copepods and were found in equal proportions in the stomachs (Figure 3).

In 2009, copepod nauplii and immature cyclopoid copepods were the most abundant zooplankton consumed by 0-14 mm gizzard shad and comprised 62% and 29% of the total number of prey, respectively. Similar feeding occurred in 15-30 mm gizzard shad which also fed most frequently on copepod nauplii and immature copepods. Gizzard shad greater than 30 mm fed on several zooplankton species, but consumed the highest number of calanoid copepods (Figure 2).

In 2008, 0-14 mm gizzard shad showed a positive preference for cyclopoid copepods, and selected against calanoid copepods. Copepod nauplii, *Daphnia* spp., and *Bosmina* spp. were consumed in amounts which were proportional to those found in the environment. Larger, 15-30 mm gizzard shad showed neutral selection for copepod nauplii, calanoid copepods and *Bosmina* spp., but showed positive selection for cyclopoid copepods and *Daphnia* spp. (Figure 3).

In 2009, 0-14 mm shad positively selected for copepod nauplii, avoided calanoid copepods and *Daphnia* spp., and showed neutral selection for cyclopoid copepods and *Bosmina* spp. Gizzard shad 15-30 mm in length did not show any preference for specific zooplankton and fed on all groups in proportions near those found in the environment (Figure 4).

Discussion

Age-0 gizzard shad in Harlan County Reservoir showed similar feeding patterns in 2008 and 2009. In both years, shad length was positively correlated with both the size and number of prey consumed for fish less than 30 mm (Table 2), and these results support the findings of other studies that found prey size increased with shad length (Cramer and Marzolf 1970; Schael et al. 1991). Shad less than 15 mm in length consumed small zooplankton including immature copepods and copepod nauplii, while larger individuals consumed more *Daphnia* spp. and adult copepods (Figure 2). As shad reached lengths greater than 30 mm, they consumed less zooplankton than shad 15-30 mm (Table 1) and their guts were primarily packed with algae and detritus.

About 9% of the shad in the 5-14 mm size group that were sampled in 2008-2009 did not have any zooplankton in their guts. This either suggests that they were sampled during a period of the day when they were not feeding, or they consumed other food sources such as algae and detritus. Larval shad have been shown to feed at different rates depending on the time of day and water temperature (Salvatore et al. 1987), and this could explain the occurrence of gizzard shad with empty guts. Another possibility is that the smallest gizzard shad had not started feeding on zooplankton. Bremigan and Stein (1997) found that gizzard shad in some Ohio reservoirs did not start feeding until they reached 15 mm.

Larval fish are gape-limited predators (Bremigan and Stein 1994), and it is not surprising that larval gizzard shad fed on larger individuals as they grew. Gizzard shad gape width increases with length (Bremigan and Stein 1994) which allows these fish to consume larger individuals as they grow. Gape limits likely explain the large number of nauplii and immature copepods consumed by 0-14 mm shad which have small gapes (Figure 2), and the lack of consumption of larger zooplankton such as *Daphnia* spp. and calanoid copepods (Figures 3 and 4).

As gizzard shad reached 15-30 mm, they consumed more and larger zooplankton (Table 1), but prey selection was not always positive for large-bodied zooplankton such as *Daphnia* spp. and mature copepods (Figures 3 and 4). A probable explanation is that although a large-bodied species may be abundant, shad need to eat less of them

compared to small zooplankton because of the larger energy gains obtained from consuming larger individuals.

Studies have shown that shad switch to a diet of detritus after reaching a length of 30 mm (Cramer and Marzolf 1970; Drenner et al. 1982), and because a significant drop in the number of zooplankton consumed by fish greater than 30 mm occurred (Table 1), they were not included in correlation tests. If included, correlations between zooplankton consumption and fish length may not have been detected because of the dramatic dietary shifts of this group. Shad which were larger than 30 mm consumed few zooplankton (Table 1) and likely obtained most of their energy from algae and detritus which filled the majority of their guts. It was difficult to quantify the percentages of each component due to differential digestion rates of individual food items, and the prolonged evacuation rates which occur in larger individuals.

Heinrichs (1982) described the physical changes which occur during gizzard shad development, and her results help explain the changes in the food habits of these fish. Gizzard shad develop a muscular gizzard when they are between 30 and 35 mm in length which aides in the digestion of algae and detritus, and their mouth moves to a sub-terminal position to aid in bottom feeding (Heinrichs 1982). They also switch to pump-filter feeding instead of sight feeding (Drenner et al. 1982). These physical and behavioral changes help explain the low zooplankton consumption by larger shad and support the findings of others who have also observed a change in the diet of shad at this length (DeVries and Stein 1992; Yako et al. 1996).

Gizzard shad have been shown to have detrimental effects on zooplankton populations in many reservoirs (DeVries and Stein 1992; Schaus and Vanni 2000). The degree to which these effects take place are often driven by larval shad density. Dettmers and Stein (1992) found high densities (38 fish/m³) had detrimental effects while low densities (4-6 fish/m³) had little to no effect on zooplankton populations. The average densities of larval gizzard shad in Harlan Reservoir during 2008 and 2009 were 0.54 and 0.97 shad/m³ (Table 4). Although not directly quantified, it did not appear that gizzard shad populations in Harlan Reservoir during 2008 and 2009 had detrimental effects on existing zooplankton communities.

The results from this study show that larval gizzard shad consume primarily zooplankton until they reach the juvenile stage (> 30 mm). Gizzard shad greater than 30 mm TL reduce their dependence on zooplankton in Harlan County Reservoir and what few zooplankton are consumed are much larger. The gizzard shad population densities observed in Harlan Reservoir during 2008-2009 did not appear great enough to impact zooplankton communities, but further studies would need to be conducted to adequately assess this impact. This is useful information for those considering the impacts of gizzard shad on sport fish because several studies have suggested gizzard shad can reduce the survival of other fish through competition. When low densities of shad are maintained, they can act as a prey base for other fish without eliminating their forage during the larval stage.

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Table 1. Descriptive statistics from all gizzard shad diets sampled at Harlan Reservoir from 2008-2009. The “# Shad” is the total number of fish sampled from each size class each year, and “# Zoo” is the number of zooplankton consumed by each size group. Values presented are means \pm standard errors. All values for “# Zoo/Fish” and “Zoo Size” are statistically different within years.

Year	Shad Size Class (mm)	# Shad	Shad Length (mm)	# Zoo	# Zoo / Fish	Zoo Size (mm)
2008	5-14	106	13.04 \pm 0.11	1531	11.43 \pm 0.94	0.32 \pm 0.01
	15-30	120	18.88 \pm 0.16	2074	17.33 \pm 1.35	0.47 \pm 0.02
	> 30	72	98.26 \pm 1.40	352	4.89 \pm 0.32	1.01 \pm 0.01
2009	5-14	90	11.5 \pm 0.20	220	1.76 \pm 0.16	0.25 \pm 0.01
	15-30	134	17.87 \pm 0.17	2464	16.81 \pm 2.07	0.38 \pm 0.01
	> 30	116	86.76 \pm 2.41	697	6.69 \pm 0.63	0.92 \pm 0.02

Table 2. Spearman's correlations between gizzard shad length and the mean number and size of zooplankton consumed per fish. N = 224 fish in 2008 and N = 225 fish in 2009. Values with an (*) are significant at $p < 0.0001$.

	Number of Zooplankton Consumed	Mean Zooplankton Size
2008 Gizzard Shad Length	0.3293*	0.2530*
2009 Gizzard Shad Length	0.8390*	0.6346*

Table 3. Strauss' (1979) electivity values from 0-30 mm gizzard shad collected at Harlan Reservoir from 2008-2009. "Cyclopoid" and "Calanoid" include all copepods from the orders Cyclopoida and Calanoida, respectively. "Daphnia" includes all immature and mature stages of *Daphnia* spp. Positive and negative values greater than ± 0.15 indicate positive or negative selectivity. "Composite" stations are those where fish from multiple locations were combined to reach the 15 fish sample size minimum.

Date	Zone	Shad Size (mm)	Nauplii	Cyclopoid	Calanoid	Daphnia	Bosmina
6/9/2008	2	5-14	0.16	0.31	-0.04	-0.09	0.00
6/9/2008	3	5-14	0.17	0.33	-0.30	-0.18	-0.03
6/19/2008	2	5-14	0.10	0.30	-0.20	-0.09	-0.10
6/19/2008	3	5-14	-0.01	0.40	-0.20	-0.13	-0.07
6/24/2008	Composite	5-14	0.14	0.14	-0.07	-0.10	-0.10
3/30/2008	1	5-14	0.03	0.27	-0.27	0.04	-0.07
6/30/2008	3	5-14	-0.05	0.54	-0.38	-0.04	-0.07
6/19/2008	2	15-30	-0.33	0.17	-0.03	0.29	-0.10
6/19/2008	3	15-30	-0.33	0.19	-0.02	0.21	-0.06
6/24/2008	1	15-30	-0.46	0.55	0.05	0.47	-0.08
6/24/2008	2	15-30	-0.39	0.07	0.06	0.36	-0.09
6/24/2008	3	15-30	-0.37	0.19	0.01	0.31	-0.15
6/30/2008	1	15-30	0.58	0.04	-0.37	-0.18	-0.07
6/30/2008	2	15-30	0.32	0.03	-0.18	-0.11	-0.06
6/30/2008	3	15-30	0.50	0.12	-0.37	-0.18	-0.07
6/3/2009	1	5-14	0.58	0.10	-0.50	-0.14	-0.04
6/3/2009	2	5-14	0.57	-0.03	-0.37	-0.15	-0.03
6/3/2009	3	5-14	0.70	-0.11	-0.46	-0.12	-0.01
6/10/2009	1	5-14	0.29	0.23	-0.29	-0.18	-0.04
6/10/2009	2	5-14	0.49	-0.07	-0.15	-0.25	-0.03
6/10/2009	3	5-14	0.43	0.16	-0.34	-0.23	-0.02
6/3/2009	2	15-30	-0.08	0.50	-0.27	-0.13	-0.03
6/10/2009	2	15-30	-0.09	0.06	0.32	-0.25	-0.03
6/10/2009	3	15-30	0.04	0.19	0.03	-0.23	-0.02
6/16/2009	1	15-30	0.27	0.06	-0.16	-0.11	-0.06
6/16/2009	2	15-30	0.08	0.14	-0.11	-0.10	-0.02
6/16/2009	3	15-30	0.43	-0.02	-0.19	-0.19	-0.03
6/22/2009	1	15-30	-0.09	0.54	-0.38	-0.05	-0.01
6/22/2009	3	15-30	0.16	0.26	-0.40	0.00	0.00
7/1/2009	1	15-30	0.01	-0.04	0.07	-0.04	-0.01
7/1/2009	2	15-30	0.14	-0.23	0.06	0.05	-0.03

Table 4. Gizzard shad and zooplankton densities measured over 8 weeks from Harlan County Reservoir in 2008 and 2009. Values presented are means \pm standard errors. Superscript letters denote statistically different values between years. Values without letters were statistically similar.

Organism	2008	2009
Shad 5-30 mm	0.54 \pm 0.11 ^a	0.97 \pm 0.16 ^b
Shad 5-14 mm	0.44 \pm 0.09	0.29 \pm 0.04
Shad 15-30 mm	0.11 \pm 0.03 ^a	0.69 \pm 0.15 ^b
Total Zooplankton	35.35 \pm 2.35	44.37 \pm 1.71
Total Copepods	28.35 \pm 1.99 ^a	36.55 \pm 1.48 ^b
Copepod Nauplii	12.56 \pm 1.07	13.74 \pm 0.76
Calanoid Copepod	10.73 \pm 0.91	19.70 \pm 0.79
Cyclopoid Copepod	2.83 \pm 0.17	3.11 \pm 0.23
Total Cladocerans	7.00 \pm 0.47	7.82 \pm 0.37
<i>Daphnia pulicaria</i>	4.24 \pm 0.36	2.68 \pm 0.17
<i>Daphnia retrocurva</i>	2.76 \pm 0.30 ^a	5.14 \pm 0.28 ^b

Figure Captions

Figure 1. Map of Harlan County Reservoir showing the three stations sampled for gizzard shad diet.

Figure 2. Gizzard shad diet composition expressed as each group's percentage of the total number of zooplankton consumed.

Figure 3. Strauss electivity index values from fish collected during 2008 at Harlan County Reservoir. Positive and negative values greater or less than ± 0.15 (horizontal dashed lines) indicate positive and negative selectivity.

Figure 4. Strauss electivity index values from gizzard shad collected during 2009 at Harlan County Reservoir. Positive and negative values greater or less than ± 0.15 (horizontal dashed lines) indicate positive and negative selectivity.

Figure 1.

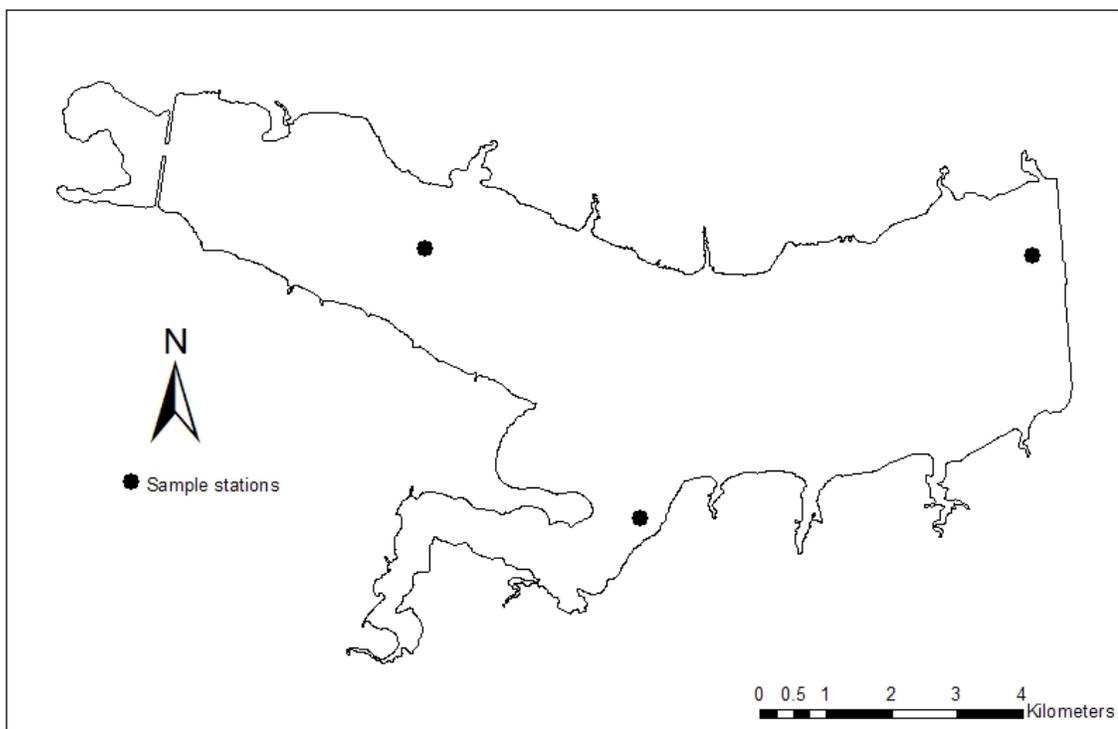


Figure 2.

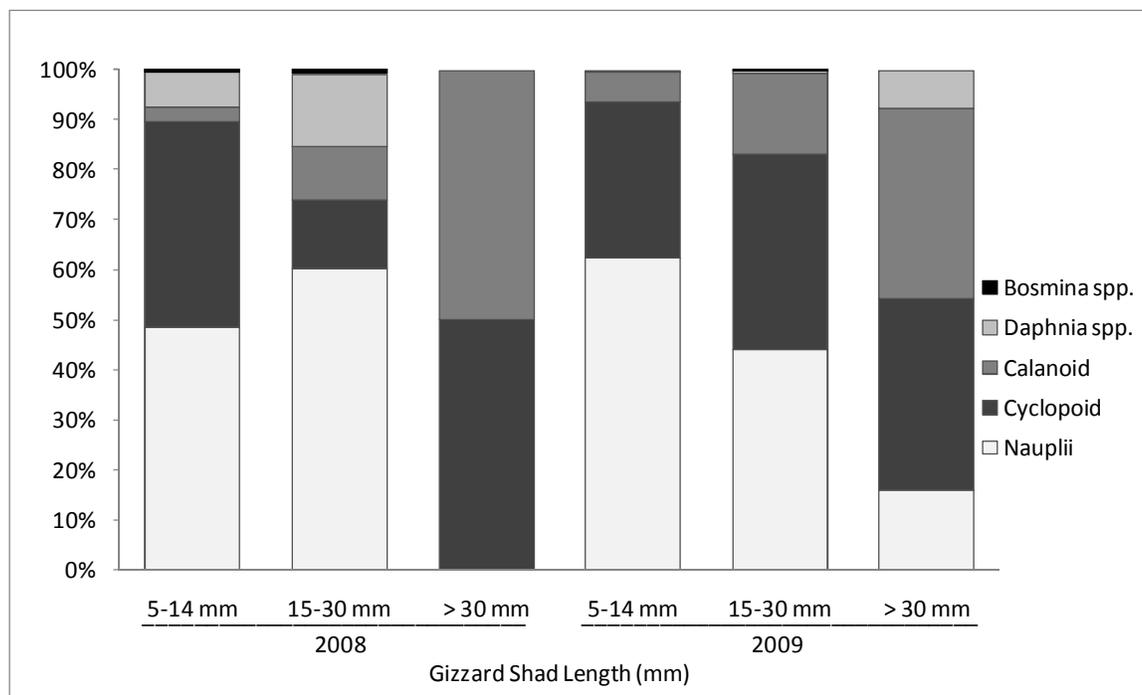


Figure 3.

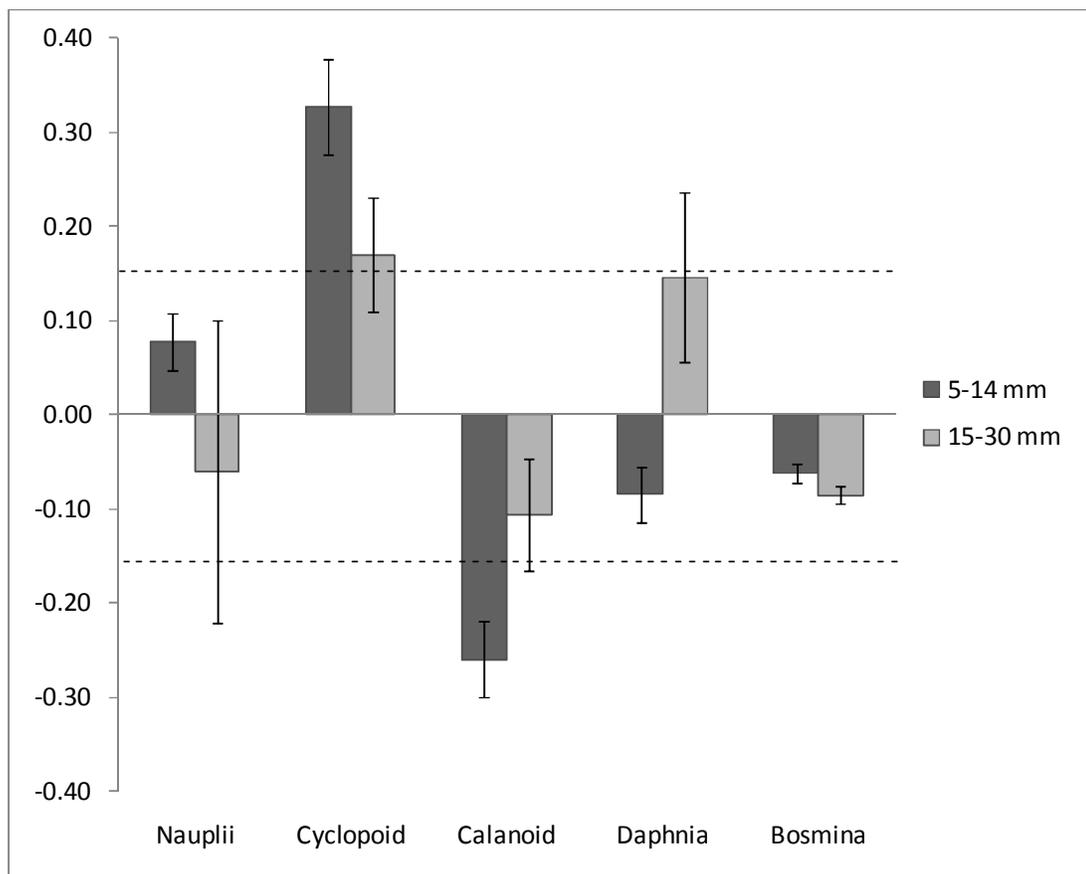
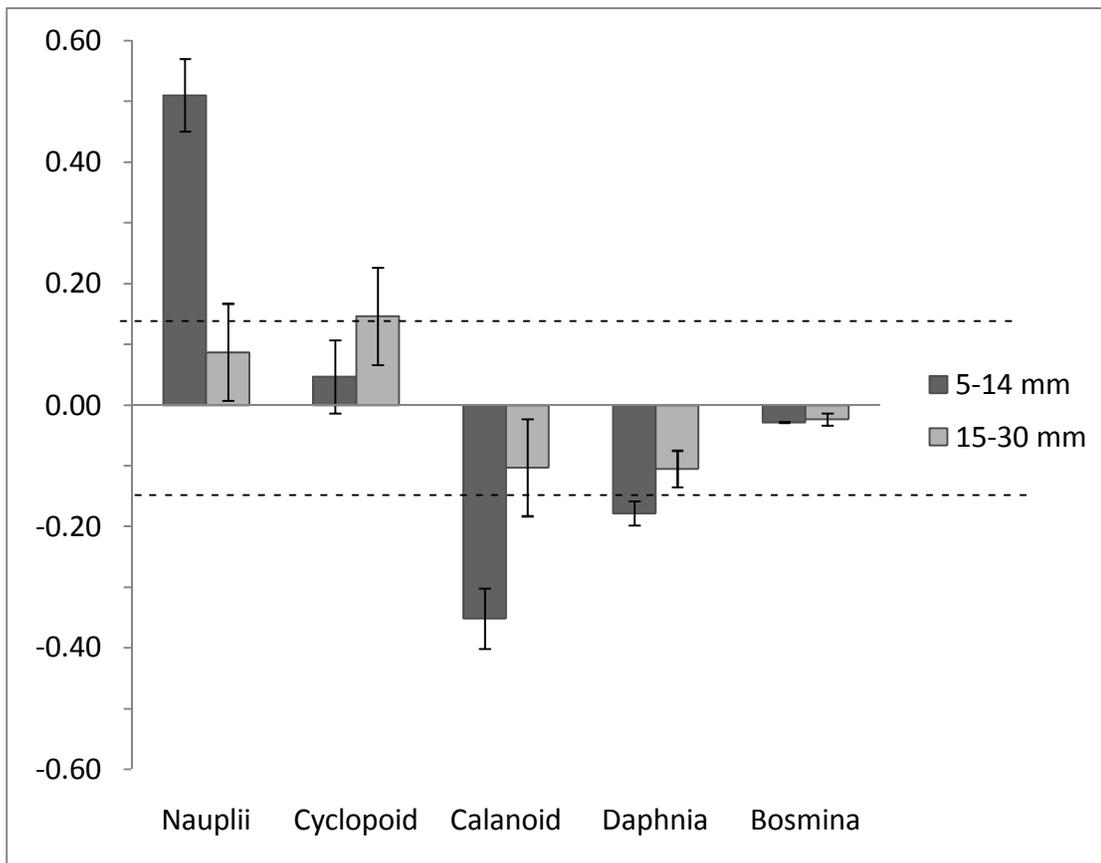


Figure 4.



Chapter 4. Food Habits and Abundance of the Freshwater Drum in a South-Central Irrigation Reservoir

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Abstract

Larval fish are often found in high densities during certain times of the year and their presence can have impacts on other members of the aquatic community. Larval gizzard shad have been shown to reduce zooplankton populations through predation, thus reducing zooplankton numbers drastically in some systems. Larval freshwater drum are abundant in Harlan County Reservoir and have also been shown to feed on zooplankton. To investigate the freshwater drum's potential impacts on zooplankton in Harlan County Reservoir, I collected larval freshwater drum and analyzed the diets of several size groups during 2008 and 2009. I found larval freshwater drum feed almost exclusively on zooplankton as larvae and consume a variety of zooplankton species. The number and size of zooplankton consumed by larval freshwater drum increased with fish length. Additionally, my results suggest that cladocerans become an important food item for freshwater drum larger than 10 mm. Small freshwater drum less than 10 mm in total length showed a high, positive selectivity for *Bosmina* spp. which is a rare zooplankton species in the system, and all larval freshwater drum showed a high negative selectivity for copepod nauplii, a small zooplankton which is abundant in the reservoir. Based on the identified food habits described in this study, larval freshwater drum in Harlan County Reservoir have the potential to impact zooplankton populations and therefore the possibility to reduce recruitment of sport fish species.

Introduction

The freshwater drum *Aplodinotus grunniens*, is the only member of the drum family Scaeniidae which lives in freshwater (Barney 1926). Freshwater drum are widespread throughout the central U.S. and inhabit the greatest latitudinal range of any North American freshwater fish (Rypel 2007). Although not economically valuable in most systems (Edsall 1967), freshwater drum can play an important role in aquatic ecosystems and can account for large amounts of biomass in some lakes, rivers, and reservoirs (Rypel 2007).

Numerous studies have investigated the interactions of larval fish and zooplankton and have documented the impacts larval fish can have on zooplankton (Dettmers and Stein 1992) and how zooplankton community structure can influence larval fish growth, survival, and recruitment (Bremigan and Stein 1994). Larval gizzard shad, *Dorosoma cepedianum*, have been shown to reduce densities of zooplankton to near zero during peak abundance (DeVries and Stein 1992). This reduction in zooplankton can be problematic for other species which also rely on zooplankton for food. For example, Welker et al. (1994) found that both larval bluegills and gizzard shad growth and survival are affected by the availability of zooplankton, which can be significantly reduced when fish densities are at their annual peak.

An assessment of larval freshwater drum food habits can provide insight to the role this life stage plays within a community. Few studies of this nature have been conducted except for Swedburg and Walburg (1970), who documented consumption of

mostly *Daphnia* and *Cyclops* by larval freshwater drum in Lewis and Clark Lake, South Dakota. It is unknown if these diet patterns are consistent in other systems, or if selectivity for certain prey exists. Larval freshwater drum have larger gape sizes than most larval fish (Schael et al. 1991) and should be less restricted in zooplankton diet items, which makes an assessment of prey selectivity useful.

In addition to the food habits study, a predictive model for larval freshwater drum abundance was created to better understand freshwater drum yearly population dynamics. Freshwater drum are long-lived (Pereira et al. 1992) and highly fecund, leading to a generally stable adult population in most systems (Rypel 2007). Unlike the adult freshwater drum populations which are stable, larval freshwater drum abundance can be sporadic and often shows episodic recruitment (Winemiller and Rose 1992). These same patterns have been found in other sciaenids such as black drum, *Pogonias cromis*, in the Chesapeake Bay (Wells and Jones 2002), and red drum, *Sciaenops ocellatus*, in estuaries of North Carolina (Lanier and Scharf 2007). Being broadcast spawners with pelagic eggs and larvae that emerge in the early summer (Swedburg and Walburg 1970), freshwater drum can face a variety of environmental conditions and biological factors which can promote growth, survival, and recruitment.

Several factors have been shown to influence larval fish abundance and some of these factors could have influenced larval freshwater drum abundance in Harlan County Reservoir. Zooplankton abundance could influence larval freshwater drum abundance because larval freshwater drum begin actively feeding within a few days of hatching and

have been shown to consume a variety of zooplankton species (Swedburg and Walburg 1970). Other larval fish including American shad, *Alosa sapidissima*, have higher survival rates when zooplankton densities are high (Crecco and Savoy 1985). Competition with other larval fish is another factor which could influence larval freshwater drum abundance. Welker and colleagues (1994) showed high diet overlap between larval fish species and found that starvation is possible if zooplankton resources cannot support the fish biomass present in a system. Gizzard shad, a species present in Harlan County Reservoir at the same time as freshwater drum (Olds 2007), have been shown to significantly reduce zooplankton numbers in other systems, limiting the recruitment of other fish (Dettmers and Stein 1992). Adult freshwater drum abundance is another factor which could influence larval freshwater drum abundance because more mature fish should equate to increased spawning activity and therefore more eggs being deposited.

An aquatic system's productivity has the potential to indirectly influence larval freshwater drum abundance. Although phytoplankton has not been shown to be a food source of larval freshwater drum, phytoplankton is consumed by zooplankton which are a food source for larval freshwater drum. Zooplankton abundance has been shown to be highly correlated with chlorophyll *a* levels in several Midwestern waterbodies (Canfield and Jones 1996).

Water temperature also has been shown to influence larval fish survival and could influence larval freshwater drum abundance in Harlan County Reservoir. In the

Mississippi River, freshwater drum have been shown to experience higher hatches when surface water temperatures were above average during spawning periods (Butler 1965).

Materials and Methods

Study Site

Harlan County Reservoir is an irrigation impoundment on the Republican River and is located in southern Nebraska. The Republican River watershed begins in eastern Colorado and extends into portions of southern Nebraska and northern Kansas. Although the reservoir was built for flood control and irrigation, recreation is an indirect benefit. The fishery within the reservoir is diverse with an abundance of different game and non-game species.

Larval Freshwater Drum Collection

Sampling for larval freshwater drum began the last week of May and continued for eight consecutive weeks. Sampling was initiated at dusk at a station that was selected based on weather conditions and sampling was continued until all 24 stations had been sampled. All stations were located using a GPS receiver to ensure location consistency.

Larval freshwater drum were collected using two bow-mounted push nets. The paired nets differed in size. The large net had a 1 m hoop diameter, 1.85 mm mesh, and a 0.75 mm cod-end collection cup, while the small net had a 0.5 m hoop diameter, 0.75 mm mesh and a 0.75 mm cod-end collection cup. A flow meter (General Oceanics Inc.) equipped with low-speed rotors was attached to each net to allow calculation of the

water volume sampled. The boat was driven at a speed of 4 kph for 5 minutes in a single direction which was dictated by lake morphology and weather conditions. Upon completion of a station, net contents were poured into separate bottles, preserved in 70 % ethyl alcohol, and the flow meter data was recorded.

Larval Freshwater Drum Food Habits

Freshwater drum were separated into four size classes: 5-6 mm, 10-11 mm, 15-16 mm, and 18-19 mm total length (TL). The digestive tract from the mouth to the anus was dissected from each fish and the contents were placed onto a microscope slide. Individual organisms within the stomach were identified to the lowest possible taxon, enumerated, and measured. When partial organisms were encountered, only those in which the head area was present were counted to avoid misidentification and double counting of organisms. For these partial organisms, a mean length for the species was calculated using 25 whole organisms found within other fish and was used to represent the length of the partial individuals.

Zooplankton samples were collected weekly at each push net station with an 80 μm Wisconsin plankton net towed vertically from the substrate to the surface. Zooplankton were preserved in sucrose-buffered formalin until they were analyzed in the lab. Zooplankton samples collected in the field were identified and enumerated, and densities of each species or groups were calculated. Densities were calculated for zooplankton groups including calanoid copepods, cyclopoid copepods, and copepod nauplii. Densities of species including *Daphnia pulicaria*, *D. retrocurva*, and *Bosmina*

spp. were also calculated. Zooplankton processing followed the methods developed by Peterson and colleagues (2005).

Prey electivity by larval freshwater drum was evaluated using the index developed by Strauss (1979):

$$L = r_i - p_i,$$

where r_i and p_i represented the relative abundance of prey in the diet and environment, respectively. The relative abundance of prey in the diet of larval freshwater drum (r_i) was determined by dividing the number of each zooplankton species or group found in the stomachs of all freshwater drum in a size class by the total number of zooplankton consumed by the same group. Zooplankton proportions in the environment (p_i) were calculated by dividing the density of each zooplankton species or group by the total density of all zooplankton during the weeks when larval freshwater drum were captured for diet analysis. The index value (L) can range from -1 (total avoidance) to 1 (perfect positive selectivity) for a given prey species. A value of ± 0.15 was chosen as the cutoff to determine selectivity or avoidance as others have used similar representative values in electivity studies (Dettmers and Stein 1992). Any index value between -0.15 to 0.15 was interpreted as fish consuming prey in equal proportion to the prey item in the environment.

Prey electivity was not calculated in 2009 because unlike 2008 when drum were captured during a short period of time, freshwater drum were collected over an eight

week period in 2009, making it difficult to accurately determine the composition of the zooplankton community at the time of freshwater drum capture.

Sampling and Data Collection for Freshwater Drum Model

In the laboratory, larval freshwater drum were processed by identifying, counting, and measuring the total length (TL) of all freshwater drum from each site and each net. Freshwater drum from 0-7 mm (TL) were counted from the small diameter net and freshwater drum ≥ 8 mm were counted from the large diameter net to avoid double counting of similar sized fish. These size distinctions were determined after analyzing length-frequency histograms from the catch data of 2008. Density at each site was calculated by summing the number of 0-7 mm freshwater drum collected in the small diameter net and 8 mm and larger freshwater drum collected in the large diameter net and dividing by the respective volumes sampled. The large and small net freshwater drum densities were combined to yield an overall density for the station. The densities at each station were then averaged for the week for the whole reservoir. The highest weekly larval freshwater drum density across 2003-2008 was selected to represent annual abundance and year class strength.

Abiotic and biotic data that could have influenced larval freshwater drum abundance were collected during the course of the study. Abiotic data included average one meter temperature and dissolved oxygen which was measured at each station during the push net sampling using a YSI-55 temperature and dissolved oxygen meter. Additionally, 15 stations were monitored weekly from April through October for water

quality parameters including turbidity and chlorophyll *a*. Data for inflow from the Republican River, discharge through the dam, and reservoir pool size were obtained from the U.S. Bureau of Reclamation (2009).

Abiotic data from the three weeks preceding the annual peak in larval freshwater drum abundance was used to build the predictive model. This time period was chosen because the peak of larval freshwater drum abundance occurred within three weeks of the first detection of freshwater drum, making the conditions during this time period most likely to affect survival, egg deposition, and hatching success.

Biotic parameters which were analyzed included weekly mean zooplankton and larval gizzard shad density, total adult freshwater drum abundance. The fall abundance data for adult freshwater drum was obtained from NGPC standardized survey data. Larval gizzard shad were captured with the larval freshwater drum and were processed in the same manner.

From the data collected, a single number for the peak larval freshwater drum density for each year was calculated. This number was the highest weekly mean density observed over the eight week sampling period. Using InStat (2009) software, multiple regression ($p < 0.10$) techniques were used to determine which abiotic and biotic variables incorporated into ten a priori models explained annual larval freshwater drum density (Table 1).

Results

Larval Freshwater Drum Diet

One-way ANOVA tests were used to test for differences in the number of prey consumed by larval freshwater drum of different lengths. The number of prey items consumed by most of the larval freshwater drum size groups differed significantly in 2008, $F(3, 78) = 53.91, p < 0.001$ (Figure 1). There were also differences in the size of prey items consumed among the groups in 2008, $F(3, 908) = 134.21, p < 0.001$ (Figure 2). The 5-6 mm larval freshwater drum consumed smaller prey items than the other three size groups.

In 2008, the diet composition of 83 larval freshwater drum was examined. A total of 909 prey items were found including nine different taxa (Table 2). Prey size ranged from 0.26 to 2.82 mm and averaged 1.01 mm (± 0.01 SE) in length. Of the total number of individuals found in the stomachs of larval freshwater drum, *Daphnia pulicaria* and *D. retrocurva* were the most abundant organisms at 30 % and 27.5 %, respectively (Table 2). Other organisms which were consumed regularly were calanoid copepods (16.2 %), cyclopoid copepods (12.1 %), and *Bosmina* (11.6 %) (Table 2).

Within the 5-6 mm size group in 2008, 166 zooplankton were extracted from the stomachs of 25 individuals. The mean prey length (\pm SE) for the group and number of prey items consumed per fish (\pm SE) was 0.62 mm (± 0.03) and 6.64 individuals (± 0.53), respectively (Figures 1 and 2). Zooplankton groups most commonly consumed by the 5-

6 mm larval freshwater drum were calanoid copepods (44.6 %), *Bosmina* (34.3 %), and cyclopoid copepods (11.5 %) (Figure 3).

Within the 10-11 mm size group in 2008, 173 zooplankton were extracted from the stomachs of 25 individuals. The mean prey length (\pm SE) for the group and number of prey items consumed per fish (\pm SE) was 0.97 mm (\pm 0.04) and 6.92 individuals (\pm 0.65), respectively (Figures 1 and 2). Zooplankton groups most commonly consumed by the 10-11 mm larval freshwater drum were *D. pulicaria* (26.0 %), *Bosmina* (23.7 %), *D. retrocurva* (17.9 %), cyclopoid copepods (15.6 %), and calanoid copepods (13.3 %) (Figure 3).

Within the 15-16 mm size group in 2008, 390 zooplankton were extracted from the stomachs of 25 individuals. The mean prey length (\pm SE) for the group and number of prey items consumed per fish (\pm SE) was 1.14 mm (\pm 0.02) and 15.0 individuals (\pm 0.98), respectively (Figures 2 and 3). Zooplankton groups most commonly consumed by the 15-16 mm larval freshwater drum were *Daphnia* spp. which made up 78.4% of the total number of individuals consumed. Copepods were the next most abundant diet item at 19.3 % of the total (Figure 3).

Within the 18-19 mm group in 2008, 180 zooplankton were extracted from the stomachs of 7 individuals. The mean prey length (\pm SE) for the group and number of prey items consumed per fish (\pm SE) was 1.13 mm (\pm 0.03) and 25.71 individuals (\pm 2.60), respectively (Figure 1 and 2). Zooplankton groups most commonly consumed by the 18-19 mm larval freshwater drum were *D. pulicaria* (48.9 %), *D. retrocurva* (26.1 %), and

copepods which comprised 18.9 % of the total number of individuals consumed (Figure 3).

In 2009 the diet composition of 33 larval freshwater drum which ranged in size from 5.0 to 11.0 mm total length was examined. A total of 249 prey items were found including five different zooplankton taxa (Table 3). Prey size ranged from 0.26 to 1.82 mm and averaged 1.01 mm (± 0.02 SE). Of the total number of individuals found in the stomachs of larval freshwater drum, calanoid copepods and *Daphnia retrocurva* were the most abundant organisms consumed at 41.0 % and 40.6 %, respectively (Table 3). Other organisms that were consumed regularly were cyclopoid copepods (10.8 %), and *Bosmina* (7.2 %) (Table 3).

Within the 5-6 mm size group from 2009, 65 zooplankton were extracted from the stomachs of 8 individuals. The mean prey length (\pm SE) for the group and number of prey items consumed per fish (\pm SE) was 0.66 mm (± 0.03) and 8.13 individuals (± 0.74), respectively (Figures 4 and 5). Zooplankton groups most commonly consumed by the 5-6 mm larval freshwater drum were calanoid copepods (47.7 %), *Bosmina* (27.7 %), and cyclopoid copepods (23.1 %) (Figure 3).

In the 10-11 mm size group from 2009, 184 zooplankton were extracted from the stomachs of 25 individuals. The mean prey length (\pm SE) for the group and number of prey items consumed per fish (\pm SE) was 1.13 mm (± 0.02) and 7.36 individuals (± 0.34), respectively (Figures 4 and 5). Zooplankton groups most commonly consumed by

the 10-11 mm larval freshwater drum were *D. retrocurva* (54.9 %), calanoid copepods (38.6 %), and cyclopoid copepods (6.5 %) (Figure 3).

Prey Electivity

In 2008 the 5-6 mm freshwater drum positively selected for *Bosmina* spp. *Daphnia pulicaria*, *D. retrocurva*, and calanoid and cyclopoid copepods were consumed in the same proportion which they were found in the environment. Compared to the prey available in the reservoir, only copepod nauplii were strongly selected against (Figure 6).

The 10-11 mm freshwater drum positively selected for *Bosmina* spp. and *D. pulicaria*, and negatively selected for calanoid copepods and copepod nauplii. *D. retrocurva* and cyclopoid copepods were both consumed in proportions near those found in the environment (Figure 7).

The 15-16 mm freshwater drum positively selected for *D. retrocurva* and *D. pulicaria*, and negatively selected for calanoid copepods, and copepod nauplii (Figure 8).

The 18 mm freshwater drum positively selected for *D. retrocurva* and *D. pulicaria*, and negatively selected for calanoid copepods and copepod nauplii. Cyclopoid copepods, and *Bosmina* spp. were both consumed in proportions near those found in the environment (Figure 9).

Model Results

The annual peak larval freshwater drum density from 2003-2009 ranged from 0.02 to 2.2 freshwater drum per cubic meter (Figure 10).

Of the models evaluated to predict larval freshwater drum abundance, only one was statistically relevant (Table 1). Adult freshwater drum catch per unit effort (CPUE) data from the previous fall explained the majority of the variability of larval freshwater drum abundance for the years 2003-2008. The following equation relating adult to larval freshwater drum was used as the predictive model:

$$\text{Larval freshwater drum abundance} = -0.0593(\text{Adult Freshwater Drum CPUE}) + 1.6102$$

The CPUE for adult freshwater drum in the fall of 2008 was 3.5, resulting in a predicted density of 1.4 larval freshwater drum per cubic meter in 2009. However, few larval freshwater drum were caught during the summer of 2009 resulting in an observed peak density of 0.02 freshwater drum per cubic meter.

Discussion

Food Habits

The prey electivity data suggest that freshwater drum feed preferentially on some zooplankton species and that these preferences change with growth. The 5-6 mm and 10-11 mm freshwater drum showed a preference for small *Bosmina* spp. but surprisingly showed negative selection for copepod nauplii, another small zooplankton taxa (Figures 6 and 7). Copepod nauplii are the most abundant zooplankton group in the reservoir, accounting for approximately 36% of the total number of zooplankton during these study years. Although highly abundant, only one was found in the stomachs of the freshwater drum examined during this study. In contrast, *Bosmina* spp. are one of the rarest zooplankton species in the reservoir yet are positively selected for

by larval freshwater drum less than 11 mm (Figures 6 and 7). Motility may account for this difference in selectivity of seemingly similar zooplankton species. *Bosmina* are less motile than small copepods (Drenner et al. 1978), and could allow more successful foraging by small freshwater drum.

Larger freshwater drum in the 15-16 mm and 18-19 mm size groups showed positive electivity toward cladocerans such as *D. pulicaria* and *D. retrocurva*, but other similarly sized calanoid and cyclopoid copepods were either eaten in proportion to availability or avoided (Figures 8 and 9). This could be explained by differential capture efficiency of the two groups because of motility differences. Copepods are able to rapidly accelerate and switch directions while swimming (Link 1996), which may make them less vulnerable to predation grazing than cladocerans.

The lack of nauplii in the diets of freshwater drum is surprising because they are the most abundant zooplankton species in the reservoir and the freshwater drum were shown to have consumed other small zooplankton regularly. Other studies have found similar results where nauplii were avoided. Results from Blackwell (2002) showed larval white bass in a glacial South Dakota lake had a high negative electivity toward nauplii despite high densities. Parmley et al. (1986) found the same strong negative selection for nauplii while investigating the diet of larval largemouth bass in Florida.

Schael et al. (1991) documented freshwater drum to have one of the largest gapes found among larval fish, and showed a positive correlation of gape and prey size. I found that larval freshwater drum consumed a wide size range of zooplankton food

sources, and that prey size increased with fish length (Figure 2). Although similarities exist between size of prey consumed by larval freshwater drum in both studies, a difference occurred when comparing the species composition in the diets. The results from this study suggest a transition to feeding on cladocerans and copepods, especially *D. retrocurva* and large calanoid copepods, as freshwater drum grew rather than feeding exclusively on copepods as was found by Schael et al. 1991 (Figure 3). This was likely because Lake Mendota had a relatively low density of *Daphnia* species compared to Harlan County Reservoir (Schael et al. 1991).

Larval freshwater drum in Harlan County Reservoir have the potential to compete with other fish, especially white bass. Studies have shown that like larval freshwater drum, white bass select for *Bosmina* spp. and various species of *Daphnia* during the larval stage (Beck et al. 1998; Quist et al. 2002). The combined predation by larval freshwater drum and white bass on these zooplankton species could reduce their abundance to the point where they are limiting to one or both larval fish species.

Predictive Model

The model developed and evaluated in this study failed to accurately predict larval freshwater drum densities in 2009. Using fall adult freshwater drum CPUE data, the model predicted 1.4 larval freshwater drum per cubic meter which was much higher than the observed 0.02 per cubic meter. Several factors including having six years of data coupled with major hydrologic and limnological changes within the reservoir (Olds 2007) during the study could explain our model's failure.

An interesting component of the model we evaluated was that adult freshwater drum abundance was negatively associated with larval freshwater drum abundance. When more adults were present during the previous fall, they produced fewer offspring during the following spring. This phenomenon has not been shown in other fish species, but could be the result of limited food resources for adults resulting in less energy for the production of gametes.

Although freshwater drum are an understudied fish, marine sciaenids have been the focus of much research near the coasts and several successful models have been developed which describe various aspects of their life history. Using models, the relationship between larval red drum growth and conditions within estuarine nursery areas of Louisiana was explored by Blatz et al. (1998). Additionally, a 20-year dataset of juvenile red drum abundance along the Texas coast was used to develop a model for future predictions of year class strength (Scharf 2000).

The successful drum modeling studies by Blatz et al. (1998) and Scharf (2000) involved marine populations which inhabited a more stable environment, however the dynamic nature of the recent water levels in Harlan County Reservoir could have had implications on the success of this model. The drought conditions which occurred in Nebraska from 2005 through 2007 significantly altered water levels as well as the reservoir limnology (Olds 2007). This lack of stability in the system could have had effects on fish populations making trends in abundance for normal years more difficult to determine.

In addition to the changing aquatic conditions in Harlan, the short duration of the monitoring may have added to the model's inaccuracy. Compared to other larval fish modeling studies which often span several decades, our six year study was likely too short to detect trends in abundance. A 23-year study conducted in Lake Winnebago, Wisconsin to develop a larval freshwater drum growth model based on spring and summer temperatures and water levels and showed higher temperatures coupled with stable water conditions improved growth (Staggs and Otis 1996).

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Table 1. Predictive models for peak larval drum density (LDD). Models with significance levels < 0.10 were used to predict larval drum abundance in 2009.

Model	P value	R ²
LDD= Total drum CPUE	0.058	0.634
LDD = Mean weekly chlorophyll <i>a</i>	0.116	0.500
LDD = Total drum CPUE + Mean previous 1 month temperature	0.185	0.675
LDD = Total drum CPUE + Zooplankton	0.218	0.638
LDD = Zooplankton	0.367	0.205
LDD = Mean previous 1 month temperature	0.403	0.179
LDD = Total drum CPUE + Zooplankton + Mean previous 1 month temperature	0.441	0.678
LDD = Zooplankton + Mean previous 1 month temperature	0.660	0.240
LDD = Total drum CPUE + Zooplankton + Mean previous 1 month temperature	0.723	0.425
LDD = Mean previous 1 month temperature + Zooplankton + Larval shad	0.848	0.285

Table 2. All organisms found in the stomachs of 83 larval freshwater drum during 2008.

The number of prey of each species, the percent of the total number of prey items, and the mean length for each species found is shown.

Organism	Number Consumed	% of Total	Mean Length (mm)	S.E.
<i>Daphnia pulicaria</i>	273	0.30	1.19	0.01
<i>Daphnia retrocurva</i>	250	0.28	1.08	0.01
Calanoid copepods	147	0.16	1.06	0.03
Cyclopoid copepods	110	0.12	1.03	0.02
<i>Bosmina</i> spp.	105	0.12	0.36	0.01
Immature <i>Daphnia</i> spp.	14	0.02	0.44	0.02
<i>Alona</i> spp.	3	0.00	0.81	0.12
<i>Diaphanosoma</i> spp.	3	0.00	0.75	0.06
Chironomid larvae	2	0.00	2.67	0.16
Copepod nauplii	1	0.00	0.26	0.00
Rotifers	1	0.00	0.51	0.00

Table 3. All organisms found in the stomachs of 33 larval freshwater drum during 2009.

The number of prey of each species, the percent of the total number of prey items, and the mean length for each species found is shown.

Organism	Number Consumed	% of Total	Mean Length (mm)
<i>Daphnia retrocurva</i>	101	0.41	1.06
Calanoid copepod	102	0.41	1.15
Cyclopoid copepod	27	0.11	0.79
<i>Bosmina</i> spp.	18	0.07	0.3
<i>Daphnia pulicaria</i>	1	0.00	0.64

Figure Captions

Figure 1. The mean number of prey consumed per fish from each of the four size classes collected in 2008. Sample size for each size class was 25, 25, 25, and 7 fish respectively. Error bars represent the standard error of the mean.

Figure 2. The mean prey length consumed per freshwater drum from each size class during 2008. Sample size for each size class was 25, 25, 25, and 7 fish respectively. Error bars represent the standard error of the mean.

Figure 3. Dietary composition of zooplankton species by number for each freshwater drum size class sampled during 2008 and 2009. Sample size for the 5-6 mm, 10-11 mm, 15-16 mm, and 18-19 mm size classes in 2008 were 25, 25, 25, and 7 fish, respectively. In 2009, sample size for the 5-6 mm and 10-11 mm size classes was 8 and 25 fish, respectively.

Figure 4. The mean number of prey consumed per fish from each size class collected in 2009. Sample size for each size class was 8 and 25 fish respectively. Error bars represent the standard error of the mean.

Figure 5. The mean prey length consumed per freshwater drum from each size class collected in 2009. Sample size for each size class was 8 and 25 fish respectively. Error bars represent the standard error of the mean.

Figure 6. Strauss electivity index values for 25 larval freshwater drum 5-6 mm in length collected during 2008. Error bars represent the standard error of the mean and the lines at ± 0.15 represent the threshold values for selectivity and avoidance.

Figure 7. Strauss electivity index values for 25 larval freshwater drum 10-11 mm in length collected during 2008. Error bars represent the standard error of the mean and the lines at ± 0.15 represent the threshold values for selectivity and avoidance.

Figure 8. Strauss electivity index values for 25 larval freshwater drum 15-16 mm in length collected during 2008. Error bars represent the standard error of the mean and the lines at ± 0.15 represent the threshold values for selectivity and avoidance.

Figure 9. Strauss electivity index values for 7 larval freshwater drum 18-19 mm in length collected during 2008. Error bars represent the standard error of the mean and the lines at ± 0.15 represent the threshold values for selectivity and avoidance.

Figure 10. The mean peak larval drum density measured at Harlan County Reservoir from 2003-2009. Error bars represent the standard error of the mean. Sample sizes for each year from 2003-2009 were 8, 8, 24, 48, 24, 26, and 26 stations respectively.

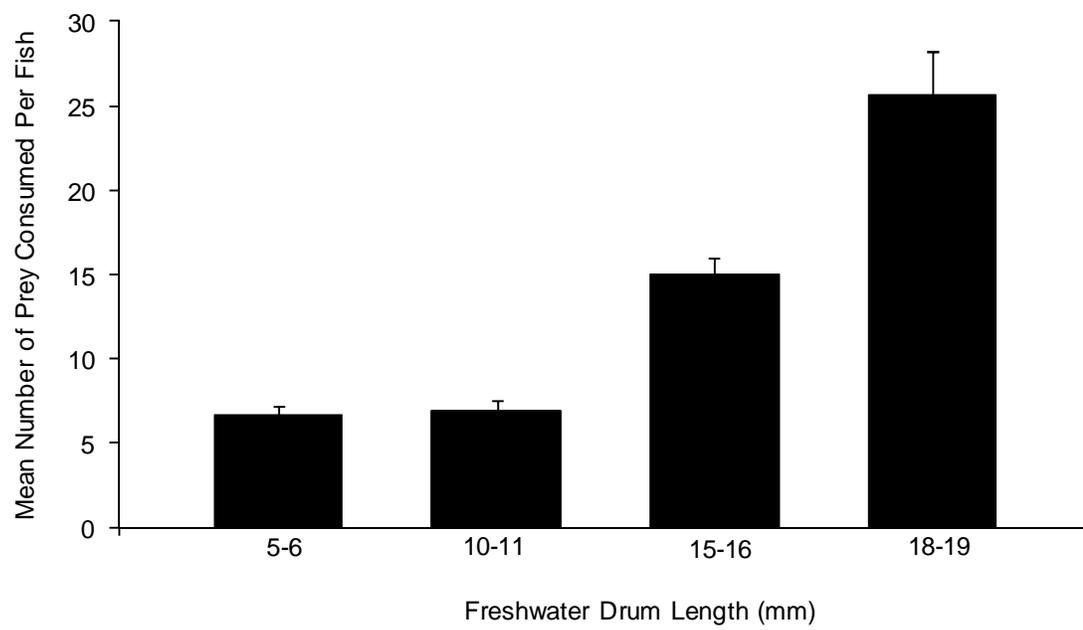
Figure 1.

Figure 2.

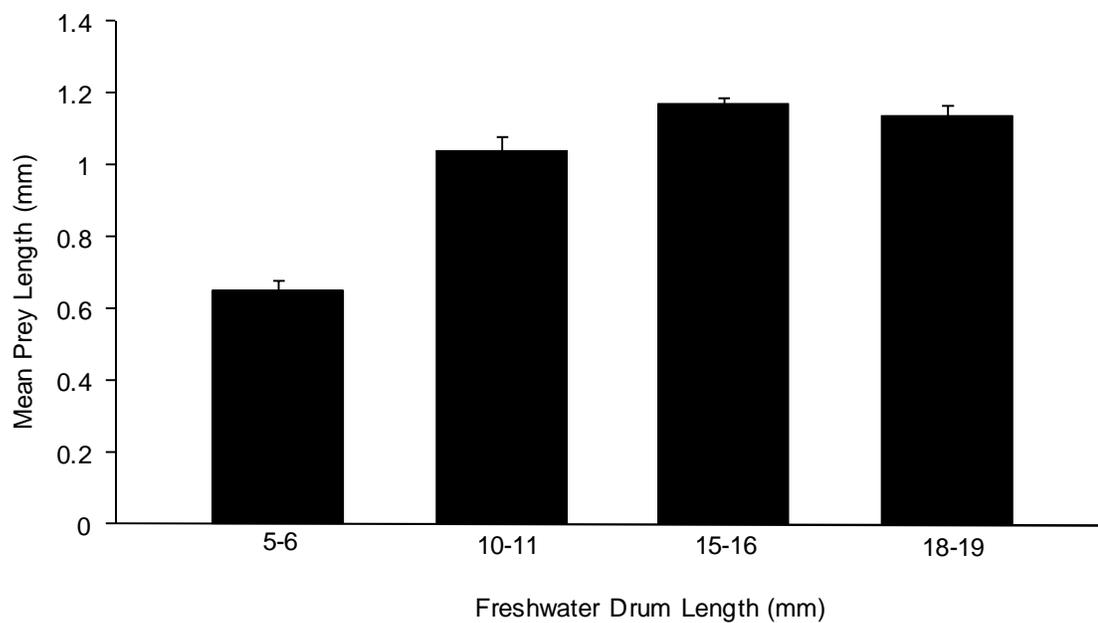


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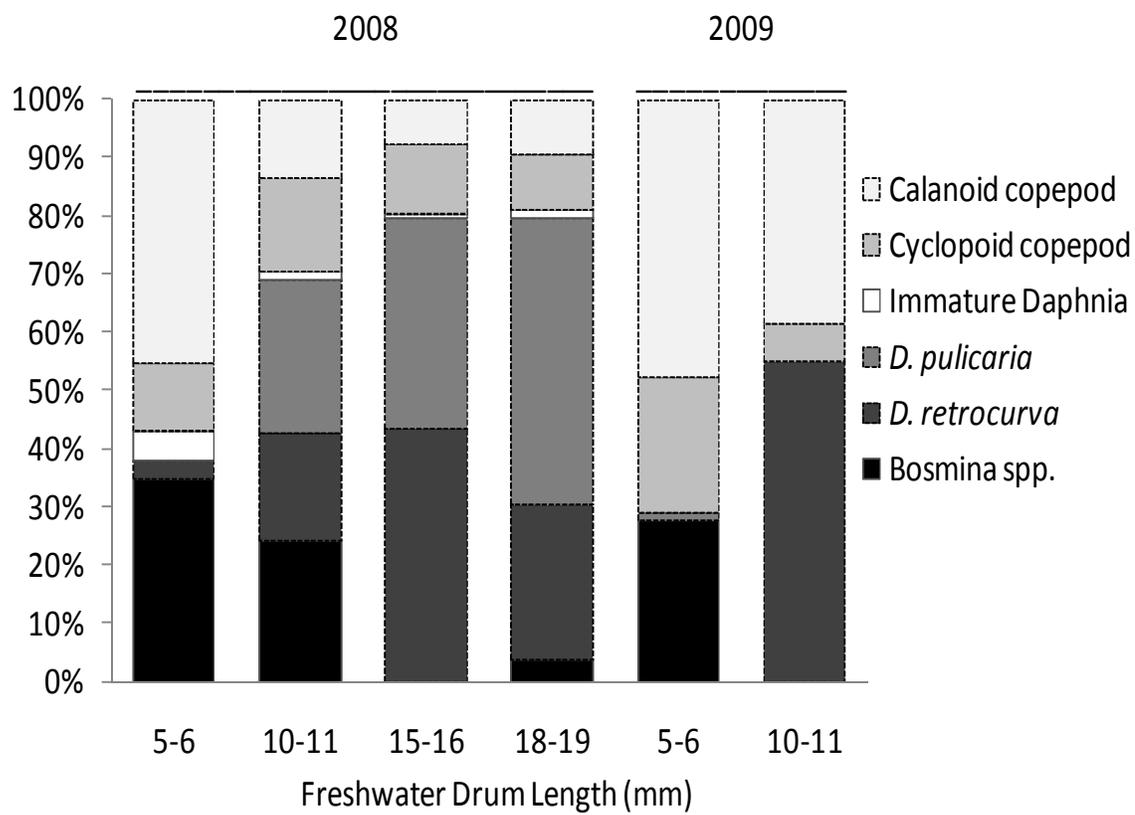


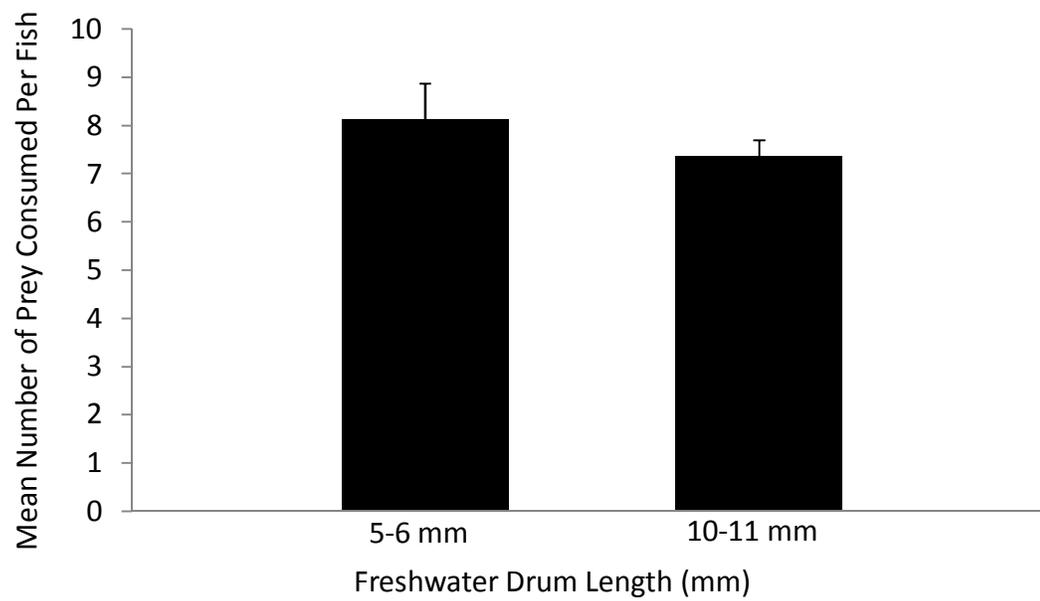
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Figure 5.

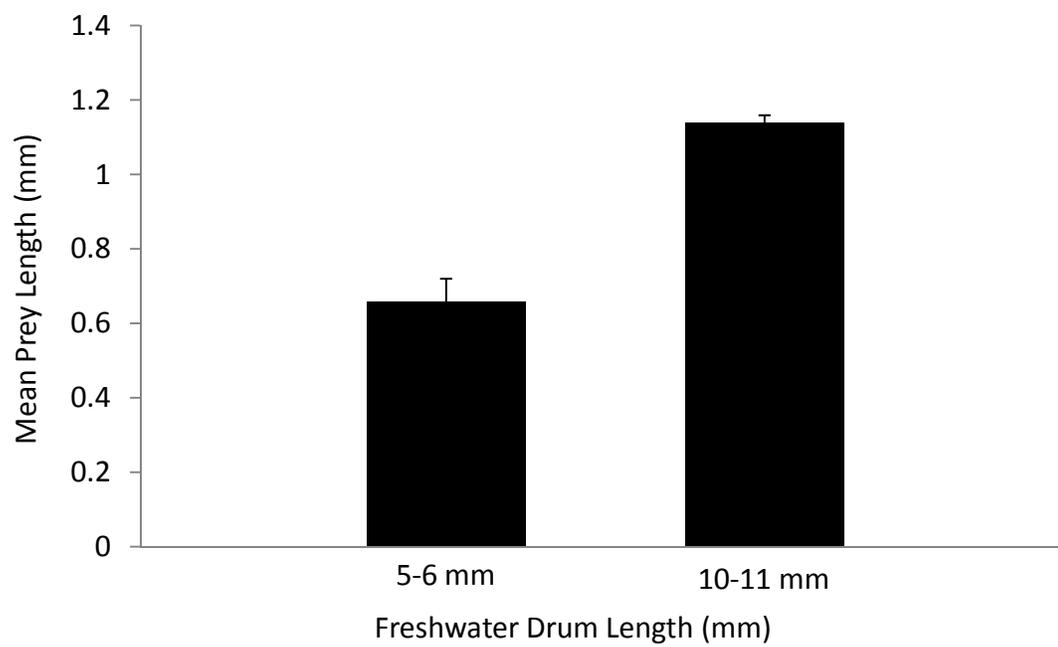


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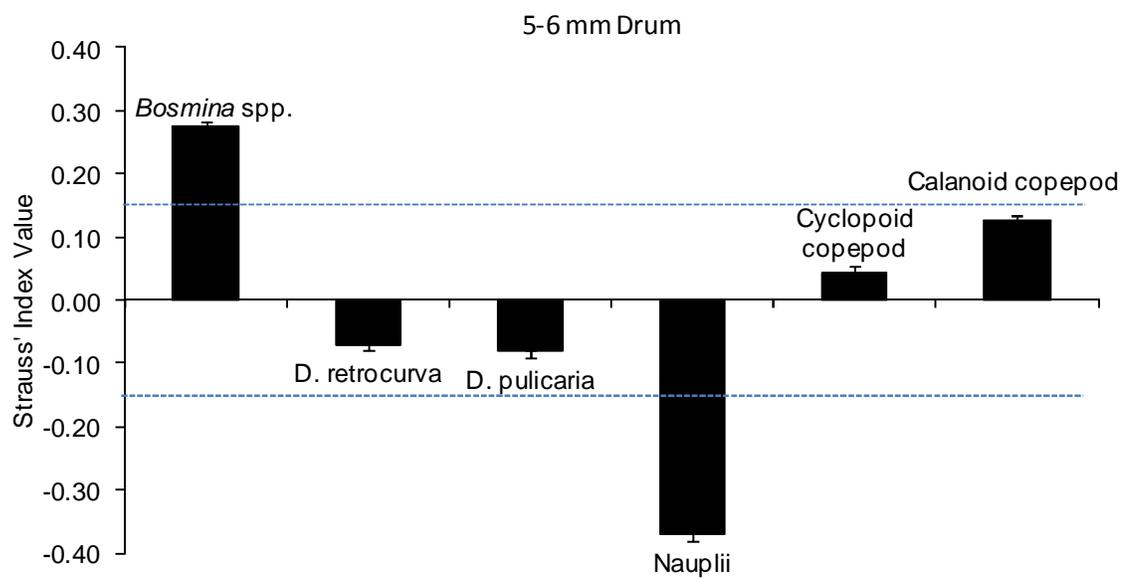


Figure 7.

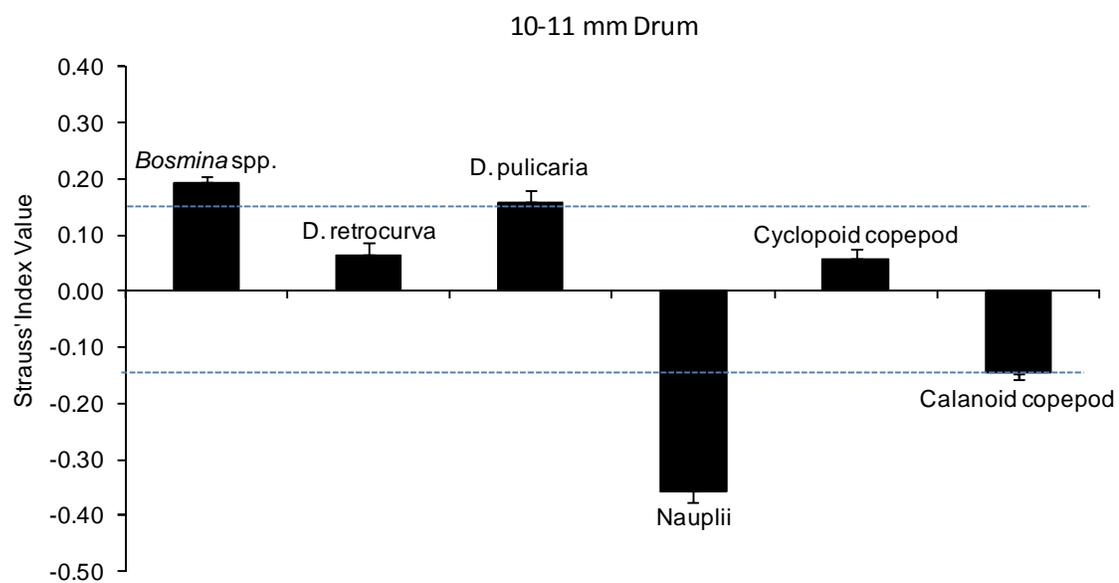


Figure 8.

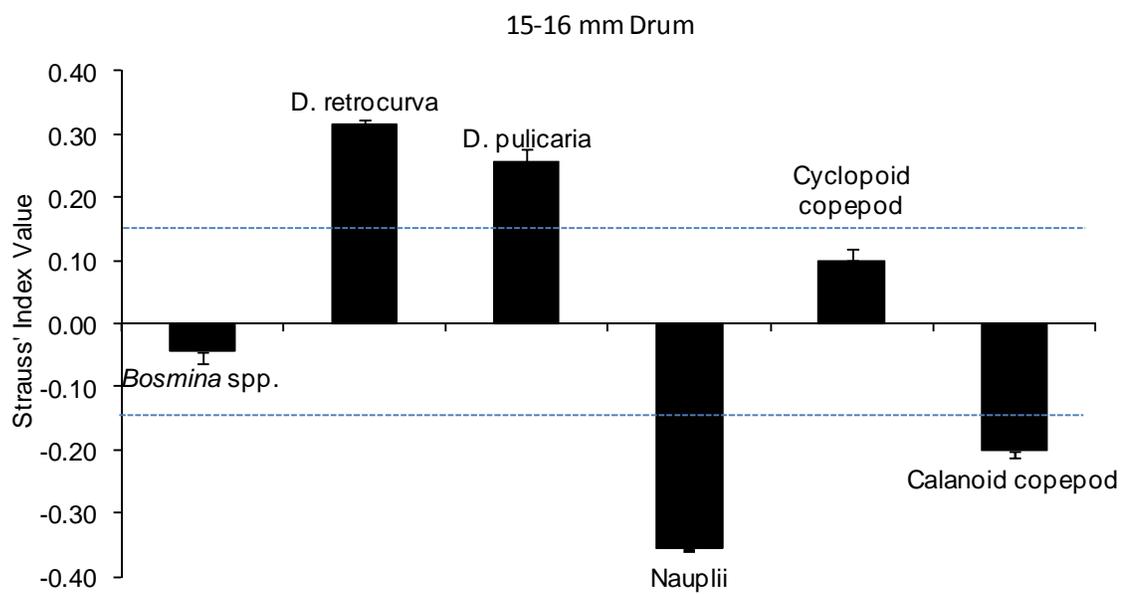


Figure 9.

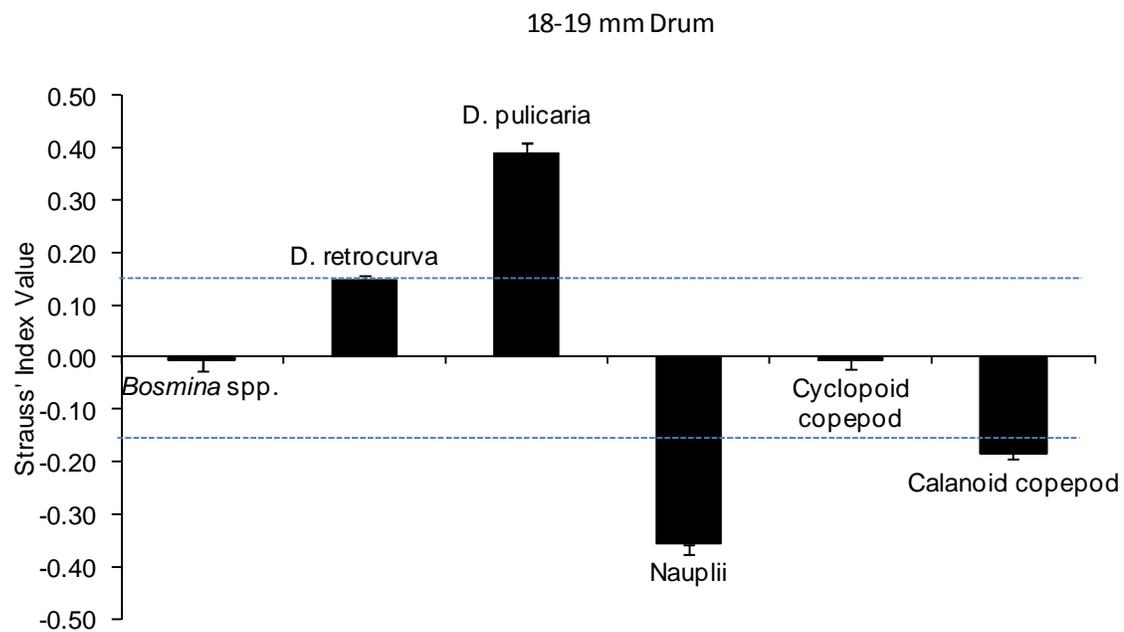
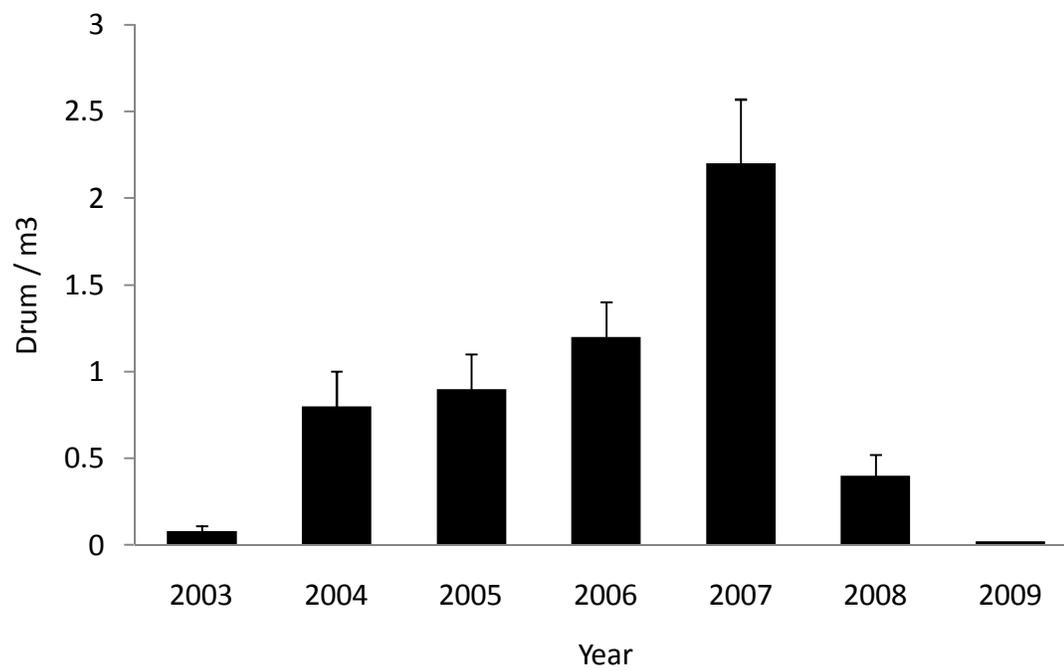


Figure 10.



Chapter 5: Research Conclusions and Recommendations

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Harlan County Reservoir is a dynamic eutrophic system that has experienced major changes in the past five years. The drought which occurred in the region from 2005-2006 reduced water levels, and influenced limnological conditions and the biotic community. When water levels stabilized in 2007, my study investigating zooplankton and larval fish interactions began.

The first objective I investigated was evaluating the spatial relationship between zooplankton and larval gizzard shad. Through this study, I found that gizzard shad and zooplankton densities were often patchy and were spatially dependent, meaning densities at stations in close proximity to one another were similar. Zooplankton and gizzard shad densities were correlated in about half of the weeks studied from 2005-2009, and the once per week, snap-shot sampling approach could explain this variation.

The patchy and unpredictable nature of zooplankton and gizzard shad populations in Harlan has implications on current sport fish management practices. Walleye are a species of concern in Harlan because of their low natural recruitment. Current stocking consists of alternating fry, fingerling, and no walleye every three years. Larval gizzard shad are a food source for young-of-the-year (YOY) walleye, and shad distribution in the reservoir can directly impact the success of stocking efforts. The data from my study suggest that walleye stocking efforts could be maximized by stocking at multiple locations in the reservoir to increase the chances of placing walleye in the areas with larval gizzard shad.

Another conclusion from my study is that the west end of the reservoir needs to be sampled to gain a better understanding of gizzard shad populations. The Harlan investigation began in 2005, and sampling stations were established during the drought period. Although these stations adequately covered the reservoir during these years, roughly a quarter of the west-end of the reservoir was not sampled when water levels returned to normal levels in 2007-2009. Adding more stations in this area in the future will not only give better spatial resolution for the GIS layers, but will provide better estimates of gizzard shad densities.

The second objective I investigated was the food habits of age-0 gizzard shad. The stomach contents of gizzard shad ranging in size from 5 to 130 mm in length were examined and a variety of food items were found. Gizzard shad less than 15 mm in length did not consume many zooplankton and this size group had the greatest number of fish with empty guts. Zooplankton were abundant in the diets of gizzard shad from 15-30 mm in length, but shad greater than 30 mm consumed more algae and detritus and fewer zooplankton. These results are consistent with the findings from other similar studies which investigated the diets of larval gizzard shad.

Larval gizzard shad showed the highest preference for small copepods, especially copepod nauplii and cyclopid copepods. Although there was high preference for these species, copepods did not show the large population declines that are reported in other systems containing gizzard shad. This could be because of the relatively low density of gizzard shad in Harlan County Reservoir compared to other systems. It is also possible

that reduction of zooplankton populations was occurring on localized scales, and the sampling regime used in this study did not detect this pattern.

Because of the gizzard shad's ability to switch to a diet of algae and detritus, it is less likely that the reduced zooplankton population in Harlan County Reservoir is affecting larval shad recruitment as much as other larval fish.

The last research objective I investigated was the food habits of larval drum and I also attempted to model their annual abundance. Understanding the impact of larval drum in Harlan was important because they have been found in densities equal to those of gizzard shad during some years, and little is known about drum during the larval stage. It was also noted that their annual abundance was highly variable, and knowing what factors caused these fluctuations in density could be useful for determining years when drum are abundant and could impact the system.

The food habits study showed that larval drum consumed more and larger zooplankton as they grew. Drum were abundant in 2008 resulting in a sufficient number of fish captured to evaluate their diet, but 2009 larval drum densities were the lowest recorded during the previous 6 years and resulted in a limited ability to analyze freshwater drum diets. Prey electivity was calculated in 2008 and showed that small drum less than 10 mm selected for *Bosmina* spp. and larger drum selected for *Daphnia* spp.

I evaluated several factors when attempting to model larval drum abundance, but I failed to accurately predict their density in 2009. The best model used the

previous fall catch-per-unit-effort data for adult drum to predict larval abundance.

Likely factors which led to the model's failure include the short duration of the dataset and the dynamic conditions within the reservoir which occurred during this study.

Continuing to monitor these data may lead to the development of a better model.

The underlying objective of my research was to explain low or unpredictable walleye recruitment at Harlan County Reservoir. Although I did not directly answer this question, the results from my individual studies can lend some insight to possible reasons for their low recruitment and rule out other factors. It is unlikely that larval gizzard shad or freshwater drum predation on zooplankton are limiting walleye recruitment through competition because earlier hatching juvenile walleye should have already become piscivorous. Inadequate forage for walleye because of low larval gizzard shad abundance is a more likely explanation. Low zooplankton densities in Harlan could be limiting the initial survival of larval walleye. The standard density of zooplankton required for successful recruitment of larval fish is 100 individuals / L, a density rarely observed in Harlan. In addition, nearly half of the zooplankton observed in Harlan are microzooplankton such as copepod nauplii, a species which has not been shown to be utilized as a food source by larval walleye. Walleye fry are usually stocked in Harlan County Reservoir weeks in advance of the first hatch of larval gizzard shad, therefore competition for zooplankton between larval gizzard shad and walleye should not be occurring in these years either. Because of these factors, low zooplankton

densities are a more probable explanation for low walleye recruitment in years when walleye fry are being stocked.

Larval freshwater drum and gizzard shad have the potential to compete with white bass for zooplankton. Other studies have shown that white bass select for the same zooplankton species as the drum studied in Harlan. Drum and white bass are also present in the reservoir during the same time and show similar growth rates. Although white bass have not experienced the low recruitment that walleye have shown in Harlan Reservoir, the potential for competition during years with high drum densities exists. Because of this, developing a predictive model to estimate drum abundance would be useful.

Based on the results from this study, it is possible that low zooplankton numbers in Harlan County Reservoir are impacting larval fish community. Larval gizzard shad are likely the least affected due to their ability to utilize algae and detritus when zooplankton densities are low. Other larval fish in Harlan County Reservoir including walleye, white bass, and freshwater drum do not have this capability and because of their dependence on zooplankton as their primary food source during the larval stage, recruitment of these fish may be limited.