ZOOPLANKTON RESPONSE TO ASIAN CARP HARVESTING IN ILLINOIS RIVER BACKWATERS: A NATURAL EXPERIMENT

BY

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THESIS

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ABSTRACT

Since the 1980's, Asian carp (*Hypophthalmichthys nobilis* and *Hypophthalmichthys molitrix*) have spread throughout the Mississippi River basin and are now approaching Lake Michigan and the Great Lakes. This poses a problem because Asian carp can have major negative impacts on the zooplankton that support much of the ecosystem. Since Asian carp have invaded the Illinois River, both main channel zooplankton abundance and planktivore body condition have decreased. In an effort to reduce the likelihood of an Asian carp invasion into the Great Lakes, commercial fishing crews are being used to reduce the Asian carp population in the Illinois River. The goal of this project, known as the Barrier Defense Asian carp Removal project, is to reduce the abundance of Asian carp near the barrier at the Brandon Road lock and dam. Zooplankton have recovered from declining planktivory in other aquatic systems: the hope is that the harvesting will reduce the Asian carp's ecosystem impact on this river as well. The Illinois River response was assessed by comparing the densities of rotifers, nauplii, copepods, and cladocerans in ten backwaters receiving three levels of harvest in late summer of 2015. Analysis indicates that both harvest level and month affect zooplankton, but that there was no interaction. Rotifer densities increased at low (951 kg/km^2 $month^{-1}$) and high (8229 kg/km^2 $month^{-1}$) harvest levels while nauplii, copepods, and cladocerans did not. Cladoceran density decreased from September to October, which may be related to a seasonal succession. In summary, while the zooplankton with the fastest generation time showed a positive response to Asian carp harvest, the current harvesting levels might not be enough for slower growing nauplii, copepods, and cladocerans to respond. The implication of this research is that continuing and even increasing harvest pressure in the future may lead to a stronger general zooplankton response.

ACKNOWLEGEMENTS

I would like to dedicate this research to my parents that supported me to further my education in the natural sciences. This research would not be possible without my advisor, Dr. Andy Casper, for all his hard work and patience. I would also like to thank my committee members Dr. Cory Suski and Dr. John Chick for their input and advice on writing and statistics.

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INTRODUCTION

Aquatic invasive species (AIS) can have profound negative impacts on an aquatic ecosystem (Wells, 1970; Johnson & Goettl Jr., 1999). Due to human introductions of AIS and modifications to waterways, AIS can escape and spread into unintended locations (U.S. Army Corps of Engineers, 2014). One AIS, Asian carp (bighead carp, *Hypophthalmichthys nobilis* and silver carp, *Hypophthalmichthys molitrix*), have increased exponentially in the Illinois River since 2000 (Chick & Pegg, 2001; Irons et al., 2010). This invasion has been associated with simultaneous declines in zooplankton abundance and biomass, and decreasing body condition of native planktivores (Irons et al., 2007; Sass et al., 2014). Due to their potential to spread and disrupt the aquatic ecosystem, Asian carp represent a significant threat to the productivity of many aquatic ecosystems (Kolar et al., 2005).

There is some evidence that management and control efforts, especially commercial harvest, may limit the spread and impacts of invasive fish (Hoffman et al. 2004, Vredenburg 2004). Because of this, a program to reduce Asian carp in the Illinois River using commercial fishing was instituted in 2010 (ACRCC, 2015; Tsehaye et al., 2013; Seibert et al., 2015). Although the Asian carp population may be reduced in the short term from harvesting (MacNamara et al., 2016), it is still not known how much harvest is needed to generate a positive ecosystem response for the native assemblage including zooplankton (Garvey et al., 2014).

Due to their inverse relationship with AIS planktivory (Brooks & Dodson, 1965), zooplankton populations can be resilient to disturbance (Keller et al., 1998). A number of studies suggest that zooplankton populations can recover to a predisturbance state after AIS dieoffs (Wells, 1970; Pace et al., 2010), after fish reductions in formerly fishless lakes (Donald et al., 2001; Knapp et al., 2001), and from trophic cascades resulting from biomanipulations (Mittelbach et al., 1995). However this type of zooplankton resiliency has seldom been documented following an invasion of a river (though see Pace et al., 2010).

The goal of this natural experiment was to determine whether or not harvesting of Asian carp could lead to a recovery of zooplankton abundances. For three months, zooplankton densities were compared among ten backwaters that received various levels of Asian carp harvesting. The hypotheses I was interested in were: 1) whether there would be greater densities of zooplankton in backwaters with higher levels of harvest; 2) whether the zooplankton taxa response would differ among rotifers (smaller sized with a faster generation time) compared to nauplii, copepods, and cladocerans (larger sized with slower generation times); and 3) whether zooplankton response would be affected by the interaction of harvest and month.

METHODS

LOCATION

The Illinois River, a tributary of the Mississippi River, was artificially connected to Lake Michigan by the construction of the Chicago Area Waterway System (CAWS) in 1900 (Delong, 2005). The CAWS connection has become an important potential AIS dispersal vector for at least 35 species of concern, including Asian carp (U.S. Army Corps of Engineers, 2014). Without any controls or effective management options to keep the Asian carp population in check, there is a strong potential for damage to occur in other connected waterbodies such as the Great Lakes.

The backwaters used in this study, which were either flooded quarries or marinas, were all connected to the main stem of the upper portion of the Illinois River. The ten backwaters in increasing river km (between river km 375.3 and 453.8, with surface area km^2) are: Starved Rock Marina (0.05 km^2), Starved Rock Yacht Club (0.07 km^2), Sheehan Island (0.16 km^2), Abandoned Marina (0.04 km^2), Heritage Harbor (0.13 km^2), Hiddencove Marina (0.06 km^2), Boondocks Harbor (0.02 km^2), Hanson Quarry Pit (1.84 km^2), Peacock Slough (0.24 km^2), and RockRun Rookery (0.33 km^2) (Figure 1). Surface areas were measured from aerial photographs (Google Inc., 2017).

FIELD SAMPLING

For each month (August, September, and October), twenty points were randomly dispersed in each backwater to ensure ten accessible sites would be available. Using ArcGIS 10.3, each backwater was delineated from the National Hydrography Dataset layer, or manually delineated if not found in the NHD layer (ESRI, 2015; U.S. Geological Survey, 2015). If a point fell in a location that was too shallow or otherwise inaccessible, the next available point was sampled instead. Basic limnological variables were collected using both an accumet™AP 115 portable pH meter kit (Fisher Scientific, Pittsburgh, PA) and an EXO2 multiparameter sonde without depth (YSI, Inc. Yellow Springs, OH). The limnological parameters used to assess the comparability of the backwaters included: water temperature (Celsius), specific conductivity (μs/cm), dissolved oxygen (mg/L), turbidity (NTU), fluorescent dissolved organic matter (ppb), chlorophyll a (μg/L), and nitrate ($N0_3$-N mg/L). The depth (m) of each site was measured from a GPSMAP® 441s at the stern of the boat (Garmin, Olathe, KS). Secchi depth (cm) was obtained by averaging the lowered and raised depth of the secchi disk. In order to have a representative limnological variable for each backwater-month replicate, each limnological variable was represented as the average of the ten sites.

In addition to the limnological variables, two vertically integrated zooplankton samples were collected at five of the ten sites within each backwater. For each zooplankton sample, a 2.5 inch diameter hose connected to a diaphragm pump was raised and lowered through the water column (Chick et al., 2010; Sass et al., 2014). A 55 μm sample, used for enumerating copepods and cladocerans, was obtained by pumping 30 L of water through a 55 μm mesh; and a 20 μm sample, used for enumerating rotifers and nauplii, was obtained by pumping 10 L of water through a 20 μm mesh (Chick et al., 2010). Both types of samples were preserved in the field with a 12% sugar-buffered formalin solution and had Rose Bengal stain added after returning to the laboratory.

HARVEST

The Illinois Department of Natural Resources (IDNR) implemented an annual harvesting program in 2010, known as the Barrier Defense Asian carp Removal project, to control Asian carp (Garvey et al., 2014; ACRCC 2015). The goal of this program is to reduce the Asian carp density near the barrier at the Brandon Road lock and dam; thus also reducing the likelihood of Asian carp from entering Lake Michigan. The commercial harvesting usually occurred at least two weeks each month in backwaters of the upper portion of the Illinois River (Figure 1). While the program has expanded over time, in 2015 it involved the use of ten commercial fishing crews between March and December. However, a late spring flood in 2015 limited the harvesting during July. The commercial fisherman customized the gear to some extent, but it primarily consisted of large mesh (76.2-127 mm) trammel and gill nets. These nets were either set for 20-30 minutes with fish being driven into the nets with noise, or set overnight without driving fish. To augment the trammel and gill net sets, commercial seines (0.27 to 0.73 km long) were occasionally used. For each harvest event (defined as a date-backwater combination), counts of all Asian carp captured were recorded and a representative sub-sample of 30 individuals of each species, bighead carp and silver carp, was weighed (in grams) to provide an estimate of the average mass of each species of Asian carp (T. Widloe, IDNR, personal communication). Finally, all Asian carp capture were processed for non-human consumptive products such as liquid fertilizer.

The total mass of Asian carp removed at each backwater harvest event was calculated by multiplying the total number of fish removed by the estimated mass of both species. The harvest total for each month was calculated as the total mass removed from an individual backwater during the 26 to 28 days prior to zooplankton sampling. Due to the wide range of surface area across the ten backwaters (0.02-1.84 km^2), each backwater total monthly mass was divided by the backwater surface area to create a proportional harvest variable (Asian carp kg km^{-2} $month^{-1}$). Then, I classified the backwaters into either no, low, or high harvest level categories in order to have approximately the same number of replicate backwaters in each category (Figure 2). The no harvest level backwaters were: Starved Rock Marina, Starved Rock Yacht Club, Hiddencove Marina, and Boondocks Marina. The low harvest level backwaters were: Abandoned Marina, Heritage Harbor, and RockRun Rookery. The high harvest level backwaters were: Sheehan Island, Hanson Quarry Pit, and Peacock Slough.

LABORATORY ANALYSIS

For microscopic examination and enumeration, the 55 μm samples were concentrated to a 50 mL standardized volume and homogenized. Next, a 5 mL subsample was transferred to a counting wheel using a Hensen-Stemple pipette (Garvey et al., 2015). Repeated subsamples were taken this way until a minimum count of 200 copepods and cladocerans was met; this equated to a subsampled volume between 60% and 100% of the entire sample. The 20 μm samples were concentrated to a volume between 10mL and 50mL. Next, a homogenized 1 mL subsample was transferred with a pipette to a gridded Sedgewick-Rafter counting cell for counting. Repeated subsamples were taken until a minimum count of 400 rotifers was met. This equated to a subsampled volume between 2% and 20% of the entire sample. Mean density for each of the 4 taxa was reported as the number of individuals per liter from 5 replicates per backwater per month. Enumeration of copepods and cladocerans from the 55 μm samples was done under a

Leica S8 APO dissecting scope (80x magnification) with a Leica DMC 2900 camera; or under a Leica S8 APO dissecting scope (80x magnification) with a Leica DFC295 camera (Leica Microsystems, 2017). The rotifer and nauplli samples were enumerated under a Leica DM750 compound scope (200x magnification) with a Leica ICC50HD camera. Digital images were taken with Leica Application Suite 4.5 (Leica Microsystems, 2017) to verify any distorted or otherwise questionable individuals.

STATISTICAL ANALYSIS

Separate 2-factor ANOVAs for each zooplankton taxa (rotifer, nauplii, copepod, and cladoceran) were tested for differences in zooplankton density (number of individuals per liter) due to harvest level (no, low, and high harvest), month (August, September, October), or the interaction of harvest level and month. Statistical analyses were completed using PROC GLM from SAS© software version 9.4 (SAS Institute Inc., Cary, NC). The limnological parameters were compared to determine if there were any anomalous differences that might have affected the zooplankton densities independent of harvest or month. Each ANOVA model was initially run with both factors and an interaction. If the ANOVA model was not significant with an interaction included, the ANOVA model was retested without an interaction (see appendix A). Normality was assessed using the Shapiro-Wilk test and from visual inspection of the plotted residuals. Homogeneity of variance was tested with Levene's test and from visual inspection of the plotted residuals. To better conform to the assumption of normality and homogeneity, our initial results suggested a $\log_{10}(X+0.001)$ transformation be applied to all zooplankton density data. Significance was set at alpha=0.05. If an ANOVA model was significant, a Tukey-Kramer method was used to determine which of the harvest means differed while a Tukey HSD was used to determine which of the month means differed (Kramer, 1956).

RESULTS

LIMNOLOGICAL VARIABLES

Table 1 shows that there were some statistically significant differences among the limnological variables across the harvest levels and months: pH ($p<0.01$), specific conductivity ($p<0.01$), and nitrate ($p<0.01$). However, while these were statistically significant, examination of the data suggests that they are not biologically significant. Depth was different between the harvest levels with the non-harvested backwaters being about a meter shallower than the other harvest levels ($p=0.01$). In practical terms if a backwater was too shallow, fisherman were not able to set nets for harvesting. Surface water temperature was different among the months ($p<0.01$) with October being the coldest. The variables that were not significant among months or harvests were dissolved oxygen ($P=0.67$), fluorescent dissolved organic matter ($P=0.11$), and secchi depth ($p=0.07$). Although the overall ANOVA models for turbidity ($p=0.03$) and chlorophyll a ($p=0.04$) were significant, the analysis either lacked the power to assign significance to a factor or an unmeasured factor may have been responsible. This was the situation for both turbidity ($p_{month}=0.06$ and $p_{harvest}=0.05$) and chlorophyll a ($p_{month}=0.07$ and $p_{harvest}=0.07$).

HARVEST

The mean monthly Asian carp harvest was 0 kg/km^2 in the no harvest level, 951 kg/km^2 in the low harvest level, and 8229 kg/km^2 in the high harvest level (Figure 2).

ZOOPLANKTON

Overall, the most abundant taxa were rotifers, followed by nauplii, copepods, and cladocerans (Figure 3). Of the four taxa, I found that rotifers were the only taxa to have a significant ANOVA model with a statistically significant interaction of month and harvest ($p=0.0078$, Table 3). Cladocerans also produced a statistically significant ANOVA model ($p=0.0084$), but the interaction was not significant and therefore dropped from the analysis (Table 3). This procedure allowed us to see that cladoceran density was lower in October than in either August or September (Table 3). I found no significant differences among harvest or month for either nauplii or adult copepods ($p>0.05$, Table 3).

DISCUSSION

Asian carp are obligate planktivores whose rapidly increasing population in the Mississippi River system are closely linked to declines in zooplankton density and native planktivore condition (Irons et al., 2007; Sampson et al., 2009; Sass et al., 2014). Because of the threat this poses to the ecosystem diversity and function, there have been recent efforts to limit the further spread of this invasive fish while also reducing the established populations through commercial harvest (ACRCC, 2015). While evidence shows that the Asian carp abundance can be effectively reduced (MacNamara et al., 2016), it is not yet clear whether the rest of the river assemblage can recover. The results of my initial assessment of an ecosystem response show that the Asian carp removals of at least 951 kg/km^2 $month^{-1}$ led to a positive response in rotifer density. In contrast, the larger macrozooplankton like copepods and cladocerans were not responsive even at a nearly tenfold greater harvest level of 8229 kg/km^2 $month^{-1}$. While these results support the use of harvest, they also suggest that higher levels may be needed to benefit all types of zooplankton.

The results from this study suggest that the harvest levels applied were not sufficient for all zooplankton taxa to respond. However, the harvest levels in this study may have reduced Asian carp planktivory low enough for rotifers to respond (Pace et al., 2010). Following a dieoff of zebra mussels (*Dreissena polymorpha*) in the Hudson River, rotifer and nauplii densities recovered to those found before the zebra mussel invasion (Pace et al., 2010). However, the relationship between zebra mussel density and zooplankton recovery did not appear to be linear; it wasn't until the zebra mussel abundance declined below a threshold level that the filtration rate was low enough for zooplankton to respond. If this non-linear effect of planktivory also holds true for Asian carp in the Illinois River, the macrozooplankton (nauplii, copedpods, and cladocerans) may not respond until the harvest reaches a higher level than in my study. This lack of a macrozooplankton response agrees with a prior study of main channel zooplankton response to the implementation of the harvest program (Garvey et al., 2014). However, this lack of a response may be due to the fact that the catch per unit effort between 2010 and 2014 was lower than in 2015 (ACRCC, 2015). Based on these other studies and my results, Asian carp harvesting may need to be greater than 8229 kg/km^2 $month^{-1}$ for all zooplankton taxa to respond.

The zooplankton taxa responses assessed to harvesting may reflect differences in their life histories such as reproductive capacity, or from their biotic interactions with planktivores. Rotifers are consistently the most abundant taxa in the Illinois River (Sampson et al., 2009; Sass et al., 2014) and generally have the fastest reproductive rates (Allan, 1976). Because rotifers make up the majority of Asian carp diet, they should be one of the first organisms to benefit from a reduction of Asian carp (Sampson et al., 2009). While my results support this Sampson et al., (2009) hypothesis, they contradict two earlier studies on the Illinois River. The first study, by Sass et al., (2014), demonstrated that an increase in main channel rotifer densities was concurrent with high Asian carp densities. The second study found no zooplankton response attributed to two consecutive high harvest events in a backwater (ACRCC, 2015). The lack of congruence of these two earlier studies with my results may be due in part to the differences in methodology; the previous two studies may have underestimated the rotifer density by not using a small enough mesh size (20 μm) to accurately sample rotifers (Chick et al., 2010). In addition, because the Sass et al. (2014) study sampled primarily in the main channel, there may have been a different zooplankton community and lower abundance sampled compared to backwaters (Dettmers et al. 2001). Hence, I can conclude that due to the macrozooplankton's relatively low density and slower reproductive rates, a greater reduction of Asian carp planktivory for a longer period of time may be needed before macrozooplankton populations can increase.

Because zooplankton assemblage structure and density can be seasonal, there was some question as to whether a response could be measured year round, or whether it might be limited to certain months. In the three months of my study, I found that cladocerans were the only taxa of the four to exhibit a decline in abundance between August and October, concurrent with the seasonal decrease in temperatures. Cladoceran declines starting in late summer have been documented in backwaters of the Upper Mississippi River (Burdis & Hoxmeier, 2011) and Lower Illinois River (Wahl et al., 2008). Statistically, the lack of an interaction between the harvest and month terms suggests that the effects are independent of each other. I can conclude that the removals of Asian carp may not be strongly reflected in cladoceran abundances, at least not later in the year. In contrast, month was not an important explanatory variable for rotifers, nauplii, or copepods, meaning that harvest may allow these taxa to respond independent of month.

There are a variety of reasons for the lack of a cumulative increase in zooplankton densities over time in the harvested backwaters. These include, because a river is an open system, high immigration rates of planktivorous fish back into the backwaters between removal events, and that macrozooplankton reproduction could not respond in just a month. In a prior study looking at the weekly zooplankton response to two high harvest events, the zooplankton densities could not be attributed as a response to the harvesting (ACRCC, 2015). This suggests that zooplankton may not be able to respond within even a few days after a large harvest event. However, the harvesting procedure is designed to allow adequate time (harvesting every other week) for Asian carp to repopulate a specific location in order to allow for repeated harvesting

(ACRCC, 2015; MacNamara et al., 2016). This practical consideration limits the interpretation of my data because Asian carp can immigrate back into the recently harvested backwaters at an uncontrolled rate. In addition, zooplankton sampling on a weekly basis in the ACRCC (2015) study, or even at the 26-28 day span in my study, may not allow enough time for the macrozooplankton population to respond due to their longer reproductive rates (Allan 1976). If there is a strong desire to conduct a more accurate assessment of the zooplankton response to removal, then I recommend that future studies sample at shorter time intervals and if possible, limit Asian carp immigration.

With the constant potential for Asian carp numbers to breach the electric barrier near Lake Michigan, continued commercial harvesting may be a necessary preventative measure to reduce the risk of an invasion into the Great Lakes (U.S. Army Corps of Engineers, 2014). The results of this study suggest that the current harvesting levels will allow rotifers to recover but are not great enough for macrozooplankton. Therefore, in order to promote a fuller ecosystem recovery, I recommend an additional increase in the harvest rates of Asian carp.

FIGURES AND TABLES

Figure 1. Map of upper Illinois River with ten backwaters of varying harvest levels from August-October 2015. (List of backwaters in increasing river mile from left to right; Red=no harvest, Yellow=low harvest, Green=high harvest) (Google Inc., 2017)

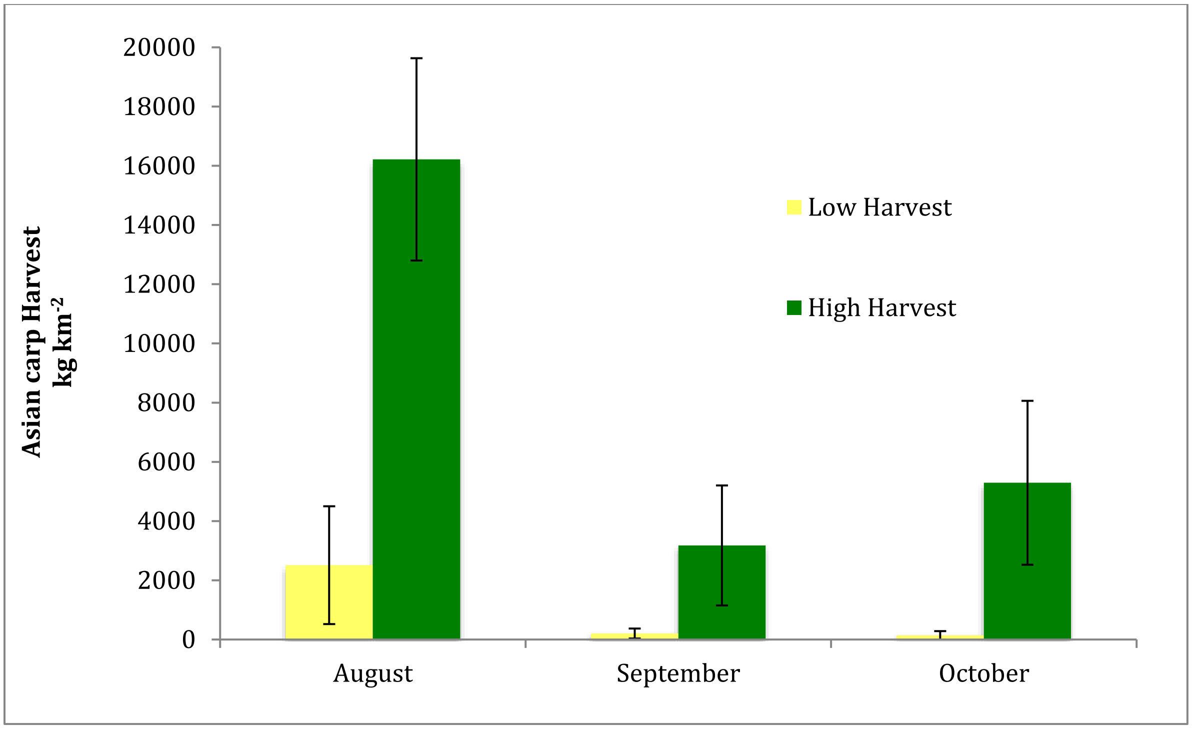

Figure 2. Mean (±S.E.) Asian carp harvest (kg km^{-2}) for August, September, and October 2015. (n=3 backwaters in each harvest level)

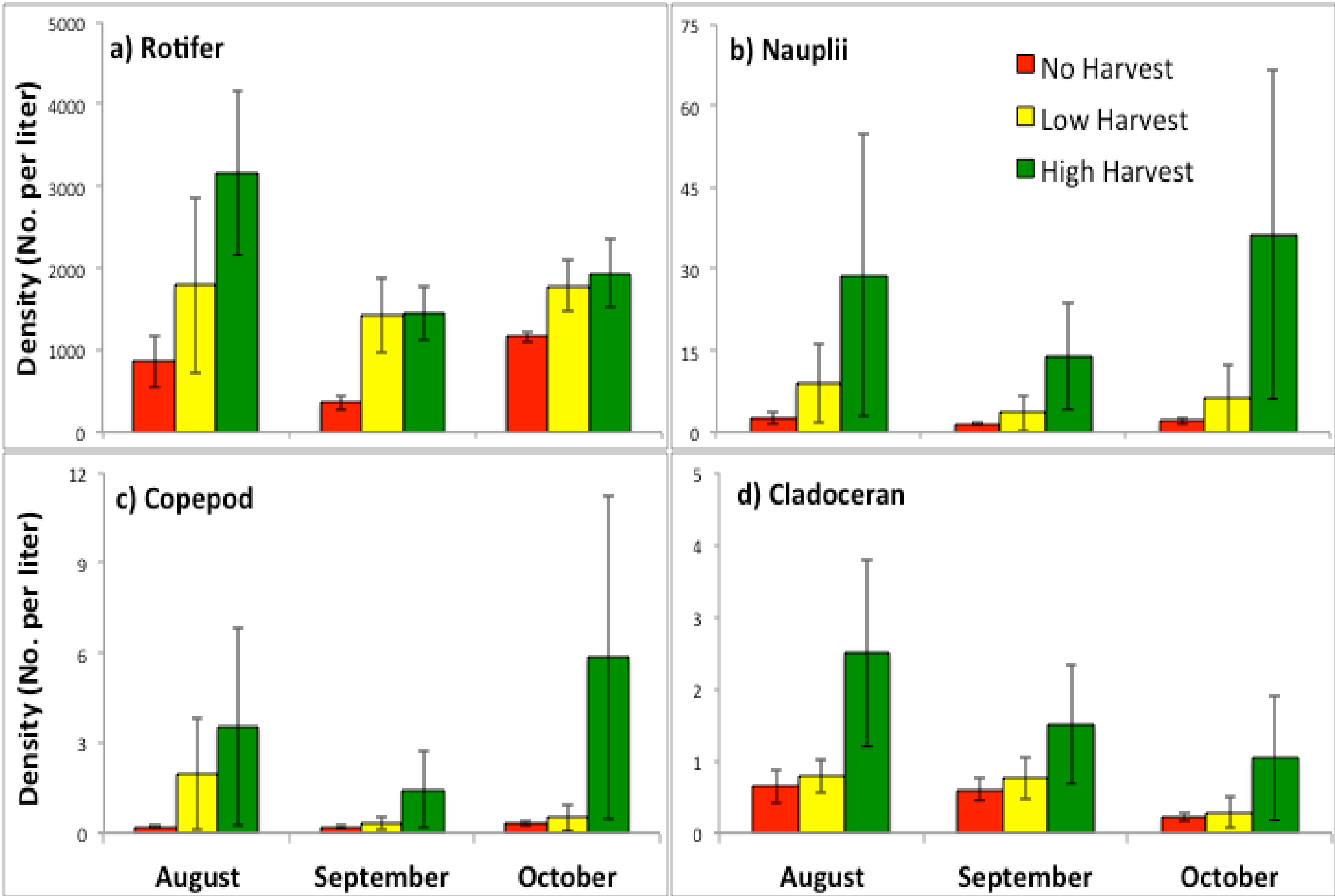

Figure 3. (a-d) Mean density per L^{-1} (±S.E.) of (a) rotifers, (b) nauplii, (c) copepods, and (d) cladocerans among three harvesting levels from August-October 2015

Table 1. Mean (standard error) limnological parameters of harvest level and month (n=4,3,3 backwaters in each harvest level of no, low, and high harvest levels respectively). Each backwater represented the mean of 10 samples. Note: DO,Dissolved Oxygen.

	Secchi (cm)	Depth (m)	pH	Temperature (C)	Specific Conductivity (μs/cm)	DO (mg/L)	Turbidity (NTU)	Fdom (ppb)	Chl a (μg/L)	Nitrate (N0$_3$-N mg/L)
					No Harvest					
Aug	34.5	1.08	8.55	24.5	724	12.7	23.7	77.4	76	3
	(5.0)	(.06)	(0.2)	(0.5)	(18)	(2.5)	(5.0)	(5.4)	(33.9)	(0.3)
Sept	35.6	1.24	8.07	23	669	8.7	21.5	78.8	26.4	4.6
	(2.8)	(0.7)	(0.13)	(0.4)	(45)	(0.7)	(2.3)	(6.9)	(11.6)	(0.3)
Oct	36	1.09	8.67	14.3	899	11	22.5	67.4	46.2	5.3
	(1.7)	(0.10)	(0.09)	(0.7)	(12)	(0.4)	(2.3)	(1.8)	(7.1)	(0.3)
					Low Harvest					
Aug	48.3	2.63	8.55	22.9	826	8.4	20.7	65.3	38.4	3.2
	(19.5)	(0.89)	(0.07)	(0.2)	(94)	(1.1)	(7.7)	(7.1)	(6.2)	(0.5)
Sept	51.5	2.62	8.59	22.9	756	12	11.1	67.7	43.3	4.6
	(9.0)	(0.53)	(0.04)	(0.5)	(87)	(0.5)	(3.3)	(9.4)	(4.7)	(0.5)
Oct	53.4	2.12	8.77	14.8	913	12.7	13.2	63	52.7	6.3
	(10.6)	(0.48)	(0.1)	(0.2)	(38)	(1.1)	(3.9)	(5.6)	(8.4)	(0.2)
					High Harvest					
Aug	30.1	2.12	8.81	23.8	680	12.1	25.9	72	99.6	2.3
	(1.3)	(0.35)	(0.12)	(0.6)	(39)	(2.3)	(1.4)	(3.7)	(29.9)	(0.3)
Sept	42.4	2.51	8.44	23.3	712	11.3	13.9	69.9	45.5	4
	(4.0)	(0.37)	(0.04)	(0.6)	(18)	(1.3)	(2.2)	(2.9)	(6.1)	(0.5)
Oct	34.1	1.91	9.09	13.7	777	12.5	20.4	65.5	93.2	3.8
	(2.6)	(0.54)	(0.1)	(0.4)	(53)	(0.7)	(2.3)	(4.6)	(10.1)	(0.9)

Table 2. Mean (standard error) density (Number per Liter) of rotifers, nauplii, copepods, and cladocerans in backwaters of no, low, and high harvest levels (n=4,3,3 respectively) from August-October 2015. Each backwater represents the mean of five samples.

Month	**August**	**September**	**October**
	Rotifer		
No Harvest	863 (316)	360 (90)	1163 (66)
Low Harvest	1789 (1068)	1423 (463)	1779 (310)
High Harvest	3168 (1005)	1441 (331)	1932 (412)
	Nauplii		
No Harvest	2.6 (1.11)	1.5 (0.2)	2.0 (0.58)
Low Harvest	8.9 (7.15)	3.5 (3.27)	6.2 (6.2)
High Harvest	28.7 (25.96)	14.0 (9.90)	36.3 (30.23)
	Copepod		
No Harvest	0.2 (.05)	0.2 (.04)	0.3 (0.07)
Low Harvest	2 (1.85)	0.3 (0.20)	0.5 (0.43)
High Harvest	3.5 (3.32)	1.4 (1.26)	5.8 (5.39)
	Cladoceran		
No Harvest	0.6 (0.23)	0.6 (0.15)	0.2 (.06)
Low Harvest	0.8 (0.24)	0.8 (0.29)	0.3 (0.21)
High Harvest	2.5 (1.3)	1.5 (0.82)	1.0 (0.86)

Table 3. Two factor ANOVA testing for differences in zooplankton density with month (August, September, and October) and harvest (none, low, and high) as factors. Means with different subscript letter are statistically significant with Tukey-Kramer or Tukey HSD post hoc test. All variables were transformed as $\log_{10}(X+0.001)$. Note: the interaction was removed if the model was not significant with it.

Model	Df	M.S.	F	p	Means
Rotifer	**8**	**0.2698**	**3.68**	**0.0078**	
Month	2	0.2252	3.07	0.0675	Aug^{A} Sept^{A} Oct^{A}
Harvest	**2**	**0.6504**	**8.87**	**0.0016**	**No^{A} Low^{B} High^{B}**
Month x Harvest	4	0.0782	1.07	0.3975	
Error	21	0.0733			
Nauplii	4	3.2361	2.58	0.0616	
Month	2	0.8939	0.71	0.4994	Aug^{A} Sept^{A} Oct^{A}
Harvest	2	5.5783	4.46	0.0221	No^{A} Low^{A} High^{A}
Error	25	1.2521			
Copepod	4	0.5513	1.25	0.3159	
Month	2	0.2366	0.54	0.5916	Aug^{A} Sept^{A} Oct^{A}
Harvest	2	0.8661	1.96	0.1615	No^{A} Low^{A} High^{A}
Error	25	0.4413			
Cladoceran	**4**	**0.6966**	**4.34**	**0.0084**	
Month	**2**	**0.9737**	**6.07**	**0.0071**	**Aug^{A} Sept^{A} Oct^{B}**
Harvest	2	0.4196	2.62	0.0929	No^{A} Low^{A} High^{A}
Error	25	0.1604			

APPENDIX A: SAS CODE

```
proc glm plot=all;
class month harvest;
model rotifer=month|harvest/ss3;
lsmeans harvest/adjust=tukey lines;run;
proc glm;
class month harvest;
model nauplii=month harvest/ss3;run;
proc glm;
class month harvest;
model copepod=month harvest/ss3;run;
proc glm;
class month harvest;
model cladoceran=month harvest/ss3;
lsmeans month/adjust=tukey lines;run;

proc glm;
class month harvest;
model secchi=month harvest/ss3;
lsmeans harvest/adjust=tukey lines;run;
proc glm;
class month harvest;
model depth=month|harvest/ss3;
lsmeans harvest/adjust=tukey lines;run;
proc glm;
class month harvest;
model ph=month|harvest/ss3;
lsmeans month harvest/adjust=tukey lines;run;
proc glm;
class month harvest;
model temp=month|harvest/ss3;
lsmeans month/adjust=tukey lines;run;
proc glm;
class month harvest;
model spconductivity=month|harvest/ss3;
lsmeans month harvest/adjust=tukey lines;run;
proc glm;
class month harvest;
model domgl=month harvest/ss3;run;
proc glm;
class month harvest;
model turbidityntu=month harvest/ss3;run;
proc glm;
class month harvest;
model fdom=month harvest/ss3;run;
proc glm;
class month harvest;
model chla=month harvest/ss3;run;
proc glm;
class month harvest;
model no3=month|harvest/ss3;
lsmeans month harvest/adjust=tukey lines;run;
```

APPENDIX B: BACKWATER GPS POINTS

Abandoned Marina	-88.81380206	41.33897932
Boondocks Harbor	-88.60396542	41.29791485
Hanson Quarry Pit	-88.43332786	41.34461139
Heritage Harbor	-88.78951836	41.34112304
Hiddencove Marina	-88.61551472	41.29718056
Peacock Slough	-88.40052797	41.36143846
RockRun Rookery	-88.1735309	41.46934705
Sheehan Island	-88.90143376	41.32348509
Starved Rock Marina	-88.94564542	41.32223532
Starved Rock Yacht Club	-88.93347846	41.32166895

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