Using fish culture ponds to examine factors affecting larval hybrid striped bass growth and survival

THESIS

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By

Erica Nicole Brumbaugh

Graduate Program in Environmental Science

The Ohio State University

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Master's Examination Committee:

Stuart A. Ludsin, Advisor

David A. Culver, Co-advisor

Harold Walker

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Abstract

Hybrid striped bass (Morone chrysops x M. saxatilis) is an important sportfish in many systems across the U.S. and is often stocked into reservoirs as fry or juveniles. However, determining the success or failure of fry stocking and factors underlying fry survival in reservoirs has been difficult for fisheries managers because of the complications in collecting larvae in reservoirs. Using fish culture ponds, I was able to examine the effects of physical and biological variables on the growth and survival of larval hybrid striped bass, providing information to help fisheries managers to identify reservoir attributes that can support hybrid striped bass stocking. I conducted experiments over three years at two Ohio fish hatcheries to determine: 1) the effects of increased fish fry stocking density on larval fish growth and zooplankton availability; 2) whether the zooplankton prey base in ponds and reservoirs is adequate to support larval and juvenile growth; 3) the potential magnitude of cyclopoid copepod predation on fry in ponds and reservoirs. I found that fry stocking density did not influence fish yield $(g \cdot m^{-3})$ or survival; however, a low density treatment produced larger, albeit fewer, juveniles at harvest than did a high density treatment. Therefore, stocking rates should be based upon whether managers wish to produce larger or higher numbers of juvenile hybrid striped bass. Hybrid striped bass growth and diet analyses indicate that copepod nauplii are an important prey during the first week of life and copepodites during the entire culture period, whereas Daphnia spp. were less important. My study also found that culture

ponds and their source waters have similar zooplankton prey composition, size frequency and densities, suggesting that a hatchery environment can serve as a good proxy for studying reservoir ecology. Cyclopoid copepod predation on larval hybrid striped bass at copepod and larval densities found in culture ponds and reservoirs is unlikely to cause significant mortality; however, other types of predation could affect growth and survival of hybrid striped bass.

Dedication

Dedicated to all my family and friends for their love, patience and understanding.

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And finally I would like to thank my husband, for all of his extra support during the three years I have worked on this project.

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<u>Vita</u>

1997	Big Walnut High School, Sunbury, Ohio
2001	B.S. Water Resources, Heidelberg College,
	Tiffin, Ohio
Autumn 2009 to present	Graduate Research Associate, Limnology
	Lab, The Ohio State University
Autumn 2009 to present	Graduate Teaching Associate, Center for
	Life Sciences Education, The Ohio State
	University

Fields of Study

Major Field: Environmental Science

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Introduction

Reciprocal hybrid striped bass (*Morone saxatilis* \mathcal{J} x *M. chrysops* \mathcal{Q}) is an important sportfish in many systems across the U.S. and is often stocked into reservoirs as larvae or juveniles. The success of larval fish stocked directly into reservoirs is highly variable, as are the harvests of juvenile (phase one) hybrid striped bass from hatchery ponds, with survival in ponds usually less than 40% and reservoir survival lower yet (Morris et al. 1999). Variable stocking success is undesirable to fishery managers, who seek to produce consistent recruitment to their recreational fisheries. Poor water quality (Harrell et al. 1990), inadequate prey (zooplankton) availability and quality (Ludwig 2002), and even predation on larval fish by cyclopoid copepods (Frimpong and Lochmann 2006) have all been suggested as causes for to poor *Morone* spp. growth and survival. However, many of these studies of are anecdotal or were performed in a laboratory setting with unnaturally high fish densities (or, in the last case, high copepod densities).

Water quality issues can include low dissolved oxygen, high pH, high un-ionized ammonia (NH₃-N concentration), and variable temperature, all of which can potentially reduce the survival of hybrid striped bass and striped bass larvae (Kerby 1986; Bergerhouse 1993; Ludwig 2002). Hybrid striped bass and its parent species have been found to survive and grow well in temperatures between 18 and 30°C, pH levels of 7.0-8.5, and dissolved oxygen levels greater than $3mg \cdot L^{-1}$ (Parker 1984; Kerby 1986; Harrell et al. 1990). Un-ionized ammonia tolerances are low in hybrid striped bass, especially during the first weeks of larval development (Bergerhouse 1993; Harcke and Daniels 1999; Ludwig et al. 2007; Oppenborn and Goudie 1993).

Zooplankton availability can determine the growth and survival of hybrid striped bass in fish culture ponds and reservoirs, since as with their parent species, hybrid striped bass are planktivorous for most of their larval stage (Geiger et al. 1985; Quist et al. 2002; Woods et al. 1985). Most previous diet studies (Geiger 1983; Humphries and Cumming 1973; Woods et al. 1985) examined striped bass or original cross bass (*M. saxatilis* \bigcirc x *M. chrysops* \bigcirc) larvae, which measure 8-10 mm in total length (TL) at stocking into rearing ponds or reservoirs. Because reciprocal hybrid striped bass larvae typically are 2-6 mm TL, their early diet should be limited to smaller organisms (Ludwig et al. 1998). That is, due to their small size at stocking, reciprocal hybrid striped bass larvae could be limited by their mouth gape size early in culture and be more dependent on smaller prey (e.g., rotifers) than during the first week after stocking than either parent species or the original cross. Graham and Sprules (1992), Culver and Wu (1997), and DeVries et al. (1998) found gape size only limits prey consumption during the first few weeks of life, and the relationship between gape size and prey selection varies with species.

Hjort (1914) and Li and Mathias (1987) suggested that the larval stage of can be a "critical period" during which mortality can be disproportionately high, owing to the absence of appropriate prey of the correct size and type following absorption of the yolk and oil globule. The "point of no return", which is the duration of time that occurs between the absorption of the yolk and oil globule and the start of exogenous feeding (after which mortality is imminent), typically occurs between 10 and 20 days for striped bass (Li and Mathias 1987). This duration is much longer than for many other species, indicating that the critical period concept (defined as starvation mortality per Hjort [1914]) may not apply to striped bass or their hybrid offspring (Li and Mathias 1987). However, since reciprocal hybrid striped bass receive their larval resources from white bass females (which have smaller eggs than striped bass), individuals from this cross may not have sufficient resources for a similarly long time to the point of no return.

Prey selection has been shown to change throughout the larval stage of fish. Ghan and Sprules (1993), Graeb et al. (2004), and Nunn et al. (2007a) have shown a pattern of prey selection that is dependent on gape size for various taxa of fish, with rotifers first being selected, followed by copepod nauplii, copepod adults, and finally to adult copepods and cladocerans (e.g. *Daphnia* spp.). However, Meshaw (1969) found that larval striped bass stocked in culture ponds selected for adult *Cyclops*, while selecting against *Bosmina, Daphnia* spp., copepod nauplii and rotifers, although he did not examine the effect of prey selection on the growth and survival of the planktivorous larvae. Studies with other fish species have shown that growth and survival were maximized in small larvae when they consumed copepod nauplii and adults and in larger larvae when they fed on adult copepods and cladocerans (Mayer and Wahl 1997; Graeb et al. 2004). When rotifers were positively selected as prey, survival and growth were reduced compared to the same size larvae consuming copepod nauplii and adults (Fulford et al. 2006).

Inability to undergo an ontogenetic diet shift because appropriate prey items are unavailable also could limit the growth and survival of larval fish. Young fish utilize zooplankton as a first food source (Whiteside et al. 1985). However, as their swimming abilities improve and their digestive systems develop, individuals are able to use more of their environment and broaden their prey base (Mark et al. 1987; Makrakis et al. 2005). The ontogenetic diet shift is typically characterized by the incorporation of new prey items such as large zooplankters, insects, larval fish, and chironomid larvae (Keast 1980; Nunn et al. 2007b). Wu and Culver (1992) observed that all yellow perch (*Perca flavescens*) > 30 mm TL could consume benthic prey, but did so only if the density of crustacean zooplankton fell below $50 \cdot L^{-1}$. If a scarcity of zooplankton forces larval fish to shift to alternate foods while in the culture ponds, their survival and growth may decrease if larvae are physiologically incapable to use these alternate prey or no alternate prey are available.

Fish density may be an important determinant of growth or survival through competition for prey resources. Fox and Flowers (1990), Qin et al. (1994), and Huang and Chiu (1997) studied larvae of different species, but all showed that with increasing density of larvae, individual growth decreases; however, these findings have been variable relative to the effects of larval fish density on percent survival and fish yield. Rees and Cook (1983) found that Georgia ponds stocked with original cross hybrid striped bass larvae at $38 \cdot m^{-3}$ had the highest rate of survival ($35.9\% \pm 6.4$), while ponds stocked at 144 larvae·m⁻³ produced the largest number of fingerlings at harvest ($41 \cdot m^{-3}$) but at a lower survival rate ($28.4\% \pm 4.6$). Tank experiments with reciprocal hybrid striped bass

revealed that individual TL and weight decreased with increased larval densities and that total yield increased with stocking density; however, the densities tested in these experiments were extremely high, ranging from 20,000 to 120,000 larvae·m⁻³ (Ludwig and Lochmann 2007). Increased fish densities have led to reductions in preferred prey, while total zooplankton populations were unaffected by lower stocking densities, leading to improved larval fish growth (Fox and Flowers 1990; Qin et al. 1994).

While zooplankton consumption appears to play a large part in larval fish growth and survival, predation on larvae by adult female cyclopoid copepods also has been shown to occur in laboratory situations, and copepods have been found grasping fry in zooplankton tow catches (Davis 1959; Fabian 1960). Several studies have examined copepod predation in reservoirs and lakes, showing damage attributed to copepods that could have caused death of larvae (Smith and Kernehan 1981; Hartig et al. 1982; Hartig and Jude 1984). However, these studies were based on larvae collected in ichthyoplankton tows that would have artificially increased the densities of larvae and copepods, thereby raising the probability of encounter. Several laboratory experiments found that mortality of several larval fish species occurred at female cyclopoid copepod densities of 150-500 individuals L^{-1} , which are densities that have been observed in natural systems (Hokanson and Lien 1986; Labay and Brandt 1994; Valderramma et al. 2000; Frimpong and Lochmann 2005). These studies, however, also used fry densities 200 to 400 times those found in culture ponds, including those studied herein.

Due to the complexity of lake and reservoir systems, determining which factors drive the growth and survival of larval fish can be difficult. By contrast, culture ponds offer a

potentially excellent environment to analyze the mechanisms underlying growth and survival of larval fishes, as the ponds are filled with source water (often from the same lake into which fry or fingerlings will be stocked) and their small size facilitates sampling of water, zooplankton, and fish through time. If the culture ponds contain similar prey sizes, composition, and densities as the corresponding source waters, then these simpler environments may provide insight into how stocked hybrid striped bass could perform in reservoir systems. Further advantages of culture ponds as study systems are 1) their small size does allows replicated experiments to be conducted in multiple ponds and 2) ponds can be drained at the end of the culture period, providing a unique opportunity to accurately quantify population size, survival, total yield, and the average size structure at harvest. Of course, limitations of using shallow culture ponds exist, including an inability to examine the effects of water movement, nearshore-pelagic water interactions, predation by larger fish, and interspecies competition. Even so, I feel that the advantages of using culture ponds outweigh the disadvantages in studying many factors affecting growth and survival of larval fish.

I designed three controlled experiments to explore the potential importance of these factors to reciprocal hybrid striped bass production in culture ponds and the reservoir systems they represent. Two experiments focused on varying stocking densities of reciprocal hybrid striped bass larvae to determine its effects on larval growth and survival, as well as zooplankton prey availability. The third experiment focused on comparing culture pond source waters to culture ponds themselves at two Ohio hatcheries of contrasting productivity to determine whether appropriate zooplankton would be

available for larval and juvenile reciprocal hybrid striped bass at stocking. If I found that the zooplankton forage base in reservoirs was similar to that found in culture ponds, then the results from my experiments may allow me to infer adequacy of the forage base in reservoirs for larval fish stocking. With these experiments, I tested four hypotheses: 1) larval hybrid striped bass growth will decline with increased fry stocking density because of increasing pressure of zooplankton prey; 2) at normal stocking densities, adequate zooplankton prey will exist to support growth of larval hybrid striped bass during the critical first week of culture and the remainder (after week 1) of the culture season, and appropriate zooplankton will be available in reservoirs to support stocked hybrid striped bass larvae and juveniles; and 3) cyclopoid copepods will not cause significant fry mortality during the first weeks of life in ponds as their abundance will be lower in culture ponds than in previous studies. In determining which factors affect reciprocal hybrid striped bass larvae, I also sought to provide insight on the variable survival observed in hatcheries and reservoir systems. This information could assist wildlife agencies in decisions of where to stock larval and juvenile reciprocal hybrid striped bass and what densities of larvae are appropriate to be stocked in hatchery ponds and reservoir systems.

Methods

Study Sites

I conducted all experiments from May through June 2006, 2007 and 2008 at the Senecaville and Hebron State Fish Hatcheries, Ohio, U.S.A. Fish production ponds at Senecaville State Fish Hatchery (SFH) were filled with water drawn from its mesotrophic source reservoir (Seneca Lake). Water was filtered through 0.5-mm screens to prevent undesired fish and other large organisms from entering the ponds; however, during 2007, screens on some ponds failed, allowing eggs and larval fish (e.g., gizzard shad *Dorosoma cepedianum* and sunfish *Lepomis* spp.) to enter. Ponds at Hebron SFH were filled from a more eutrophic reservoir (Buckeye Lake) and similarly filtered. Ponds used varied in volume, surface area, and maximum depth: 4,580-6,040 m³, 0.45-0.49 ha and 2.2-2.6 m, respectively. Ponds at both hatcheries were filled 5-7 days before the stocking of the hybrid striped bass fry.

During 2006, I sampled five ponds at both Hebron and Senecaville State Fish Hatcheries weekly (4 weeks total) for water quality, zooplankton and larvae; however, larval data are not presented because catch numbers were low and no fish were caught during the first two weeks. I collected zooplankton samples weekly in both source water reservoirs from the shore (two sites at Hebron Lake and three at Seneca Lake, all sampled previously by the Limnology Lab, Ohio State University). I collected water quality and zooplankton samples during 2007 from four Senecaville SFH ponds weekly (four weeks total) and

hybrid striped bass larvae twice per week. During 2008, water quality, zooplankton, and larvae samples were sampled from six ponds at Senecaville SFH twice per week (four weeks total).

I measured pH and dissolved oxygen with an YSI multimeter in each pond on each sample date in the deepest end of the pond. Pond water temperature was measured *in situ* every 15 minutes (nearest 0.1°C) throughout the culture period, using temperature loggers (Onset Computer Corp.) placed in the middle of the pond a depth of 1.5 meters. Staff at Senecaville SFH measured concentrations of ammonia, nitrate and phosphate in each pond weekly to determine the amount of fertilizer to be applied with a high pressure sprayer to restore each pond to a 20:1 inorganic N:P ratio. Each pond was then fertilized with liquid inorganic nitrogen and phosphorus fertilizers to maintain the inorganic N:P ratio, in turn stimulating production of edible algae (Helal and Culver 1991; Qin et al. 1995). Free ammonia was calculated during 1) 2007 from total ammonia nitrogen measurements provided by Senecaville SFH, pH, and temperature on the closest sampling date and 2) 2008 from total ammonia nitrogen from water samples processed by the National Center for Water Quality Research (Heidelberg University, Tiffin, OH, USA), pH, and temperature.

I sampled zooplankton from a rowboat in each pond once per sample date with a metered 0.5-m diameter (64- μ m mesh) net mounted on a pole that was pulled across the entire length of the pond in an undulating vertical pattern (n=1 replicate per date). Care was taken to avoid any decomposing plant matter during zooplankton collection. Collected

zooplankters were preserved in 4% formalin-sucrose solution (Haney and Hall 1973) to be analyzed in the laboratory. I enumerated zooplankters and measured lengths of the cladocerans, copepods, and rotifers from each sample following subsampling methods from Kane (2004). I calculated zooplankton biomass (μ g dry weight·L⁻¹) by multiplying the density of each species by the mean individual dry weight calculated from lengthweight regressions (Culver et al. 1985). Rotifer biomass was calculated by multiplying the density of each taxon by an average biomass (Kane 2004). I included all adult cladoceran species, adult copepod species, copepod nauplii, and all unidentified cladocerans and copepods when reporting total zooplankton biomass or densities.

I sampled fish larvae from each pond on each sampling date throughout the entire culture period. During 2006, seines were used to collect larvae. During 2007 and 2008, I used light traps at night (Secor et al. 1992) to capture younger larvae. One trap was setup once per sample date in each pond for one hour after sunset. Once larvae reached 11 mm standard length (SL), collections were made using daytime seining (6.4mm mesh seine pulled by two people). Up to 10 larvae were collected from each pond on each sampling date and preserved in a sugar formalin (10%) solution. In the laboratory, I measured each larva (nearest 0.1 mm SL) and wet weight (nearest 0.01 g) after blot drying; no adjustment was made for formalin effects on fish weight or lengths.

During 2006, five ponds at both Hebron and Senecaville State Fish Hatcheries were stocked five ponds with 52 and 48 larvae·m⁻³, respectively. During 2007 at Senecaville SFH, I examined the effects of stocking density on hybrid striped bass growth and

zooplankton availability by stocking ponds with two different densities of larvae (30 or $60 \cdot m^{-3}$) with two replicates of each treatment. Ponds used during 2007 and 2008 were chosen by Senecaville SFH staff; however, I randomly assigned densities to those ponds provided. The average stocking density during the last ten years at Senecaville SFH is 60 larvae·m⁻³ (Ohio Division of Wildlife, unpublished data) and thirty larvae·m⁻³ was used instead of our ideal goal of 120 larvae·m⁻³ during 2007 due to lower availability of larvae. During 2008, the experiment was repeated using higher densities (60 or 100 m⁻³) with four and two replicates, respectively. Stocking densities were increased during 2008 to explore whether competition for zooplankton resources could influence reciprocal hybrid striped bass growth and survival. All ponds were scheduled to be stocked on the same date, but the first shipment of larvae experienced at least 50% mortality en route to Senecaville SFH, so a second shipment of fry was required to complete the desired stocking rates. In turn, ponds stocked at $60 \cdot m^{-3}$ were stocked one week before those receiving $100 \cdot m^{-3}$; however, all ponds were filled with source water at the same time.

The Ohio SFH staff typically harvest hybrid striped bass when they reach 25 mm TL or when the fish are no longer adding 2-3 mm of length per week. During 2006, fish at Hebron SFH were harvested after 36 days and at Senecaville SFH after 33 days. During 2007, fish were harvested after 34 days (mid-June) based on their observations of fish length. During 2008, slow growth rates of fish in the low-density ponds caused Senecaville SFH staff to delay harvest until 36 days after stocking, whereas they harvested high-density ponds 30 days after stocking.

Larval Stocking Density Effects (Hypothesis 1)

I quantified the effects of larval stocking density by comparing total harvest (as numbers and total weight·m⁻³), average individual fish weight at harvest and % survival from time of stocking to harvest. Average hybrid striped bass growth rate and zooplankton density and biomass between stocking treatments were compared between sample dates during 2007 and 2008. Staff at both hatcheries provided total harvest numbers for each pond, including total estimated numbers of fish, total weights of fish harvested and average individual fish lengths and weights, which I used to determine the number of fish m⁻³ and yield (g·m⁻³) for each pond. I calculated average % weight change per day using wet weights of all fish dissected and the following formulas:

$$W_2 = W_1 e^{g(t^2-t^1)}$$
 and $G = 100g$

where W is weight of fish at a given time, g is the specific growth rate (day⁻¹), t is the corresponding day after stocking and G is the % weight gained per day during the period between t₁ and t₂ (Wootton 1998). I examined the effect of density on electivity in fish diets and the onset of ontogenetic diet shift to determine whether intra-specific competition may have caused a diet change due to lowered zooplankton prey availability. The effects of larval hybrid striped bass density on the zooplankton prey base were examined by comparing changes in the biomass and density of total zooplankton and individual zooplankton taxonomic groups (i.e. *Bosmina*, daphnids, copepods, calanoid and cyclopoid nauplii and rotifers) among ponds through time between larval stocking density treatments

Zooplankton Prey Adequacy (Hypothesis 2)

I determined the adequacy of zooplankton prey by examining zooplankton size and taxonomic composition in relation to the growth rates of larval hybrid striped bass during 2007 and 2008 at Senecaville SFH. We included the following metrics in the analyses: gape size limits, prey selectivity, prey size frequency, dietary ontogeny based on first occurrence of benthos in the diet, and larval growth rates.

I quantified prey biomass consumed in the digestive tract (stomach and intestine) of larvae under a dissecting microscope and identifying prey items to species or genus level. Intact prey items were measured (nearest 0.001 mm) during diet examination as follows: 1) zooplankters and benthic cladocerans TL; 2) *Chaoborus* larvae head capsule length and width; and 3) chironomid larvae TL (when possible) or head capsule length and width. In turn, lengths were used to estimate biomass of consumed prey items using published length-weight equations (Culver et al. 1985; Dumont and Balvay 1979; Johnston and Cunjak 1999) or from dry weights determined in the laboratory from whole organisms found in fish traps and zooplankton samples (terrestrial insects and ostracods). The number of diets examined varied from a minimum of 3 fish to a maximum of 22 per pond per sampling date (excluding empty stomach that comprised only 1% of all diets examined). During 2007, a total of 120 diets were examined from low-density ponds and 168 from high-density ponds (Table 1). During 2008, we quantified a total of 329 diets from low-density ponds and 182 from high-density ponds (Table 2). I characterized dietary contents by classes of lentic, epibenthic, benthic, and other (Table 3) to determine the amount by dry weight biomass and percentage by dry weight biomass each class

comprised of the diet of the fish. We analyzed dietary ontogenies, including identifying the date that benthic organisms (e.g., chironomid larvae, pupae, ostracods) first appeared in the diets in each pond.

Hybrid striped bass gapes were measured to determine the maximum prey size that the larvae could potentially consume relative to the size range of ambient prey. I measured larval gape size by opening the mouth with jeweler's forceps and measuring the dorsal to ventral gape under a dissecting microscope (Nunn et al. 2007b). Gape size (nearest 0.01 mm) was positively correlated with SL (gape = 0.1957SL-0.3935 n=955, R²=0.94), for larvae collected during 2008, which we then applied to larvae collected during 2007 as well. I then compared average gape size to zooplankton lengths found in the stomachs of larvae for that date as well as to zooplankton sizes available in the environment.

A prey electivity index was used to determine whether larvae were selecting for or against a particular zooplankton taxon. I calculated prey electivity using Chesson's index (Chesson 1983):

$$\epsilon_{i} = (m(\alpha_{i}) - 1) / ((m-2)(\alpha_{i}) + 1)$$

where ε_i is the electivity index value for prey species *i*, α_i is the preference for prey type *i*, and m is the number of prey taxa. Electivity values range from -1 to +1, where -1 indicates selection against a prey taxon, +1 indicates positive selection for a taxon and 0 signifies random selection. I calculated the α_i value using the following equation:

$\alpha_i = (r_i/n_i) / \Sigma (r_i/n_i)$

where the r_i and n_i are the proportion of the prey type *i* (by number) in the stomach and ponds, respectively (Chesson 1983). I calculated prey electivity for the following zooplankton groups: *Bosmina, Daphnia* spp., cyclopoid and calanoid nauplii, adult copepods, and rotifers. Prey electivity could not be calculated for benthic organisms and terrestrial insects since we did not know their abundance in the ponds.

Zooplankton sizes (Table 4) in the environment and in fish diets were compared to better understand availability of consumed prey during the culture period. I compared prey size in fish diets by examining the stomach contents of all fish on each study date, measuring the first 20 individuals of each taxon found and determining the total number of each type prey consumed in each stomach. If more than 20 organisms of a taxon were consumed, or more organisms were consumed than could be measured due to damaged prey, the corresponding length measurements from that fish stomach and taxon were randomly chosen (from a uniform distribution) to represent the unmeasured prey, and thus accounted for the variability in zooplankton length, especially in copepods and daphnids. Because rotifers were not measured in our samples, *Asplanchna* individuals were assigned a length of 0.25 mm, whereas all other rotifers were assigned a length of 0.24 mm. Prey size selectivity was calculated as was taxonomic electivity discussed above using Chesson's index (Chesson 1983).

Zooplankton species composition, density, biomass, and size frequency distribution were compared between ponds and their source water during 2006, including density and relative contribution of six zooplankton groups utilized by larval fish (*Bosmina*, daphnids, copepods, calanoid nauplii, cyclopoid nauplii, and rotifers) also were compared between ponds and their source waters.

Cyclopoid Copepod Mortality (Hypothesis 3)

I determined the density of adult cyclopoids present in ponds, and in Hebron and Seneca reservoirs throughout the culture period. I calculated the encounter rate of cyclopoid copepods with hybrid striped bass larvae using the following equation developed for zooplankton (Gerritsen 1980):

$$Z_{\rm p} = (\pi R^2 N_{\rm h}/3)(u^2 + 3v^2/v)$$

where Z_p is the encounter rate per second of the copepods with a larva, R is the constant encounter radius of the copepods (0.5 mm from Williamson and Gilbert 1980), N_h is the density of fish (#·L⁻¹), u is the length-based mean speed (mm·s⁻¹) of fish larvae (freshwater drum *Aplodinotus grunniens*, white bass, white perch and yellow perch) based on length (Trauben 1991) and v is the mean speed of the copepods (1.7 mm·s⁻¹ Gerritsen 1980). I estimated the encounter rate for the lakes during 2006, the ponds during 2006, 2007, and 2008, and for the results of laboratory studies (Valderrama et al. 2000; and Frimpong and Lochmann 2005). Fish density for 2006 for the reservoirs and ponds was set at the average stocking densities used at each hatchery during 2006 (54·m⁻) ³at HSFH and $66 \cdot \text{m}^{-3}$ at SSFH). Stocking densities for 2007 and 2008 were set to their corresponding density (30, 60, or $100 \cdot \text{m}^{-3}$) and at 20,000 $\cdot \text{m}^{-3}$ for the two laboratory studies from the literature.

Statistical Analysis

I tested the effect of stocking density on the following variables at harvest using a t-test for 2007 and 2008: harvest density, average fish weight, percent survival and yield ($g \cdot m^{-3}$). I used a linear mixed model to determine effects of larval stocking density on fish growth, individual fish mass, gape measurements, zooplankton, and water quality parameters throughout the culture period in ponds (SPSS Statistics 17.0, SPSS Inc.). The statistical model for this analysis is:

$$Y_{ijk} = \mu + T_i + D_j + T_i D_j + p_k + \varepsilon_{ijk},$$

where Y is the measured response variable, μ is the grand mean, T_i is the fixed effect of ith treatment, D_j is the fixed effect of jth day of culture, T_iD_j is the fixed effect representing the interaction of ith treatment and jth culture day, p_k is the random effect associated with replicated ponds (k) in each treatment, and ε_{ijk} = error term. Statistical significance from these tests will be reported as follows: p_{den} = density effect, p_{das} = time effect, p_{inter} = interaction effect. I compared zooplankton and water quality variables between ponds and their source water using the same linear mixed effects model. Statistical significance from these tests will be reported as follows: p_{Loc} = source effect, p_{das} = time effect, p_{inter} = interaction effect. Electivity indices were tested for effect of density using a

Kolmogorov-Smirnov Z test, as were size frequency data (ponds vs. diets and ponds vs. source water). All data were tested to determine whether they met the assumptions of normality (Kolmogorov-Smirnov) and homogeneity of variance (Levene's) and they were transformed to meet assumptions when needed. I set α =0.05 for all statistical analyses.

Results

Larval Stocking Density Effects (Hypothesis 1)

During 2007, I found larval density had no affect on fish produced m⁻³, fish yield (g m⁻³), or percent survival; however, low density ponds produced heavier individuals. Highdensity ponds appeared to produced more fish per cubic meter at harvest than did the low-density ponds, but the difference was not statistically significant (t_{stat} = 0.211) (Table 5). Individual fish weights at harvest were significantly higher in low-density ponds (t_{stat} <0.0001), although overall fish yields did not differ between treatments (t_{stat} =0.40) (Table 5). Percent survival was similar between treatments with high-density ponds averaging 44% and low-density ponds 49% (t_{stat} =0.722) (Table 5).

During 2008, I found that high larval density produced more fish m⁻³ and smaller fish, while larval density had no effect on fish yield or percent survival. High density ponds produced more fish m⁻³ ($t_{stat} = 0.001$), than did low density ponds (Table 6). Individual fish weights were lower in high-density ponds ($t_{stat} < 0.0001$), however, the total pond yields were similar between treatments ($t_{stat} = 0.809$), averaging 4.58 g m⁻³ in low-density ponds and 4.72g m⁻³ in low-density ponds (Table 6). Percent survival was similar (p=0.09) between densities (Table 6). I adjusted the fish weights (assuming an specific growth rate at day 30) to account for the difference in length of culture, individual

weights at harvest in the high-density ponds still were lower than those of fish in lowdensity ponds (p=0.01).

During 2007, the percent of body weight gained per day decreased through the culture period (F=24.77, $p_{das}<0.001$) for both larval stocking density treatments ($p_{den}=0.60$, $p_{inter}=0.88$) (Fig.1). The individual weights (natural log transformed for analysis) of larvae increased throughout the culture period and were higher in low-density ponds than high density ponds later in the culture period only (F=0.94 $p_{den}=0.006$, F=2564 $p_{das}<0.001$, F=10.2 $p_{inter}=.002$) (Fig. 1). Percent body weight gained per day decreased over the culture period during 2008 ($p_{das}=0.002$) but was not influenced by density ($p_{den}=0.84$, $p_{inter}=0.41$) (Fig. 1). However, fish density and time of culture did affect individual fish weight (F=59.8 $p_{den}<0.001$, F=6740.4 $p_{das}<0.001$, F=24.0 $p_{inter}<0.001$) with low-density ponds again having larger fish than the high-density ponds during the end of the culture period (Fig. 1).

During 2007, total zooplankton density was unaffected by time throughout the culture period ($p_{das}=0.60$) or by hybrid striped bass stocking densities ($p_{das}=0.34$, $p_{inter}=0.45$), as was total zooplankton biomass ($p_{den}=0.81$, $p_{das}=0.28$, $p_{inter}=0.7$) (Fig. 2). None of the zooplankton groups was affected by larval density or day after stocking (p_{den} from 0.21 to 0.99, p_{das} from 0.12 to 0.97, p_{inter} from 0.06 to 0.97), except that copepods decreased through the culture period ($p_{das}=0.01$, $p_{inter}=0.06$). The density of total zooplankton did not differ during 2008 between larval stocking densities ($p_{den}=0.23$) or day after stocking ($p_{das}=0.19$, $p_{inter}=0.14$) (Figure 2). Likewise, zooplankton biomass did not differ with

larval density ($p_{den}=0.22$) or day after stocking ($p_{das}=0.23$, $p_{inter}=0.64$). Daphnids, copepods, and rotifers decreased throughout the culture period ($p_{das}<0.001$ for all) but no other group did. No zooplankton group density was affected by larval density (all $p_{den}>0.31$, all $p_{inter}>0.16$).

No significant differences were observed between larval stocking density treatments in either year for any of the water quality parameters measured in culture ponds (Table 7). However, all four water quality parameters were affected by time in 2008 ($p \le 0.001$) due to the one week difference in stocking between treatments. Daily average temperature in the culture ponds ranged from 20.1 to 28.4 °C with minimum and maximum temperatures of 14.4 and 32.2 °C recorded during the culture period (Fig. 3). Pond pH values were alkaline, with treatment averages ranging from 7.5 to 9.5 (Fig. 3). Average dissolved oxygen ranged from 5.9 to 15.2 mg·L⁻¹ (Fig. 3) and only one pond on one date in 2007 dropped below 4.0 mg·L⁻¹. Calculated levels of unionized ammonia were 0.0 to 0.065 mg·L⁻¹ (Fig. 3).

Zooplankton Prey Adequacy (Hypothesis 2)

No effect of larval stocking density on food sizes consumed by larvae, prey size frequency in ponds and larval diets, prey size electivity, and prey taxa electivity was detected (all p>0.15). Data were in each year was pooled for analysis of patterns in hybrid striped bass prey selection. Gape size was different between treatments due to larger fish in low density treatments and growth through time, therefore densities for each year were not pooled for gape limitation analysis.

Larval hybrid striped bass diets varied throughout the culture period during both years. Diets early in culture consisted mainly of cyclopoid nauplii and early copepod instars (Fig. 4). Larvae consumed a wide variety of organisms later in culture including cladocerans, copepods, ostracods, chironomid larvae and pupae, insects, *Chaoborus* larvae, and other larval fish (Fig. 4).

Prior to the 8th day after stocking during 2007, larvae consumed prey items ranging in size from 0.11 to 1.0 mm, consisting of cyclopoid nauplii and early cyclopoid instars that were much smaller than the average gape size (Fig. 5). From day 13 after stocking until harvest, however, the average gape size of all treatments exceeded the average prey item size available or consumed (Fig. 5). Larvae during 2008 consumed prey items between 0.11 and 0.60 mm prior to the 10th day after stocking that were less than or equal to the fishes' maximum gape (Fig. 5). After day 15 in 2008, maximum gape of fish exceeded the maximum prey items available or consumed, but the average consumed prey items consumed did not exceed 0.8 mm in length (Fig. 5).

During 2007, prey sizes consumed by larvae during week 1 were similar to the most abundant sizes of zooplankton available in culture ponds (Fig. 6). Zooplankton less than 0.24 mm in length (i.e. rotifers and calanoid nauplii) were negatively selected for during the entire culture period (Fig. 6). On average, fish were consuming zooplankton prey of 0.25 to 0.49 mm in length , including small cladocerans, and early instar copepodites, which were positively selected for during the first week of culture, then negatively selected until the last week of culture when selection was random (Fig. 6). Larger prey (<0.50 mm), including large cladocerans and adult copepods, were selected by larvae starting during the second week, and preference for these prey became more pronounced later in the season (Fig. 6).

During the first week of 2008, prey sizes consumed by larvae were similar to the size distribution of prey in the ponds (Fig. 6). Zooplankton prey in the 0.25-0.49 mm group were positively selected, while those less than 0.24 mm were neutrally selected (Fig 6). During weeks two and three, larvae consumed a higher proportion of the 0.25-0.49 mm and larger size classes than those size classes represented in the ponds; however, selection was variable for these larger groups (Fig. 6). During week 4 during 2008, individuals selected for larger prey items in higher frequency than was available in the culture ponds, and prey larger than 0.5 mm were positively selected (Fig. 6).

During 2007 and 2008, *Bosmina, Daphnia* spp., calanoid nauplii, and rotifers were selected against despite differences in zooplankton group densities between years (Fig.7). Cyclopoid nauplii were positively selected during the first week during both years despite very low densities (Fig. 7). Cyclopoid nauplii were negatively selected for after day 10 during both years (Fig. 7). Adult copepods were positively selected for throughout the culture period in both years despite a large difference in copepod density between years, (except on day 7 in 2008) (Fig. 7). *Daphnia* spp. were selected against in all treatments during the first half of the culture period and positively selected in the later half during 2007(Fig. 7). Larvae began to select for *Daphnia* spp. after its population increased and continued to do so even after the *Daphnia* spp. population declined (Fig. 7). During

2008, *Daphnia* spp. were selected against or randomly, despite densities being higher than during 2007 (Fig. 7).

No differences were observed between larval stocking densities in terms of the timing of the onset of ontogenetic diet shift during 2007, with some larvae first consuming benthic organisms on the 19^{th} day after stocking (Fig. 4). Throughout the culture period, benthic organisms were found in stomachs of larvae >14 mm SL. During 2008, larvae in low-density ponds underwent an ontogenetic diet shift on day 20 and high-density ponds on day 23 (Fig. 4). Those larvae containing benthic organisms during 2008 were > 10.2 mm in SL. Benthic organisms were observed in zooplankton and fish sampling gear in both years starting at the beginning of the sampling period.

Despite the higher nutrient content of the fill water in the Hebron SFH than that found at the Senecaville SFH, during 2006 the Hebron SFH ponds produced only 0.36 to $6.8 \cdot m^3$, whereas the Senecaville SFH ponds produced 10.1 to $21.9 \cdot m^3$, similar to those observed during 2007(See Table 5) and 2008 (See Table 6). However, zooplankton species composition between ponds and source water were similar at both Hebron and Senecaville (Table 8). Zooplankton biomass and density in the culture ponds were similar to those in their source water lake at Hebron (biomass all p>0.06, density all p>0.32) and at Senecaville (biomass all p>0.29, density all p>0.47) (Fig. 8). Senecaville ponds biomass and density in Senecaville SFH ponds during 2006 were in the same range as ponds during 2007 and 2008 (Fig. 2 and 8). *Bosmina*, daphnids, calanoid nauplii, cyclopoid nauplii, and rotifers densities changed over the culture period (all $p_{das}<0.007$)
in both ponds and source water (Fig. 9). Daphnid concentrations were greater across time in Hebron ponds (all p<0.001) (Fig. 9). Rotifers, calanoid nauplii, and daphnids at Senecaville were not affected by location or time ($p_{den}>0.17$, $p_{das}>0.09$, $p_{inter}>0.22$) (Fig. 9). Cyclopoid nauplii and *Bosmina* increased over time ($p_{das}=0.04$ and .001, $p_{den}=0.32$ and 0.84, both $p_{inter}=0.22$, respectively) and *Bosmina* were in higher densities in Seneca Lake than culture ponds ($p_{loc}=0.002$, $p_{inter}=0.08$) (Fig. 9). Densities of copepods in Hebron source water and ponds was the only group not affected by location or time (all p>.30 K-S). No differences in zooplankton size frequency were observed between ponds and their source waters on any date (all p>0.35 K-S) (Fig. 10). Zooplankton size frequencies were similar (all p>0.08) in culture ponds between 2006, 2007, and 2008 across dates. Source water and culture ponds were dominated by small-bodied zooplankton (>0.5 mm) for the entire culture period (Fig. 10).

Cyclopoid Copepods Predation Mortality (Hypothesis 3)

Concentrations of adult cyclopoid copepods in the ponds averaged $17 \cdot L^{-1}$ in 2007 throughout the culture period, whereas during 2008 the average was $229 \cdot L^{-1}$ (Fig. 11). The highest concentrations of adult female cyclopoids occurring during the early part of the culture season (when fry were likely most vulnerable) ranged from 2 to $9 \cdot L^{-1}$ during 2007 and 10 to $115 \cdot L^{-1}$ during 2008 (Fig. 11). The density of cyclopoid copepods in the source waters of Seneca and Hebron lakes ranged from 1-9 and 2-140 $\cdot L^{-1}$ respectively.

The calculated rates of cyclopoid copepods encountering larval hybrid striped bass in laboratory experiments by Valderrama et al. (2000) and Frimpong and Lochmann (2005) were between $23,000 \times 10^{-7}$ and 580×10^{-7} per second with the highest encounter rates at smaller larval lengths (Fig. 12). Encounter rates at Hebron Lake and culture ponds were much lower, from 5.0×10^{-7} to 2.6×10^{-7} sec ⁻¹, whereas Seneca Lake and ponds rates were 11.6×10^{-7} to 0.994×10^{-7} sec ⁻¹ (equivalent to 0.1 and 0.0086 encounters/day), respectively (Fig. 12).

Discussion

Does increased fish stocking density decrease larval growth and zooplankton availability?

At harvest, the densities I tested (30 -100 larvae·m⁻³) did not affect percent survival or fish yield, in contrast to previous studies in which survival was typically high at low densities (10-20·m⁻³) and yield differed with increasing densities (40-60·m⁻³) (Fox and Flowers 1990; Qin et al. 1994). However, my study did find that growth rate and larval individual weights increased in lower fish densities, possibly due to decreased competition for food and habitat resources. No differences in zooplankton abundance were seen between treatments; however, the ratio of zooplankton prey to larvae in low density treatments would have been double that in low density treatments, allowing for greater fish growth.

Zooplankton populations in this study followed the pattern typically seen in fish culture ponds with an increase in zooplankton during the first weeks of culture and then a quick decline due to the increased predation pressure of the growing fish (Qin 1996; Tew et al. 2006). Fox and Flowers (1990) and Qin et al. (1994) found reductions in preferred zooplankton prey groups with increasing fish densities; however, I observed no decrease in any preferred zooplankton group in relation to stocking density of larvae, only reductions through the culture period. Cushing (1983) found that larvae are likely too dilute $(1-100 \cdot m^{-3})$ to affect their zooplankton prey, which, combined with the incorporation of alternate food resources, could explain the lack of effect of my varying larval densities on the zooplankton population.

Water quality appeared to have no adverse effects on hybrid striped bass survival or growth in this study, as water quality variables did not differ between density treatments, whereas larval growth did. Water quality parameters fell within recommended values for the rearing of larval striped bass and its hybrids for dissolved oxygen, pH, and temperature (Harrell et al. 1990; Kerby 1986; Parker 1984). In addition, unionized ammonia in the ponds (0.002-0.009 mg·L⁻¹ as N) were below lethal levels (0.32-1.01 mg·L⁻¹) for hybrid striped bass (Ludwig et al. 2007; Oppenborn and Goudie 1993; Weirich et al. 1993).

Is zooplankton forage base adequate for first week growth of fry and during later culture?

I found that the zooplankton prey in culture ponds is adequate in prey size, species composition and prey density to support growth of larval hybrid striped bass during the first week of pond culture. However, reduced growth during the last week of culture occurred perhaps due to several factors including: 1) zooplankton prey is insufficient with respect to preferred prey sizes, species and/or densities; 2) dietary ontogenetic shifts to benthic prey; 3) changes in resource allocation; or 4) sampling bias for fish or their prey. Inadequate zooplankton availability was indicated by the decrease in growth of the larvae that coincided with a reduction of preferred prey in the last week of culture. A switch to

benthic prey also occurred concurrent with decreased growth was observed and could be due to insufficient development of the digestive system to adequately assimilate benthic prey. The growth pattern observed could also be explained by a change of resource allocation from weight gain to development of organ systems that occur in fish development. Lastly, the decrease in growth rates in the last weeks of culture could be attributed to equipment sampling bias, since I used hand drawn seines that could have allowed the larger, faster larvae to avoid collection until harvest.

Hybrid striped bass are only gape limited until they reach about two weeks of age. However, even after this point the fish consume much smaller prey on average than is allowed by their gape size, probably due to the high concentrations of *Bosmina* or due to selection of copepods that can be found among the smaller zooplankton in the ponds. Larval striped bass have been found to consume early instar copepodites and small cladocerans until they achieved a size of 10 mm TL at which time they switched to consuming adult copepods, cladocerans, and insect larvae (Humphries and Cumming, 1973). Walleye studies have shown that the smallest walleye (*Sander vitreum*) consume the largest prey that their gape will allow but larger fish consume intermediate sized prey as well (Graham and Sprules 1992). Similar patterns to my hybrid striped bass also have been found in larval white crappies (*Pomoxis annularis*), dace (*Leuciscus leuciscus*), roach (*Rutilus rutilus*), chub (*Leuciscus cephalus*) and European perch (*Perca fluviatilis*) (DeVries et al. 1998; Nunn et al. 2007a). Gape size affected selectivity of consumed zooplankton during the first week after stocking by restricting larvae to consuming zooplankton smaller than 0.5 mm (which mainly consisted of rotifers, nauplii and small copepods). Once larvae achieved larger gapes during the second week, they began to select for larger zooplankton (e.g. Adult copepods, *Daphnia* spp.), as evidenced by increased size electivities for these organisms with their decreasing abundance in the culture ponds. Ghan and Sprules (1993) showed that larval burbot (*Lota lota*) revealed a similar pattern of selecting nauplii and cyclopoid copepods at small gape sizes and then switching to larger *Daphnia* and calanoid copepods. In addition, burbot selected for cyclopoid copepods for a large portion of the larval stage as did the hybrid striped bass in this study. Ghan and Sprules (1993) high electivity for cyclopoid copepods suggests that a behavioral or nutritional benefit of these zooplankters favors their consumption over other larger or more plentiful prey organisms. The change in preferred prey types and sizes also could be due to increased larval swimming speeds and capture capabilities as they develop (Makrakis et al. 2005).

Prey selectivity by larvae in this study was similar to striped bass selectivity in other systems; however, Meshaw (1969) did not demonstrate selection for cyclopoid nauplii during the first week of striped bass diets. This result may be due to the size differences of larvae with striped bass typically being 4-6 mm larger than hybrid striped bass at that point in development. Larvae in this study selected for cyclopoid nauplii when small, which coincided with high fish growth rates. As larvae grew, individuals selected larger prey (adult copepods and daphnids), which likely helped to sustain high fish growth rates

until preferred prey concentrations, similar to patterns seen in other larval fish studies (Mayer and Wahl 1997; Graeb et al. 2004).

Diet patterns in this study were similar to those found for original cross hybrid striped bass, white bass, and striped bass (Geiger et al. 1985; Quist et al. 2002; Woods et al. 1985). The earliest diets examined in this study were from 5 day post-stocking larvae and contained only copepod adults and nauplii but not rotifers as was expected from previous work (Ludwig 1993). I was unable to sample fish closer to stocking and may have missed a period that larvae were consuming rotifers; however, it is possible that rotifers may not be energetically favorable for hybrid striped bass fry when copepod nauplii and early instars are in the same size range and provide more energy. Theilacker and Kimball (1984) found that the rotifer *Brachionus* contains 4.8 calories/mg, whereas copepod nauplii and copepodites contain 5.8 - 6.0 calories/mg, indicating that more energy could be obtained from preying on copepods than on rotifers.

Wu and Culver (1992) found that yellow perch did not consume benthic organisms until the fish were >30 mm and then only after crustacean zooplankton concentrations dropped below $50 \cdot L^{-1}$. Stomach analyses in my study suggest reciprocal hybrid striped bass began consuming benthic organisms and other prey near day 19, when the fish length averaged 14.0 and 21.7 mm TL and zooplankton density was still greater than $150 \cdot L^{-1}$. This result indicates that the hybrid striped bass digestive system may develop earlier and allow larvae to exploit these alternate food resources. However, I observed that fish growth declined around the same time that benthic organisms were being incorporated into fish diets, which suggests either that larvae are not able to consume sufficient benthic prey to continue growth, larvae are unable to extract sufficient energy due to lack of digestive capability, or that my sampling equipment eliminated larger fish from analysis underestimating average fish growth near the end of culture.

My comparison of zooplankton populations between culture ponds and source waters indicates that the littoral areas of source water lakes would provide adequate zooplankton prey for stocked hybrid striped bass. Total larval fish density in littoral areas can be highly variable with total larval fish concentrations (all taxa) 0-286 fish \cdot m⁻³ in reservoirs (Quist et al. 2002; Claramunt et al. 2005) with the median ~10 fish·m⁻³. In a study in a large reservoir, Quist et al. (2002) found white bass larvae to reside mainly in river inlet habitats (1.5m in depth). The Ohio Department of Natural Resources stocks between 0.004 and 0.04 reciprocal hybrid striped bass larvae·m⁻³into reservoirs, which would add little additional burden to the larval and other planktivorous fish in the reservoir for food and space compared to the densities typically seen in culture ponds at harvest for hybrid striped bass (2 to 52 fish \cdot m⁻³). Additionally, reservoirs may provide a more stable zooplankton prey resource. Stahl et al. (1996) stocked fingerlings of saugeye (a sauger/walleye hybrid) into four Ohio reservoirs, and found the reservoirs maintained concentrations of zooplankton during the time when stocking and hybrid striped bass growth would occur, even with increased predation on zooplankton from large densities of gizzard shad. Reservoirs should be able to support growth of larval and juvenile hybrid striped bass since the zooplankton population is likely to be stable, providing preferred prey sizes and species, and also possibly providing presence of other larval fish (e.g., gizzard shad) that could serve as an additional food source for juveniles, as I found to happen in the culture ponds.

Do adult cyclopoid copepods cause fry mortality?

Cyclopoid copepod predation likely did not affect the survival of hybrid striped bass in the culture ponds or the reservoirs because cyclopoids were present at insufficient density. Valderrama et al. (2000) and Frimpong and Lochmann (2005) found high mortality only when the concentration of cyclopoid copepods was over 400 adults $\cdot L^{-1}$. Concentrations of cyclopoid copepods in this study only reached a high of 50 adults $\cdot L^{-1}$ during the first two weeks when the fish are the most vulnerable due to their small size. In addition to the low numbers of cyclopoids, the larval density in the hatchery ponds ranged from 0.033 to 0.066 fish $\cdot L^{-1}$ and 0 to 0.286 fish $\cdot L^{-1}$ in reservoirs and lakes. By contrast the above-mentioned studies used concentrations of 20 larvae $\cdot L^{-1}$. These higher rates of stocking in previously published studies can the higher encounter rates of the cyclopoid copepods preying on fish in relation to my study).

While cyclopoid copepod predation was not a likely cause of mortality in my study, I was unable to quantify other types of predation in the culture ponds or whether damage caused by cyclopoid attacks could lead to mortality. Cyclopoid copepods that have been found attached to larvae from plankton tows are typically found grasping fins and yolk sacs, which if damaged could lead to larval mortality (Smith and Kernehan 1981; Hartig et al. 1982). Cyclopoids have been observed attacking the fins of larval fish, even removing large pieces during an attack (Davis 1959; Fregadolli 2003). Other sources of predation of larval fish could include adult fish, other fish species, cannibalism, and invertebrate predators. I found no evidence of cannibalism in my analysis of reciprocal hybrid striped bass diets involving 1,218 larvae during three study years, suggesting that this is not an important issue for hybrid striped bass rearing.

Conclusions

My study demonstrates that hybrid striped bass stocked in culture ponds at densities between 30 and 100 larvae $\cdot m^{-3}$ do not affect fish yield or survival, but high stocking densities will produce smaller juveniles at harvest than at low stocking densities. My recommendation for fish hatchery managers stocking culture ponds with hybrid striped bass is to stock at fish densities near 100 larvae $\cdot m^{-3}$ if fish size at harvest is less imperative than numbers produced. Diets and growth measurements from my study indicate that cyclopoid nauplii and adult copepods are important to hybrid striped bass larvae, so hatchery managers would want to ensure that these prey items are present in source waters used to fill culture ponds. Additionally, I found that culture ponds and reservoir littoral areas contain similar zooplankton prey at the times of larval and juvenile hybrid striped bass stocking. As such, I recommend that sportfish managers stock either larval or juvenile hybrid striped bass at high densities (since current Ohio stocking rates are unlikely to affect zooplankton) in reservoirs that contain similar zooplankton to those found here. Additional work needs to be performed, however, to verify hybrid striped bass larval growth, survival, and dietary preferences in littoral and pelagic zones of reservoirs are comparable to culture ponds. Future work using culture ponds for studying larval hybrid striped bass survival and growth should also focus on creating stronger comparisons of the water quality, phytoplankton, and zooplankton

concentrations of reservoirs and culture ponds, and determining the effects of even higher densities of larvae to achieve maximum harvest of desired juvenile sizes for stocking.

References

- Bergerhouse, D. L. 1993. Lethal effects of elevated pH and ammonia on early life stages of hybrid striped bass. Journal of Applied Aquaculture **2:** 81-100.
- Chesson, J. 1983. The estimation and analysis of preference and its relation to foraging models. Ecology **64:** 1297-1304.
- Claramunt, R. M., D. E. Shoup and D. H. Wahl. 2005. Comparison of push nets and tow nets for sampling larval fish with implications for assessing littoral habitat utilization. North American Journal of Fisheries Management **25**: 86-92.
- Culver, D. A., M. M. Boucherle, D. J. Bean, and J. W. Fletcher. 1985. Biomass of freshwater crustacean zooplankton from length-weight regressions. Canadian Journal of Fisheries and Aquatic Sciences 42: 1380-1390.
- Culver, D. A., and L. Wu. 1997. Relative importance of predation and competition in the seasonal dynamics of zooplankton: Results from larval fish rearing ponds. Archiv für Hydrobiologie Special Issues: Advances in Limnology 49: 27-35.
- Cushing, D.H. 1983. Are fish larvae too dilute to affect the density of their food organisms? Journal of Plankton Research **5:** 847-854.
- Davis, C.C. 1959. Damage to fish fry by cyclopoid copepods. The Ohio Journal of Science **59:** 101-102.
- Devries, D. R., M. T. Bremigan, and R. A. Stein. 1998. Prey selection by larval fishes as influenced by available zooplankton and gape limitation. Transactions of the American Fisheries Society 127: 1040-1050.
- Dumont, H. J., and G. Balvay. 1979. The dry weight estimate of *Chaoborus flavicans* as a function of length and instars. Hydrobiologia **64:** 139-145.
- Fabian, M.W. 1960. Mortality of freshwater and tropical fish fry by cyclopoid copepods. The Ohio Journal of Science **60:** 268-270.
- Fregadolli, C.H. 2003. Laboratory analysis of predation by cyclopoid copepods on first-feeding larvae of cultured Brazilian fishes. Aquaculture **228**: 123-140.
- Fox, M.G. and D.D. Flowers. 1990. Effect of fish density on growth, survival, and food consumption by juvenile walleyes in rearing ponds. Transactions of the American Fisheries Society 119: 112-121.
- Frimpong, E. A., and S. E. Lochmann. 2005. Mortality of fish larvae exposed to varying concentrations of cyclopoid copepods. North American Journal of Aquaculture 67: 66-71.
- Frimpong, E. A., and S. E. Lochmann. 2006. An evaluation of the effect of treatments for pond water reuse on zooplankton populations. North American Journal of Aquaculture 68: 103-109.
- Fulford, R.S., J.A. Rice, T.J. Miller, F.P. Binkowski, J.M. Dettmers and B. Belonger. 2006. Foraging selectivity by larval yellow perch (*Perca flavescens*): implications

for understanding recruitment in small and large lakes. Canadian Journal of Fisheries and Aquatic Sciences **63**: 28-42.

- Geiger, J. G. 1983. A review of pond zooplankton production and fertilization for the culture of larval and fingerling striped bass. Aquaculture **35:** 353-369.
- Geiger, J. G., C. J. Turner, K. Fitzmayer, and W. C. Nichols. 1985. Feeding habits of larval and fingerling striped bass and zooplankton dynamics in fertilized rearing ponds. Progressive Fish-Culturist 47: 213-223.
- Gerritsen, J. 1980. Adaptive responses to encounter problems. *In* W.C. Kerfoot [ed.], Evolution and Ecology of Zooplankton Communities. University Press of New England.
- Ghan, D., and W. G. Sprules. 1993. Diet, prey selection and growth of larval and juvenile burbot *Lota lota* (L). Journal of Fish Biology **42**: 47-64.
- Graeb, B.D.S., J.M. Dettmers, D.H. Wahl and C.E. Caceres. 2004. Fish size and prey availability affect growth, survival, prey selection, and foraging behavior of larval yellow perch. Transactions of the American Fisheries Society **133**: 504-514
- Graham, D. M., and W. G. Sprules. 1992. Size and species selection of zooplankton by larval and juvenile walleye (*Stizostedion vitreum vitreum*) in Oneida Lake, New York. Canadian Journal of Zoology-Revue Canadienne De Zoologie **70**: 2059-2067.
- Haney, J. F., and Hall, D. J. 1973. Sugar-coated *Daphnia*: a preservation technique for Cladocera. Limnology and Oceanography 18:331-333.
- Harcke, J. E., and H. V. Daniels. 1999. Acute toxicity of ammonia and nitrite to reciprocal cross hybrid striped bass *Morone chrysops* x *M. saxatilis* eggs and larvae. Journal of the World Aquaculture Society **30**: 496-500.
- Harrell, R. M., J. H. Kerby, and R. V. Minton [eds.]. 1990. Culture and propagation of striped bass and its hybrids. Striped Bass Committee Southern Division, American Fisheries Society.
- Hartig, J.H., D.J. Jude and M.S. Evans. 1982. Cyclopoid predation on Lake Michigan fish larvae. Canadian Journal of Fisheries and Aquatic Sciences **39**: 1563-1568.
- Hartig, J. H., and D. J. Jude. 1984. Opportunistic cyclopoid predation on fish larvae. Canadian Journal of Fisheries and Aquatic Sciences **41**: 526-532.
- Helal, H. A., and D. A. Culver. 1991. N:P ratio and plankton production in fish hatchery ponds. Verh. Int. Verein. Limnol. **24:** 1508-1511.
- Hjort, J. 1914. Fluctuations in the great fisheries of northern Europe viewed in the light of biological research. Rapports et Procés-Verbaux des Reunions Conseil International pour l'Exploration de la Mer 20:1-228.
- Hokanson, K.E.F., and G.J. Lien. 1986. Effects of diet on growth and survival of larval walleyes. The Progressive Fish-Culturist **48:** 250-258.
- Huang, W-B., and T-S. Chiu. 1997. Effects of stocking density on survival, growth, size variation, and production of *Tilapia* fry. Aquaculture Research **28**: 165-173.
- Humphries, E. T., and K. B. Cumming. 1973. An evaluation of striped bass fingerling culture. Transactions of the American Fisheries Society **102**: 13-20.
- Johnston, T. A., and R. A. Cunjak. 1999. Dry mass-length relationships for benthic insects: a review with new data from Catamaran Brook, New Brunswick, Canada. Freshwater Biology 41: 653-674.

- Kane, D.D. 2004. The development of a planktonic index of biotic integrity for Lake Erie. PhD dissertation. The Ohio State University, Columbus, Ohio.
- Keast, A. 1980. Food and feeding relationships of young fish in the 1st weeks after the beginning of exogenous feeding in Lake Opinicon, Ontario. Environmental Biology of Fishes 5: 305-314.
- Kerby, J. H. 1986. Striped bass and striped bass hybrids. *In* R. R. Stickney [ed.], Culture of Nonsalmonid Freshwater Fishes. CRC Press.
- Labay, A.A. and T.M. Brandt. Predation of *Cyclops vernalis* on Florida largemouth bass and fountain darter larvae. The Progressive Fish-Culturist **56:** 37-39.
- Li, S. and J.A. Mathias. 1987. The critical period of high mortality of larvae fish-Discussion based on current research. Chinese Journal of Oceanology and Limnology 5: 80-96.
- Ludwig, G. M. 1993. Effects of trichlorofon, fenthion, and diflubenzuron on the zooplankton community and on production of reciprocal-cross hybrid striped bass fry in culture ponds Aquaculture **110**: 301-319.
- Ludwig, G. M. 2002. The effects of increasing organic and inorganic fertilizer on water quality, primary productivity, zooplankton, and sunshine Bass, *Morone chrysops* x *M. saxatilis*, fingerling production. Journal of Applied Aquaculture **12**: 1-29.
- Ludwig, G. M., M. Hobbs, and P. Perschbacher. 2007. Ammonia, pH, and plankton in sunshine bass nursery ponds: the effect of inorganic fertilizer or sodium bicarbonate. North American Journal of Aquaculture **69:** 80-89.
- Ludwig, G.M. and S.E. Lochmann. 2007. Effect of tank stocking density on larval sunshine bass growth and survival to the fingerling stage. North American Journal of Aquaculture **69:** 407-412.
- Ludwig, G. M., N. M. Stone, and C. Collins. 1998. Fertilization of fish fry ponds. Southern Regional Aquaculture Center Publication Number 469.
- Makrakis, M. C., K. Nakatani, A. Bialetzki, P. V. Sanches, G. Baumgartner, and L. C. Gomes. 2005. Ontogenetic shifts in digestive tract morphology and diet of fish larvae of the Itaipu Reservoir, Brazil. Environmental Biology of Fishes 72: 99-107.
- Mark, W., R. Hofer, and W. Wieser. 1987. Diet spectra and resource partitioning in the larvae and juveniles of three species and six cohorts from a subalpine lake. Oecologia **71:** 388-396.
- Mayer, C.M. and D.H. Wahl. 1997. The relationship between prey selectivity and growth and survival in a larval fish. Canadian Journal of Fisheries and Aquatic Sciences **54:** 1504-1512.
- Meshaw, J.C. 1969. A study of feeding selectivity of striped bass fry and fingerlings in relation to zooplankton availability. MS Thesis.
- Morris, J.E., C.C. Kohler, and C.C. Mischke. 1999. Pond culture of hybrid striped bass in the north central region. North Central Regional Aquaculture Fact Sheet Series **#107**.
- Nunn, A. D., J. P. Harvey, and I. G. Cox. 2007a. The food and feeding relationships of larval and 0+year juvenile fishes in lowland rivers and connected waterbodies. I. Ontogenetic shifts and interspecific diet similarity. Journal of Fish Biology 70: 726-742.

- Nunn, A. D., J. P. Harvey, and I. G. Cox. 2007b. The food and feeding relationships of larval and 0+year juvenile fishes in lowland rivers and connected waterbodies. II. Prey selection and the influence of gape. Journal of Fish Biology **70**: 743-757.
- Oppenborn, J. B., and C. A. Goudie. 1993. Acute and sublethal effects of ammonia on striped bass and hybrid striped bass. Journal of the World Aquaculture Society **24:** 90-100.
- Parker, N. C. 1984. Culture requirements for striped bass. *In* J. P. McCraren [ed.], The aquaculture of striped bass: a proceedings. Maryland Sea Grant Publication UM-SG-MAP-84-01.
- Qin, J., D. A. Culver, and N. Yu. 1994. Comparisons of larval walleye and saugeye (walleye X sauger hybrid) growth and impacts on zooplankton in experimental ponds. The Progressive Fish-Culturist **56**: 91-99.
- Qin, J., and D.A. Culver. 1996. Effect of larval fish and nutrient enrichment on plankton dynamics in experimental ponds. Hydrobiologia **321**: 109-118.
- Qin, J. G., S. P. Madon, and D. A. Culver. 1995. Effect of larval walleye (*Stizostedion vitreum*) and fertilization on the plankton community Implications for larval fish culture. Aquaculture 130: 51-65.
- Quist, M. C., C. S. Guy, and R. J. Bernot. 2002. Ecology of larval white bass in a large Kansas reservoir. North American Journal of Fisheries Management **22**: 637-642.
- Rees, R.A., and S.F. Cook. 1983. Evaluation of optimum stocking rate of striped bass x white bass fry in hatchery rearing ponds. Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies **37:** 257-266.
- Secor, D. H., J. M. Dean, and J. Hansberger. 1992. Modification of the Quatrefoil light trap for use in hatchery ponds. The Progressive Fish-Culturist **54**: 202-205.
- Smith, R., and R. Kernehan. 1981. Predation by the free-living copepod, *Cyclops bicuspidatus thomasi*, on larvae of the striped bass and white perch. Estuaries 4: 81-83.
- Stahl, T.P., G.P. Thiede, R.A. Stein, E.M. Lewis, M.R. Austin, and D.A. Culver. 1996. Factors affecting survival of age-0 saugeye *Stizostedion vitreum X S. canadense* stocked in Ohio reservoirs. North American Journal of Fisheries Management 16: 378-387.
- Tew, K. S., J. D. Conroy, and D. A. Culver. 2006. Effects of lowered inorganic phosphorus fertilization rates on pond production of percid fingerlings. Aquaculture 255: 436-446.
- Theilacker, G.H., and A.S. Kimball. 1984. Comparative quality of rotifers and copepods as foods for larval fishes. California Cooperative Oceanic Fisheries Investigations Report **25**: 80-86.
- Trauben, B. K. 1991. Potential competition among young-of-year fish in Western Lake Erie. PhD dissertation. The Ohio State University, Columbus, Ohio.
- Valderrama, D., S. E. Lochmann, and M. Jackson. 2000. Predation of cyclopoid copepods on sunshine bass fry. North American Journal of Aquaculture 62: 144-148.
- Weirich, C. R., J. R. Tomasso, and T. I. J. Smith. 1993. Toxicity of ammonia and nitrite to sunshine bass in selected environments. Journal of Aquatic Animal Health 5: 64-72.

- Whiteside, M. C., W. L. Doolittle, and C. M. Swindoll. 1985. Zooplankton as food resources for larval fish. Verhandlungen der Internationale Vereinigug fur Theoretische und Angewandte Limnologie 22.
- Williamson, C.E. and J.J. Gilbert. 1980. Variation among zooplankton predators: The potential of Asplanchna, Mesocyclops, and Cyclops to attack, capture and eat various rotifer prey. In W.C. Kerfoot [ed.], Evolution and Ecology of Zooplankton Communities. University Press of New England.
- Woods, L. C., J. C. Lockwood, J. H. Kerby, and M. T. Huish. 1985. Feeding ecology of hybrid striped bass in culture ponds. Journal of World Mariculture Society 16: 71-81.
- Wootton, R.J. ed. 1998. Ecology of teleost fishes, 2nd edition. Kluwer Academic Publishers.
- Wu, L., and D.A. Culver. 1992. Ontogenetic diet shift in Lake Erie age-0 yellow perch (*Perca flavescens*): A size-related response to zooplankton density. Canadian Journal of Fisheries and Aquatic Sciences 49: 1932-1937.

Appendix A. Tables and Figures

	Day 5	Day 8	Day 15	Day 19	Day 22	Day 26	Day 34
High-density	4†	10†	10	20	10	21	10
High- density	3†	10†	10	20	10	20	10
Low-density	5†	10†	10	16	8	14	10
Low-density	4†	10†	10	11	10	12	10

Table 1. Numbers of hybrid striped bass specimens at Senecaville State Fish Hatchery used to calculate growth, measure individual weights, and analyze fish diets during 2007. † indicates all fish were caught using light trap, all others include fish caught with light trap and seine.

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	Day 8	Day 10	Day 14	Day 17	Day 21	Day 24	Day 28	Day 31	Day 36
High-density	3†	10†	3†	10	10	14	20	10	*
High-density	6†	10†	8†	20	13	15	20	10	*
Low-density	*	10†	*	10	11	21	10	15	10
Low-density	3†	10†	*	14	12	22	10	9	10
Low-density	9†	*	*	20	20	10	10	5	10
Low-density	4†	*	*	13	10	11	10	10	10

Table 2. Numbers of hybrid striped bass specimens at Senecaville State Fish Hatchery used to calculate growth, measure individual weights, and analyze fish diets during 2007. * denotes no fish collected. † indicates all fish were caught using light trap, all others include fish caught with light trap and seine.

Lentic	Epibenthic	Benthic	Other
Bosmina	Alona	Chironomid	Terrestrial adult
		larvae	insects
Ceriodaphnia	Chydorus	Chironomid	Chaoborus spp.
		pupae	larvae
Daphnia ambigua	Scapholebris	Ostracods	Larval fish
D. galeata	Simocephalus		
D. lumholtzi	Moina		
D. parvula			
Diaphanasoma			
Acanthocyclops vernalis			
Diacyclops thomasi			
Leptodiaptomus minutus			
L. siciloides			
Mesocyclops edax			
Skistodiaptomus oregonensis			
Tropocyclops prasinus			
mexicanus			
Calanoid nauplii			
Cyclopoid nauplii			
Asplanchna			
Brachionus			
Keratella			
Polyarthra			
Other rotifers			
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Table 3. Designation of prey taxa found in larval hybrid striped bass diets during 2007 and 2008 at Senecaville State Fish Hatchery.

	< 0.25 mm	0.25-0.49	0.50-0.74	0.75-1.0	>1.0
	group	mm group	mm group	mm group	mm
					group
Rotifers	Х	Х			
Cyclopoid nauplii	Х				
Calanoid nauplii	Х	Х			
Bosmina	Х	Х			
Copepods		X	X	X	Х
Daphnia spp.		Х	Х	Х	Х

Table 4. Size ranges of zooplankton taxa found in ponds and larval hybrid striped bass diets during 2006, 2007, and 2008 at Hebron and Senecaville State Fish Hatcheries.

	Stocking density (#/m ³)	Harvest density (#/m ³)	Yield (g/m ³)	Average Individual Fish Weight (g)	Percent Survival
High-density pond #1	66	32	6.14	0.18 ± 0.03	48
High-density pond #2	69	27	4.47	0.16 ± 0.01	40
Low-density pond #1	28	11	6.03	0.56 ± 0.03	39
Low-density pond #2	33	19	6.73	0.31 ± 0.03	58

Table 5. A comparison of reciprocal hybrid striped bass yield, weight and percent survival in high and low-density ponds at harvest during 2007 at Senecaville State Fish Hatchery. (For individual fish weights n=10).

	Stocking density (#/m ³)	Harvest density (#/m ³)	Yield (g/m ³)	Average Individual Fish Weight (g)	Percent Survival
High-density pond #1	98	14	4.21	$\begin{array}{c} 0.42 \pm 0.02 \\ (0.45 \pm 0.02) \end{array}$	14
High-density pond #2	98	23	5.22	$\begin{array}{c} 0.17 \pm 0.01 \\ (0.23 \pm 0.01) \end{array}$	24
Low-density pond #1	50	4	2.73	0.61 ± 0.03	8
Low-density pond #2	50	8	6.50	0.70 ± 0.06	14
Low-density pond #3	49	5	4.65	1.01 ± 0.17	11
Low-density pond #4	48	5	4.41	0.88 ± 0.04	11

Table 6. A comparison of reciprocal hybrid striped bass yield, weight and percent survival in high and low-density ponds at harvest during 2008 at Senecaville State Fish Hatchery. (For individual fish weights n=10). Weights in parentheses are corrected for harvest date using growth rate from day 30.

	Temperat	ure	Dissolved	O ₂	pН		Free amm	ionia
2007	p-value	F-value	p-value	F-value	p-value	F-value	p-value	F-value
Density	0.81	0.05	0.518	0.44	0.49	0.50	0.9	.015
Day after Stocking	0.24	1.5	0.51	0.45	0.89	0.02	0.13	2.6
Interaction	0.90	0.01	0.33	1.02	0.39	0.77	0.96	0.002
2008								
Density	0.60	0.27	0.34	0.92	0.09	2.9	0.36	0.86
Day after Stocking	0.000	94	0.000	22	0.000	29.9	0.001	7.6
Interaction	0.37	0.81	0.17	1.9	0.53	0.38	0.12	2.5

Table 7. Results of statistical analysis (from mixed linear model) showing no effect of treatment on four water quality variables measured in culture ponds at Senecaville State Fish Hatchery during 2007 and 2008.

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	Hebron	Hebron	Seneca	Senecavi
	Lake	ponds	Lake	lle ponds
Cladocerans				
Alona	Х	Х	Х	X
Bosmina	Х	Х	Х	Х
Ceriodaphnia	Х	Х	Х	Х
Chydorus	Х	Х	Х	Х
Daphnia ambigua			Х	Х
D. galeata	Х	Х	Х	Х
D. lumholtzi				Х
D. parvula	Х	Х		
Diaphanasoma	Х	Х	Х	
Scapholebris		Х		
Simocephalus		Х		
Copepods				
Acanthocyclops vernalis	Х	Х	Х	Х
Diacyclops thomasi	Х	Х	Х	Х
Leptodiaptomus minutus	Х	Х	Х	Х
L. siciloides	Х	Х		
Mesocyclops edax	Х	Х		
Skistodiaptomus oregonensis	Х	Х	Х	Х
Tropocyclops prasinus mexicanus	Х	Х	Х	Х
Calanoid nauplii	Х	Х	Х	Х
Cyclopoid nauplii	Х	Х	Х	Х
Rotifers				
Asplanchna	Х	Х	Х	Х
Brachionus	Х	Х	Х	Х
Keratella	Х	Х	Х	Х
Polyarthra		Х		
Other rotifers	Х	Х	Х	Х

Table 8. Comparison of zooplankton species composition at Hebron and Seneca lakes and their corresponding culture ponds during 2006. X denotes presence of taxon in at least one sample on at least one date.

Figure 1. Comparison of seasonal variation in percent weight gain per day (left panels) and individual weights (right panels) of hybrid striped bass larvae in the high and low stocking density treatments at the Senecaville State Fish Hatchery during 2007 and 2008. Key for percent weight change: High-density (grey), Low-density (hashed). Error bars denote standard error. Key for individual fish weights: Low-density (triangles, dashed regression line), High-density (open circles, solid regression line).



Figure 1

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Figure 2. Comparison of the seasonal variation in mean biomass and density of crustacean zooplankton in the high- and low-stocking hybrid striped bass density treatments for 2007 and 2008 at the Senecaville State Fish Hatchery (low-density = solid with open circles; high-density = dashed with closed circles). Error bars denote standard error.

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Figure 3. Comparison of four water quality parameters in hybrid striped bass ponds in high- and low-stocking density treatments (shown as means with standard error) as a function of days after stocking at Senecaville State Fish Hatchery during 2007 and 2008. Key: low-density = open circles, high-density = solid circles.

Figure 4. Weekly variation in the percentage (by biomass) of average larval hybrid striped bass diets in the low-density (LD) and high-density (HD) treatments during 2007 (left panels) and 2008 (right panels) at Senecaville State Fish Hatchery. Key: cladocerans (grey), copepods (grey dotted), insects (slashed), ostracods (white) and miscellaneous (black). The date of the observed ontogenetic diet shifts to benthic organisms (ostracods, chironomid larvae and pupae) is indicated by arrows determined by the first day benthos was found in a fish diet.





Figure 5. Weekly variation in the mean zooplankton size consumed by larval hybrid striped bass (solid line with triangles) in relation to mouth size in treatments (high-density = solid circles, low-density = open diamonds, with standard error) for 2007 and 2008 at Senecaville State Fish Hatchery. Dotted lines with triangles signify the smallest and largest prey items consumed. Dashed line with solid diamonds represents the largest zooplankters sampled by zooplankton tow on the same dates.



Figure 6. Weekly variation in length-frequency distributions of zooplankton (left panels) from the Senecaville State Fish Hatchery ponds (2007-dark gray, 2008-light gray) and in fish diets (2007-dark grey hashed, 2008-light gray hashed) for 2007 and 2008. Weekly variation of size electivity (Chesson's ε) in larval hybrid striped bass diets (right panels) during 2007 (diagonally slashed) and 2008 (horizontally slashed) at Senecaville State Fish Hatchery.



Figure 7. Weekly variation in zooplankton density (left panels) and electivity (Chesson's ε , right panels) of larval hybrid striped bass during 2007 (solid circles) and 2008 (open circles) at Senecaville State Fish Hatchery for six zooplankton taxa: *Bosmina, Daphnia* spp., calanoid and cyclopoid nauplii, all adult copepods, and rotifers. Error bars denote standard error.



Figure 7 continued



Figure 8. Weekly variation in total mean crustacean zooplankton density and biomass in the Hebron State Fish Hatchery ponds (closed circles) with those in Buckeye Lake (open circles), and those in the Senecaville State Fish Hatchery ponds (closed triangles) with those in Seneca Lake (open triangles) during 2006. Error bars denote standard error. Solid arrows indicate date of larval hybrid striped bass stocking in ponds. Dashed arrows indicate start of juvenile hybrid striped bass harvest in ponds.

Figure 9. Weekly variation of the density of six zooplankton groups in culture ponds and their source waters at Hebron and Senecaville State Fish hatcheries during 2006. Key: rotifers (grey), cyclopoid nauplii (black), calanoid nauplii (grey with black dots), *Bosmina* (white with black dots), copepods (grey with black dashes), and daphnids (black with white dots).






Figure 10. Comparison of the seasonal variation in zooplankton length distribution between the source water reservoirs (black) and the culture ponds (gray) in samples from Hebron (left panels) and Senecaville (right panels) State Fish Hatcheries during 2006.



Figure 11. Weekly variation in adult cyclopoid (potentially capable of injuring or killing hybrid striped bass fry) for the high- and low-stocking density ponds and Seneca Lake: (low-density 2007 = dashed with squares, high-density 2007 = solid with squares, low-density 2008 = dashed with stars, high-density 2007 = solid with stars, lake = dotted with diamonds which is indistinguishable from other low densities). Error bars denote standard error.



Figure 12. Calculated adult cyclopoid encounter rates with hybrid striped bass larvae for Hebron and Seneca lakes and culture ponds (during 2006, 2007 and 2008) and the studies of Valderrama, et al. (2000) and Frimpong and Lochmann (2005). Key: dashed line with diamonds = previous studies, closed circles = Seneca Lake 2006, open circles = Hebron Lake 2006, closed triangles = 30 larvae/m³ Senecaville ponds 2007, open triangles = 60 larvae/m³ Senecaville ponds 2007, closed squares = 60 larvae/m³ Senecaville ponds 2008, and open squares = 100 larvae/m³ Senecaville ponds 2008.