Final Report to Illinois-Indiana Sea Grant

Evaluating Asian Carp Colonization Potential and Impact in the Great Lakes

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Abstract

Filter-feeding Asian carp (bighead carp, *Hypophthalmichthys nobilis*, and silver carp, *Hypophthalmichthys molitrix*) threaten to invade Lake Michigan and other Great Lakes through the Chicago Sanitary and Ship Canal and through introductions via bait use or the release of fish from live markets. These carp consume plankton, the base of the pelagic food web, and could disrupt a critical food source for larval and adult fish currently inhabiting the lakes. However, it is not clear that Asian carp, which are usually found in productive habitats, could survive on the relatively sparse plankton typical of most of the Great Lakes. Respirometry, mesocosm growth studies, and bioenergetic models were used in this study to evaluate the potential for growth and successful establishment by Asian carp introduced into the Great Lakes. Respiration, a key component in bioenergetic models, was measured for >130 bighead and silver carp over a range of body sizes and environmental temperatures in both static and flowing-water respirometers. The respiration data were incorporated into standard bioenergetic models that calculated basic energy requirements of the carp. These requirements were then compared to planktonic food resources to predict when and where Asian carp could grow and survive in the Great Lakes. The modeling results and mesocosm growth experiments suggest that filter-feeding Asian carp will be unable to colonize most open water regions within the Great Lakes because of limited plankton availability. Productive embayments and wetlands are more likely to support Asian carp growth, and resource managers should focus monitoring and preventative efforts there.

Introduction

Invasive species have had extensive and well-documented negative effects on Great Lake ecosystems. Two new threats are the Asian carps: the bighead carp *Hypophthalmichthys nobilis* and silver carp *Hypophthalmichthys molitrix*. These fish have strong potential to invade the Great Lakes via an artificial connection between the Great Lakes and Mississippi River drainage basins. The connection between these drainage basins occurs via the Chicago Sanitary and Ship Canal (CSSC). Improvements in surface water quality during the late 20th century have recently transformed the man-made CSSC into a gateway for the transfer of invasive fishes between the Mississippi River and Great Lakes drainage basins. Bighead carp have moved up the Illinois River and are now within about 50 river miles of Lake Michigan. Bighead and silver carps migrate upstream to spawn (Verigin et al. 1978), so it is very probable that these fishes could naturally invade Lake Michigan through the CSSC if nothing were done to slow their advance upstream. An electric dispersal barrier currently operates in the CSSC about 22 miles below the Chicago River Lock in Chicago, but there is no guarantee that the barrier will be 100% effective at repelling fish under all conditions. Furthermore, although the CSSC is the most prominent invasion pathway, it is not the only one. Other pathways for introduction of the Asian carps into the Great Lakes remain. These pathways include the introduction of carp through the use of live bait or through illegal trade in live fish.

Both bighead and silver carp are planktivores, capable of consuming the phytoplankton and zooplankton that form the base of the pelagic food web in the Great Lakes. The ability of these filter-feeding carps to reduce plankton densities and potentially compete with native planktivores is of special concern in the Great Lakes. Zooplankton reductions mediated by zebra mussel colonizations have already been linked to reduced recruitment success of an important sport fish, the yellow perch, in Lake Michigan (Dettmers et al. 2003; Janssen and Luebke 2004). Furthermore, recent declines in alewife condition may also be related to reduced zooplankton and *Diporeia* availability since the zebra mussel invasion (Madenjian et al. 2002). If efficient planktivores like the bighead and silver carp establish themselves in the Great Lakes, populations of important native or naturalized fishes that rely on planktonic food sources, including yellow perch, rainbow smelt *Osmerus mordax*, and alewife, may be even further depressed. A reduction of the forage base could jeopardize the multi-billion dollar sport fishery for salmonines, as well as further complicate lake trout restoration efforts across the basin.

The potential impacts of bighead and silver carp to the aquatic fauna of the Great Lakes raise serious concern about these two invaders in the basin. Therefore, it is important to first understand whether these fish can survive and flourish in the Great Lakes. Not only will such information provide a critical first look at the potential for these invaders to establish large populations, but it also will be useful ecological information if these invaders do become established and decisions are made to attempt to control these carps.

A tacit assumption made in identifying Asian carp as significant threats to Great Lake ecosystems is that they will be able to grow on the relatively dilute plankton that occurs in large portions of the Great Lakes. Flourishing populations of filter-feeding Asian carp are historically associated with eutrophic conditions that feature abundant phytoplankton and zooplankton. Most areas of the Great Lakes are oligotrophic to slightly mesotrophic, and feature relatively low abundances of phytoplankton and zooplankton, especially since the arrival of zebra mussels. For example, mean chlorophyll *a* values in Lake Michigan and Lake Superior are <1 µg/L (EPA GLNPO Open Water Surveillance Program data), whereas mean chlorophyll a values in areas of the Mississippi River where Asian carp now thrive are >20 µg/L (J. Chick, INHS, personal communication). The ability of Asian carp to successfully exploit the relatively sparse food environment of the Great Lakes may be limited, particularly since these filter-feeding fish are likely to devote a substantial portion of their energy budget to swimming expenditures.

Our overarching objective was to provide solid scientific information on the likelihood that Asian carp will be able to colonize and impact the plankton of the Great Lakes. This information was intended to be used by resource managers and decision makers in prioritizing invasive threats and developing prevention and management strategies. Our specific objectives were to: (1) develop a predictive model of Asian carp consumption and growth in the Great Lakes using a bioenergetics approach; (2) test model predictions with growth and consumption experiments in mesocosms; (3) predict where in the Great Lakes Asian carp are likely to survive by feeding on plankton; and (4) provide initial estimates of the potential impact of Asian carp on Great Lake plankton communities.

The research described in this report was broken into several different components. First, we describe extensive respirometry measurements needed to provide data on carp respiration critical to the construction of bioenergetics models. This research was performed at the University of Nebraska and the Illinois Natural History Survey's Illinois River Biological Station, and it formed the basis of Jen Hogue's Masters's thesis. Second, we describe mesocosm growth experiments performed at the Jake Wolf fish hatchery along the Illinois River. These experiments measured the growth response of bighead carp to different plankton densities (including a density similar to that found in Lake Michigan) and also examined the effect of carp on zooplankton species composition. Third, we examined the combined effect of food quality and food quantity on the growth of bighead carp in mesocosm experiments performed at the University of Illinois to explore the possibility that the nitrogen or phosphorus content of Great Lakes plankton could limit carp growth in the Great Lakes. Fourth, we modeled potential carp growth with bioenergetic models that employed respiration coefficients obtained as part of this project, and compared the bioenergetics demands of growth to the energy available in plankton in various parts of the Great Lakes. We conclude from these studies that filter-feeding Asian carp are unlikely to colonize most open-water habitats in the Great Lakes because of food scarcity, but the carp may be able to persist in productive near-shore habitats if they are able to reach them.

<u>Narrative</u>

1. Respirometry

The objective of this part of the project was to measure oxygen consumption (respiration) rates for bighead carp and silver carp in relation to water temperature, swimming speed, and life-stage. These data were subsequently incorporated into bioenergetics models that predicted potential growth and food consumption rates of bighead and silver carp in Lake Michigan and other Great Lakes (see Narrative part 4 [below] for a description of the modeling results). The methods and results of the respiration measurements are presented in full detail in Hogue (2008) and Hogue and Pegg (submitted), and only the major points will be described here. Briefly, oxygen consumption was measured in both static and flowing-water respirometers. Respiratory rates were measured on >130 individuals that included juvenile and adult fish of both species. Established respirometry methods were employed to measure respiration over a range of water temperatures (5, 10, 15, 20, and 25°C), different life stages (juvenile fish < 50-cm, and adult fish >50-cm), and different activity levels (0.0-m/s, 0.3-m/s, and 0.6-m/s). Trials were conducted over one hour using a static respirometer to measure resting respiration rates and a swim chamber to conduct active trials.

Respiration was influenced by fish size, temperature, and activity. Figure 1 illustrates the overall relationship between oxygen consumption rate (OCR) and fish size, which was allometric.

Body mass correlated to OCR (r=0.92 (bighead carp), r=0.63 (silver carp)). The calculated b value, a coefficient used to correct mass related bias, for bighead carp was 0.7, while the calculated b value for silver carp was 0.76. These values were important for scaling respiration to different sized fish in the bioenergetic models. Temperature significantly affected OCR in both species; whereas life-stage did not. Activity level affected OCR in adult silver carp (P=0.48). Oxygen consumption rates did not differ between species (P=0.60). These results suggested that Asian carp have relatively high metabolic rates, and as a consequence, relatively high demands for food.

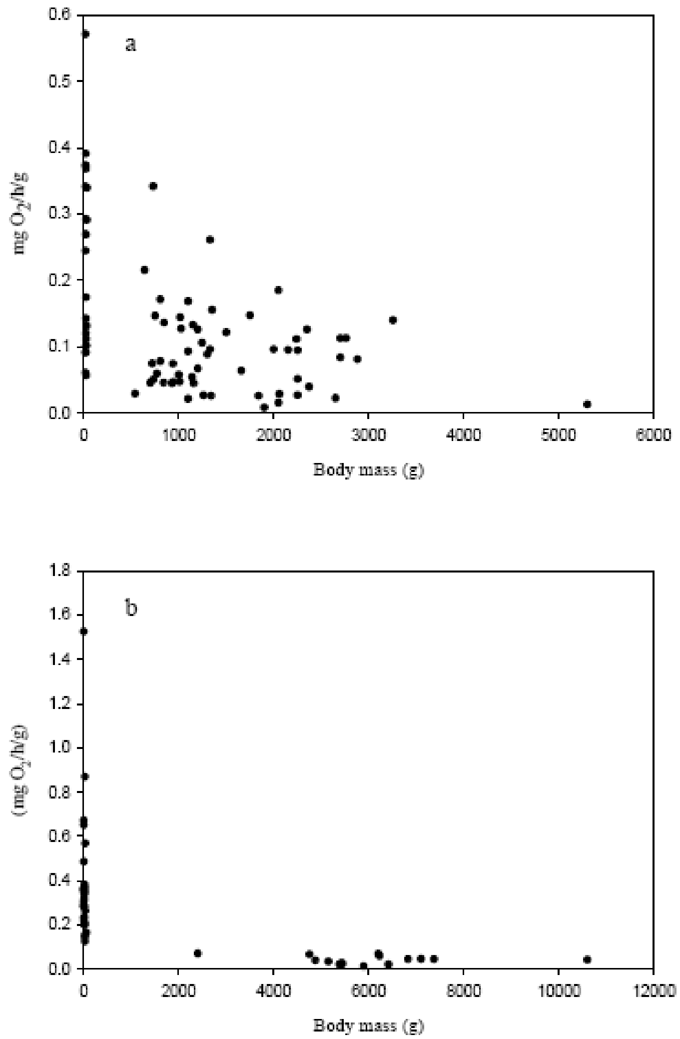

Figure 1. Oxygen consumed per gram of body mass (mg O_2/hr/g) in relation to body mass (g) for silver carp (a) and bighead carp (b).

2. Mesocosm growth experiments

This portion of the project provided an empirical test of the effect of plankton density on Asian carp growth, and it also identified potential effects of carp on zooplankton. Experiments were carried out in large mesocosms (678-L tanks) at the Jake Wolf Fish Hatchery near the Illinois River. The methods and results are presented in full detail in Cooke et al. (currently under review at *Hydrobiologia*), and only the main points will be described here. The experiment was a 2x2 factorial design that that crossed two levels of plankton densities (approximating the low food environment of the Great Lakes and the higher food environment of the Illinois River) with to levels of bighead carp (present and absent) in replicated mesocosms. Plankton was sampled throughout the 37 day experiment to identify the effects of carp on zooplankton, and growth of the carp was measured by comparing length and mass of individual fish at the beginning and end of the experiment. Carp significantly depleted zooplankton populations (including both cladocerans and copepods) in the mesocosms even though zooplankton were replenished every two days, indicating the potential effect they would have in invaded habitats. Carp effects were significant even in the high plankton density treatment. The fish were particularly effective in reducing the populations of large-bodied zooplankton such as *Daphnia*. Figure 2 illustrates the disproportionate effect carp had on *Daphnia*, reducing the proportion of this taxon in the zooplankton community nearly three-fold by the end of the experiment.

The carp consistently lost weight in the mesocosms with low plankton densities, while those in the mesocosms with higher plankton densities exhibited positive growth, on average (Figure 3). Because the low plankton densities used in the experiment were similar to densities in the open water zone of the Great Lakes, the results suggest that bighead carp would have difficulty establishing populations in this zone.

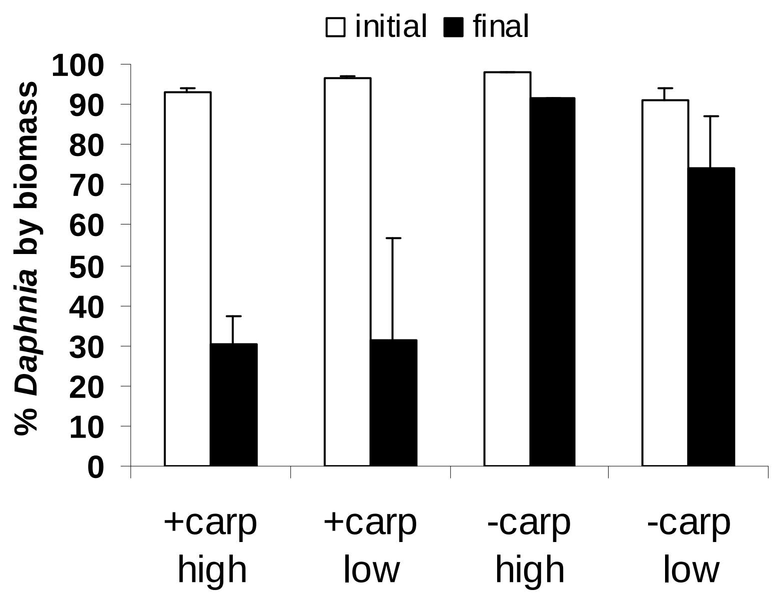

Fig. 2. Percentage of the zooplankton biomass that was *Daphnia magna* in each treatment at the beginning and end of the experiment. Each bar is the mean of the three replicate mesocosms in each treatment. Error bars represent SE.

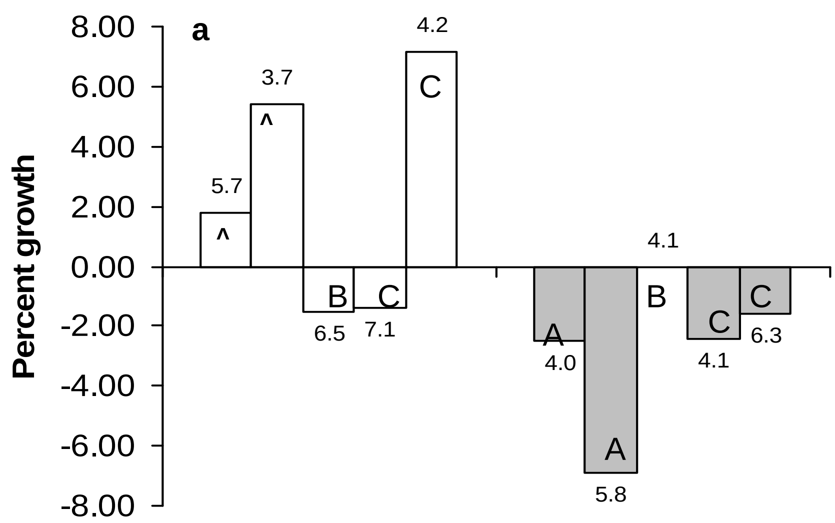

Figure 3. Percent growth of bighead carp over the course of the 37 day experiment in the high (open bars) and low (shaded bars) plankton treatments. Percent growth is 100*(final mass – initial mass) / initial mass, and percent change in total length was calculated similarly. Each bar represents a single fish, and is labeled with the initial mass (g) of that fish of that fish. The letters indicate to which replicate tank each fish was assigned (replicate B of both treatments lost one fish). Note that some of the bars have a value of zero because the fish experienced no change.

3. Nutrient budgets

Phosphorus and nitrogen budgets were created in this part of the project to provide information about the potential effect Asian carp could have on nutrient recycling if the fish became established in the Great Lakes. The budgets were also created to indicate the potential that low quantities of either phosphorus or nitrogen in plankton biomass could limit the growth of filter-feeding Asian carp. The budgets were created by measuring rates at which phosphorus and nitrogen were consumed, assimilated, excreted, and transferred into carp biomass in mesocosm experiments at the University of Illinois (Urbana-Champaign). The methods and results of these experiments are reported in full detail in Meyer (2008), and only the main results will be reported here. Bighead carp excreted nitrogen and phosphorus at a surprisingly low ratio of 10:1. This ratio was lower than that generally reported for copepod zooplankton (12:1). Fish possess internal skeletons that are relatively rich in phosphorus and they should therefore have a relatively high phosphorus demand and a consequently low phosphorus excretion rate (relative to nitrogen). The carp were therefore expected to excrete at a higher N:P than the zooplankton that they would presumably replace if they became established in the Great Lakes. The lower N:P ratio in the excretion of carp could have important ramifications for nutrient cycling and phytoplankton composition should they become established. Low N:P ratios promote the growth of planktonic cyanobacteria such as the toxic taxon *Microcystis*. The nutrient budgets calculated from the mesocosm experiments included rates of consumption of phosphorus and nitrogen at growth rates (and plankton densities) that were both positive and negative. By comparing consumption rates theoretically possible in Lake Michigan (using a literature-derived maximum filtration rate and literature-reported Lake Michigan plankton densities) to consumption rates in the mesocosm studies, it is possible to make a rough estimate of the carp's ability to obtain sufficient phosphorus and nitrogen to experience positive growth. Figure 4 compares the theoretical consumption rate of fish (as a function of average fish mass) in open water Lake Michigan (lines) to consumption rates when fish gained weight (filled symbols) and lost weight (open symbols).   The calculated consumption rates of phosphorus and nitrogen in Lake Michigan are clearly less than those required for positive growth.

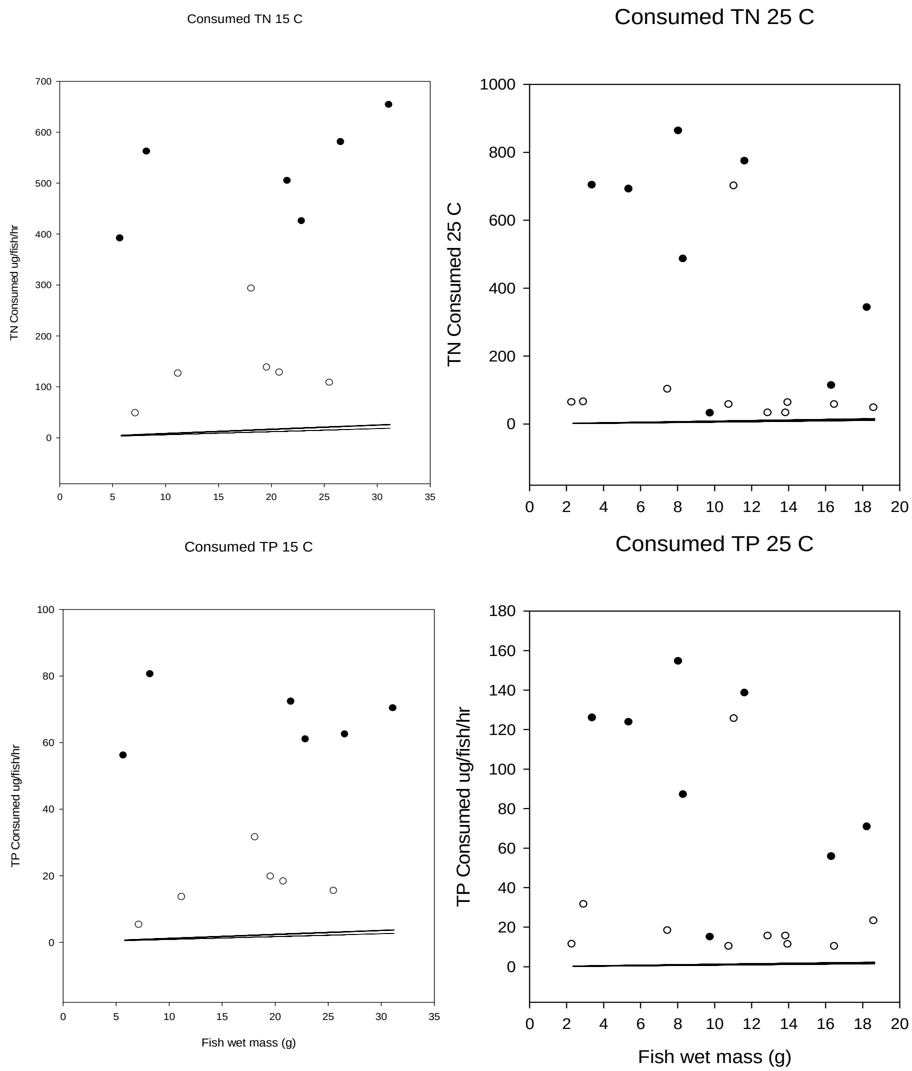

Figure 4. This figure is a comparison of bighead carp nutrient consumption (all points on the graphs) with nutrients that the fish could consume based on biomass found offshore and the fish's potential filtration rates (Opuszynski et al, 1991)(solid lines). Offshore biomass includes crustacean zooplankton and phytoplankton (Kerfoot et al. 2008). The range of consumption is based on filtration rates for bighead carp (Opuzynski et al. 1991) and the available plankton biomass at each

location. Filled circles on the figures indicate fish that gained weight during laboratory trials, and open circles are fish that lost weight.

However, the same analysis using plankton densities from Green Bay and Western Lake Erie (results available in Meyer 2008), indicate sufficient phosphorus and nitrogen available in the plankton to support the growth of bighead carp.

4. Bioenergetic modeling

The purpose of this part of the project was to develop bioenergetics models for bighead and silver carps using our empirically-determined respiration rates and other literature-derived bioenergetic parameters. From these models we predict the basic food requirements of silver and bighead carp for different body sizes, swimming speeds, and reproductive stages. We then compare these requirements to zooplankton densities in various regions of the Great Lakes to predict where and when there is sufficient food to support carp growth and survival. The methods and results of the bioenergetic modeling are presented in full detail in Cooke and Hill (currently under review in *Biological Invasions*), and only the major points will be presented here.

We structured bighead carp and silver carp models following the widely-used Wisconsin bioenergetics model (Hanson et al. 1997). The basic energy balance equation described by the model is

$$C = (R + A + SDA) + (F + U) + (\Delta B + G) \qquad (1)$$

where total consumption of energy (C) is equal to the sum of metabolism (respiration, R, active metabolism, A, and specific dynamic action, SDA), wastes (fecal egestion, F, and urinary excretion, U), and growth (somatic growth, ΔB, and gonad production, G). Each component of this overall equation has different forms of the temperature- and mass-dependence functions that can be used, depending on the physiology of each species.

We used the form of the consumption function designed for warm-water species (Equation 2 in Fish Bioenergetics 3.0 software; Kitchell et al. 1977, Hanson et al. 1997)

$$C = CA \cdot W^{CB} \cdot p \cdot V^{x} \cdot e^{(X \cdot (1-V))} \qquad (2)$$

where *C* is the specific consumption rate (g · g^{-1} d^{-1}); *CA* and *CB* are the intercept and slope of the allometric mass function, respectively; *W* is fish mass (g); and *p* is the proportion of maximum consumption. More details on the modeling are presented in Cooke and Hill (in review).

In addition to using the model to predict minimum energetic requirements, we also used it to predict carp growth in different regions of the Laurentian Great Lakes based on zooplankton and phytoplankton availability. Data on chl *a*, phytoplankton biomass, zooplankton densities and zooplankton biomass were compiled from multiple regions within the five Great Lakes. Our goal was to include a selection of recently sampled sites representative of offshore pelagic habitats as well as coastal embayments and wetlands that would be expected to have higher plankton biomass. This selection of locations and seasons is far from comprehensive, but nevertheless represents a broad range of habitats within the Great Lakes. The data selected include a recent study of a late winter production pulse in southern Lake Michigan (Kerfoot et al. 2008); a survey of Great Lakes wetlands (Lougheed and Chow-Fraser 2002; we included open water habitats only); and a comparison of zooplankton biomass and chl *a* in embayment, nearshore, and offshore regions in Lake Ontario (Hall et al. 2003). Additionally, we applied the model to several riverine sites in order to demonstrate that the model predicts positive growth in habitats where Asian carps have already invaded.

The projected growths of non-swimming silver and bighead carps feeding on phytoplankton and zooplankton in different regions of the Great Lakes were negative in almost all open water regions of the Great Lakes (Table 1). However, positive growth was predicted in Green Bay, the embayment regions of Sodus Bay and Sandy Pond, western Lake Erie, and some wetlands. Modeled growth was positive in the riverine habitats where Asian carp have established reproducing populations (Table 1). However, the maximum allowable swimming speeds (mean value over 30 days) for Asian carp feeding in these regions of positive growth were quite low (<2 cm/s), which would seriously constrain the foraging capabilities of carp even in the more productive habitats (Table 2).

The modeling results suggest that zooplankton and phytoplankton biomass in many representative regions within the Laurentian Great Lakes would not support growth of silver and bighead carps. Our results do indicate that at certain times of year regions such the western basin of Lake Erie and some embayments and wetlands may contain enough plankton biomass to meet Asian carp energetic requirements. Embayments, wetlands, and other coastal zones are important habitats and nurseries for larval fishes such as alewives (Klumb et al. 2003) and walleye (Roseman et al. 2005). Therefore, although Asian carp would probably not become established in nearshore or offshore pelagic habitats of Lakes Ontario, Michigan, Superior, and Huron, they could still indirectly affect those ecosystems if they became established in adjoining embayments and wetlands.

Recent spatially comprehensive studies show that the low plankton conditions are prevalent throughout both nearshore and offshore regions of Lake Michigan (e.g., Vanderploeg et al. 2007). If Asian carps were to enter the "plankton desert" of Lake Michigan via the Chicago Sanitary and Shipping Canal (CSSC), it seems unlikely that they would be able to consume enough energy to swim to Green Bay or another "plankton oasis". A greater invasion risk may be that of bait contamination or Canadian live fish markets in close proximity to productive harbors and embayments of Lakes Ontario and Erie (Rixon et al. 2005, Herborg et al. 2007, Keller and Lodge 2007). We do not, however, recommend abandoning the electric barrier in the CSSC.

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Table 1 (next page). Projected growth, based on bioenergetics models, of juvenile (10 cm, 10 g) and adult (60 cm, 2400 g) non-swimming bighead carp (BC) and silver carp (SC) foraging on zooplankton (zoop) and phytoplankton (phyto) for 30 days at 20 ^{o}C at different times of year and in different regions of Lakes Michigan, Superior, Huron, Erie and Ontario, and riverine habitats currently invaded by Asian carp (Spr. = spring; Sum = summer). Open water habitats near wetlands are indicated after the site name (wet), zooplankton samples excluding rotifers are noted in the reference column (NR), and negative growth values are highlighted in boldface.

Table 1.

Location	Time of year	Phyto. wet mass (mg L^{-1})	Zoop. wet mass (mg L^{-1})	Predicted % biomass gain or loss over 30 days				References
				10 g BC	10 g SC	2400 g BC	2400 g SC	
Lake Michigan								
southern basin, nearshore	May 2003	0.69	0.024	**-32.1**	**-34.2**	**-7.00**	**-11.44**	Cáceres et al. unpublished data (zoop); Gardener et al 2004 (chl *a*)
	July 2003	0.69	0.15	**-30.1**	**-32.3**	**-6.52**	**-10.98**	
	Sept. 2003	0.69	0.79	**-20.0**	**-22.4**	**-4.10**	**-8.61**	
within production pulse	April 2006	0.52	0.18	**-32.2**	**-34.3**	**-7.03**	**-11.47**	Kerfoot et al. 2008
outside production pulse	April 2006	0.19	0.045	**-39.5**	**-41.4**	**-8.80**	**-13.21**	
Green Bay	April 1999	5.5	0.16	+45.8	+41.7	+11.3	+6.46	Fulford et al. 2006 and pers. comm.. (zoop, NR); Qualls et al. 2007 (chl *a*)
	June 1999	5.5	4.72	+121	+115	+28.5	+23.2	
Lake Superior								
western arm	May 2001	0.31	0.16	**-35.9**	**-37.9**	**-7.92**	**-12.3**	Brown and Branstrator 2004 (NR)
	Aug. 2001	0.32	0.59	**-28.9**	**-31.1**	**-6.23**	**-10.7**	
Chippewa Park (wet)	July 1998	1.42	2.52	+19.1	+15.7	+5.13	+0.42	Lougheed and Chow-Fraser 2002 and pers. comm.
Pine Bay (wet)	July 1998	1.13	2.22	+9.80	+6.60	+2.95	**-1.71**	
Hurkett Cove (wet)	July 1998	0.07	3.19	+8.60	+5.40	+2.67	**-1.98**	
Lake Huron								
Collingwood Harbour (Georgian Bay)	July 1998	1.42	1.83	+8.00	+4.90	+2.54	**-2.11**	Lougheed and Chow-Fraser 2002 and pers. comm.
Oliphant Bay (wet)	July 1998	0.57	0.056	**-33.5**	**-35.6**	**-7.35**	**-11.8**	
Baie du Dore (wet)	July 1998	0.07	0.024	**-41.6**	**-43.4**	**-9.31**	**-13.7**	

Table 1, continued

Location	Time of year	Phyto. wet mass (mg L^{-1})	Zoop. wet mass (mg L^{-1})	Predicted % biomass gain or loss over 30 days				References
				10 g BC	10 g SC	2400 g BC	2400 g SC	
Lake Erie								
west basin	Spr. 2002	3.31	0.69	+19.5	+16.0	+5.21	+0.50	Conroy et al. 2005 (NR)
	Sum. 2002	3.12	1.74	+33.5	+29.7	+8.48	+3.69	
central basin	Spr. 2002	0.63	1.14	**-15.5**	**-18.0**	**-3.02**	**-7.55**	
	Sum. 2002	1.21	0.95	**-9.5**	**-12.2**	**-1.59**	**-6.15**	
east basin	Spr. 2002	1.82	0.29	**-10.5**	**-13.1**	**-1.82**	**-6.38**	
	Sum. 2002	1.06	0.62	**-17.2**	**-19.6**	**-3.39**	**-7.91**	
Rondeau Prov. Park (wet)	June 1998	0.14	0.46	**-33.7**	**-35.7**	**-7.39**	**-11.82**	Lougheed and Chow-Fraser 2002 and pers. comm.
Long Point Prov. Park (wet)	July 1998	0.36	0.40	**-31.4**	**-33.5**	**-6.84**	**-11.29**	
Lake Ontario								
Sodus Bay embayment	July 1997	1.87	5.91	+81.9	+76.8	+19.6	+14.5	Hall et al. 2003 and pers. comm. (NR)
Sodus Bay nearshore	July 1997	0.29	0.81	**-25.9**	**-28.2**	**-5.51**	**-9.99**	
Sandy Pond embayment	July 1997	1.11	6.06	+72.2	+67.3	+17.4	+12.4	
Sandy Pond nearshore	July 1997	0.64	0.76	**-21.2**	**-23.6**	**-4.38**	**-8.88**	
Frenchman's Bay (wet)	June 1998	8.94	1.57	+125	+119	+29.3	+24.1	Lougheed and Chow-Fraser 2002 and pers. comm.
Bronte Creek (wet)	June 1998	1.84	0.42	**-8.0**	**-10.7**	**-1.23**	**-5.80**	

Table 1, continued

Location	Time of year	Phyto. wet mass (mg L^{-1})	Zoop. wet mass (mg L^{-1})	Predicted % biomass gain or loss over 30 days				References
				10 g BC	10 g SC	2400 g BC	2400 g SC	
Middle Mississippi River								
Chester	Aug. 2003	5.00	0.05	+36.0	+32.1	+9.05	+4.25	Williamson and Garvey 2005 (NR)
Grand Tower	Oct. 2003	10.0	0.01	+116	+110	+27.3	+22.1	
Upper Mississippi River	Sum. 2004-5	8.77	3.75	+159	+151	+36.8	+31.3	Levchuk 2007
Missouri River	Sum. 2005	5.30	1.39	+62.8	+58.2	+15.2	+10.3	Dickerson 2008 (zoop); Bukaveckas pers. comm. (chl *a*)

Table 2 (next page). Maximum swimming speed, based on bioenergetics models, that can be maintained by juvenile (10 cm, 10 g) and adult (60 cm, 2400 g) bighead carps (BC) and silver carps (SC) for 30 days at 20 ^{o}C in different habitats different times of year. Open water habitats near wetlands are indicated after the site name (wet).

Table 2.

Location	Time of year	Maximum swimming speed over 30 days (cm s^{-1})			
		10 g BC	10 g SC	2400 g BC	2400 g SC
Lake Michigan, Green Bay	April 1999	0.70	0.64	0.77	0.36
	June 1999	1.30	1.23	1.37	0.97
Lake Superior					
Chippewa Park (wet)	July 1998	0.35	0.29	0.42	0.03
Pine Bay (wet)	July 1998	0.20	0.13	0.26	NA
Hurkett Cove (wet)	July 1998	0.17	0.13	0.24	NA
Lake Huron, Collingwood Harbour	July 1998	0.16	0.10	0.23	NA
Lake Erie, west basin	Spr. 2002	0.35	0.30	0.43	0.03
	Sum. 2002	0.65	0.24	0.55	0.49
Lake Ontario					
Sodus Bay embayment	July 1997	1.03	0.97	1.10	0.70
Sandy Pond embayment	July 1997	0.96	0.89	1.02	0.63
Frenchman's Bay (wet)	June 1998	1.32	1.25	1.39	0.99
Rivers					
Middle MS River (Chester)	Aug. 2003	0.59	0.51	0.66	0.25
Middle MS River (Grand Tower)	Oct. 2003	1.27	1.20	1.34	0.93
Upper MS River	Sum. 2005	1.50	1.43	1.56	1.16
Missouri River	Sum. 2004-5	0.88	0.80	0.94	0.54

Potential Applications:

The results of this research will help resource managers evaluate the risk of invasion by filter-feeding Asian carp in Lake Michigan and the other Great Lakes. The results indicate that Asian carp are more likely to colonize productive embayments and wetlands and that their impacts are most likely to be limited to these environments. This should encourage managers to focus monitoring and prevention efforts on a much smaller portion of the Great Lakes than possible without this bioenergetic approach.

Keywords: Asian carp, bighead carp, silver carp, filter-feeders, invasive species, growth, plankton, bioenergetics, chlorophyll, zooplankton, mesocosm, Lake Michigan, Lake Superior, Green Bay, Lake Erie, Lake Ontario, Great Lakes.

Lay Summary:

Two species of Asian carp (bighead carp and silver carp) threaten to invade Lake Michigan and the other Great Lakes through the Chicago Sanitary and Ship Canal and through introductions via bait use or the release of fish from live markets. These carp are filter-feeders, consuming small organisms such as algae and zooplankton which form the base of the food web in the Great Lakes. If they become established, the carp could deplete the plankton through their feeding activities, disrupting a food source critical for larval and adult fish currently inhabiting the lakes. However, it is not clear that Asian carp could grow feeding on the relatively sparse plankton typical of most of the Great Lakes. Filter-feeding carp are usually found in more productive waters with higher plankton abundances. Using a combination of laboratory experiments and modeling, we conclude that filter-feeding Asian carp will be unable to colonize most open water regions within the Great

Lakes because of limited amount of food (plankton) available there. Productive embayments and wetlands are more likely to support Asian carp growth, and we suggest that resource managers focus monitoring and preventative efforts in these more limited areas of the Great Lakes.

International Implications:

The results clearly have implications for both Canada and the U.S. since these two countries share the Great Lakes.

Partnerships with other institutions:

Academic institutions: University of Nebraska.

Publications:

Peer-reviewed journal articles:

Cooke, S. L., and W. R. Hill. *Submitted*. Using bioenergetics models to predict invasion of the Laurentian Great Lakes by filter-feeding Asian carp. *Biological Invasions*.

Cooke, S. L., W. R. Hill, and K. P. Meyer. *Submitted.* Bighead carp growth under different zooplankton and phytoplankton densities. *Hydrobiologia.*

Hogue, J. L., and M. Pegg. *Submitted*. Oxygen consumption rates for bighead and silver carp in relation to life-stage, temperature, and activity level. *Journal of Fish Biology*.

Technical report:

Cooke, S. L., and W. R. Hill. Bioenergetics of invasive Asian carp. 2007. Illinois Natural History Survey Reports. October.

Conference presentations:

Cooke, S., and W. Hill. 2007. Bioenergetic approach to testing the capability of Great Lakes plankton to support Asian carp. Invited presentation at the International Joint Commission 2007 Biennial Meeting and Great Lakes Conference, Chicago, IL, June.

Cooke, S. L., and W. R. Hill. 2008. Using a bioenergetics model to predict the potential impact of invasive silver carp in the laurentian great lakes. Summer meeting of the American Society of Limnology and Oceanography, St. John's, Newfoundland, 8 June.

Theses:

Meyer, K. P. 2008. Phosphorus and nitrogen budgets for bighead carp (*Hypophthalmichthyes nobilis*): potential impacts of bighead carp and their potential for survival in Lake Michigan. M. S. Thesis, University of Illinois Urbana-Champaign.

Hogue, J. L. 2008. Oxygen consumption rates for bighead and silver carp in relation to life-stage, temperature, and activity level. M.S. Thesis, University of Nebraska., Lincoln.

Graduate Students Supported:

Kevin Meyer, Master of Science, Department of Natural Resources and Environmental Sciences, University of Illinois Urbana-Champaign. Degree expected December 2008. Thesis title: see above. Grant provided research stipend.

Jennifer Hogue, Master of Science, School of Natural Resources, University of Nebraska, Lincoln. Degree obtained May 2008. Thesis title: see above. Grant provided financial support for equipment (e.g., respirometer).

Awards and Honors, Patents/Licenses, and Performance Measures:

Not applicable.