A NATIVE SPECIES, THE AMERICAN EEL (*ANGUILLA ROSTRATA*), AS A BIOLOGICAL CONTROL FOR AN INVASIVE CRAYFISH (*ORCONECTES RUSTICUS*) IN TRIBUTARIES TO THE HUDSON RIVER, NY

A Final Report of the Tibor T. Polgar Fellowship Program

Sarah J. Mount

Polgar Fellow

Biology Program
Bard College
Annandale-on-Hudson, NY 12504

Project Advisors:

Catherine M. O'Reilly
Biology Program
Bard College
Annandale-on-Hudson, NY 12504

David L. Strayer
Cary Institute of Ecosystem Studies
Millbrook, NY 12545

Mount, S.J., C.M. O'Reilly, and D.L. Strayer. 2011. A Native Species, the American Eel (*Anguilla rostrata*), as a Biological Control for an Invasive Crayfish (*Orconectes rusticus*) in Tributaries to the Hudson River, NY. Section VII: 1-22 pp. In D.J. Yozzo, S.H. Fernald, and H. Andreyko (eds.), Final Reports of the Tibor T. Polgar Fellowship Program, 2009. Hudson River Foundation.

ABSTRACT

Invasive species often disrupt ecosystems by displacing native species; however, the use of native biological controls is not a well studied method of controlling invasive species and lessening their impacts . The rusty crayfish (*Orconectes rusticus*) is a strong invasive species that has not yet invaded many tributaries to the Hudson River, while it has invaded other areas of New York. This may be due to the presence of American eels (*Anguilla rostrata*), which may act as a biological control through predation and competition for shelter and food. Stream surveys showed that where eels were abundant, there were few or no crayfish, and vice versa. Shelter competition laboratory experiments showed that eels outcompete native spinycheek crayfish (*Orconectes limosus*) of all sizes for shelter, and eels outcompete invasive rusty crayfish for shelter in most cases. However, when eels were small and rusty crayfish were large, the rusty crayfish sometimes outcompeted the eel for shelter. These findings suggest that only larger eels may act as a native biological control for the invasive rusty crayfish.

TABLE OF CONTENTS

Abstract………………………………………………………………… VII-2

Table of Contents………………………………………………………. VII-3

List of Tables and Figures…….………………………………………….. VII-4

Introduction…………………………………………………………….. VII-5

Methods………………………………………………………………… VII-8

Study Sites……………………………………………………… VII-8

Stream Surveys………………………………………………….. VII-10

Shelter Experiments…………………….……………………….. VII-11

Experimental Animals and Set Up………………………………... VII-11

Shelter Preference……………………………………………….. VII-12

Shelter Competition…………………………………………….. VII-12

Data Analysis…………………………………………………… VII-13

Results…………………………………………………………………… VII-13

Stream Surveys………………………………………………….. VII-13

Shelter Use Alone……………………………………………….. VII-16

Shelter Competition…………………………………………… VII-16

Discussion………………………………………………………………….. VII-19

Acknowledgements………………………………………………………… VII-22

References………………………………………………………………….. VII-23

LIST OF TABLES AND FIGURES

Table 1 – Summary of stream survey data…………………………………… VII-14

Figure 1 – Map of sample sites……………………………………………… VII-9

Figure 2 – Numbers of eels and crayfish caught above and below barriers… VII-15

Figure 3 – Relationship between numbers of eels and crayfish…………….. VII-16

Figure 4 – Shelter use by eels and native and invasive crayfish……………. VII-17

Figure 5 – The relationship between the size difference between eels and rusty crayfish and shelter use by rusty crayfish paired with eels... VII-18

INTRODUCTION

Invasive species can severely disrupt the function of an ecosystem (Mack et al. 2000; Gurevitch & Padilla 2004) particularly in aquatic systems (Kolar & Lodge 2002; Rahel 2007; Rahel & Olden 2008). Aquatic invasive species can quickly spread though ballast water, fish stocking, boating, and other human activities. They can alter the native ecology because they do not have built-in checks from co-evolution, such as pathogens or predators, as native species do (Keane & Crawley 2002; Torchin & Mitchell 2004). Invasive species can be hard to manage. One management strategy is the use of biological controls, but biocontrols typically consist of introducing an additional non-native species to the system to decrease populations of the invasive.

Native species may have the potential to act as a biological control for invasive species through predation (DeRivera et al. 2005; Carlsson et al. 2009; Santos et al. 2009) and competition (Perry et al. 2004). If a native predator can quickly adapt to the introduction of a novel potential food item, it can decrease the negative impacts associated with invasion. A native species may also be able to control the impact and spread of an invasive species by outcompeting the invasive for food and/or shelter. Invasive species are usually studied with an emphasis on the impact of invasion on species of equal or lower trophic levels because those effects are more pronounced. However, higher trophic level species may also have important effects on the ability of an invasive species to become a widespread nuisance. This facet of the ecology of invasive species has not been studied in most cases.

There are, however, a few studies that have addressed the effect of a native predator adapting to eat a newly abundant invasive species. One case is the native Lake

Erie water snake (*Nerodia sipedon insularum*) incorporating the invasive round goby (*Neogobius melanostomus*) into its diet (King et al. 2006). Just a few generations after invasion, the round goby constituted more than 92% of the diet of the Lake Erie water snake. Adapting their diet to the new species allowed the water snake to increase its growth rate and body size. In this example, an invasive species had a positive effect on a native predator. In another case, numbers of an invasive spider (*Achaearanea riparia*) were up to 80% higher in areas that excluded both native and alien bird predators (Gruner 2005), highlighting the potentially important role of generalist predators on controlling invasive species.

This study focused on and the potential of the native American eel (*Anguilla rostrata*) to control the invasive rusty crayfish (*Orconectes rusticus*). The rusty crayfish is native to the Midwest, but has invaded many areas in northern and eastern North America, including New York State (Daniels 1998). Rusty crayfish often displace native crayfish (Capelli 1982; Olden et al. 2006) and greatly decrease preferred prey items, such as aquatic macroinvertebrates and macrophytes (Olden et al. 2006), thereby altering the ecology of the system.

The American eel may act as a native biological control through predation, competition, or a combination of the two. Eels are catadromous fish: they mature in freshwater systems and spawn in the ocean. Eels drift in ocean currents during their larval stage, and eventually end in freshwater. Incoming migratory eels (known as glass eels) are small and transparent. After they migrate into freshwater, they grow and gain pigmentation, and at one or two years old are known as elvers. As elvers grow, they develop a yellow pigmentation on their underside, and are known as yellow eels. When eels are ready to return to the ocean to spawn, they are known as silver eels, because their underside turns a silver color.

The American eel (*Anguilla rostrata*) population has declined in recent decades, as have other species of eel, such as the European eel (*Anguilla anguilla*) (Haro et al. 2000; Feunteun 2002). The decline in numbers of American eels has been attributed to numerous factors, including overfishing, habitat loss, and changes in oceanic patterns. Key contributors to habitat loss are man-made barriers (dams) that restrict upstream migration, which is important in the life cycle of catadromous fish (Machut et al. 2007). One restoration effort that has been implemented to increase numbers of American eels is the use of eel ladders. An eel ladder allows eels to pass over a barrier to a more upstream location. In 2006, an eel ladder was set up in the Saw Kill, a tributary to the Hudson River, to allow for passage of eels over a dam (Schmidt et al. 2009).

Stomach content studies have shown that crayfish constitute more than half of the diet of larger eels (Lookabaugh & Angermeier 1992; Machut 2006); therefore, predation is an important interaction between eels and crayfish. Competition between eels and crayfish has not yet been studied. Both eels and crayfish are benthic: they live under rocks in streams. At high population densities, eels and crayfish could compete for shelter. The organism that loses shelter could be more vulnerable to predators.

To address the possibility of eels acting as a native biocontrol, stream surveys and laboratory experiments were performed. In the field, stream surveys were conducted on several tributaries to the Hudson River to assess numbers of eels and crayfish. Laboratory experiments were done on shelter competition between eels and both invasive and native crayfish of varying sizes. The native spinycheek crayfish (*Orconectes limosus*) was used as a comparison species to the invasive rusty crayfish (*O. rusticus*). The spinycheek crayfish is a commonly found species in the Hudson River watershed. The two species of crayfish are similar in size, except that rusty crayfish have slightly larger claws. The hypotheses tested were that 1) that both eels and crayfish would prefer to be in a shelter, and 2) that eels would outcompete crayfish for shelter, but that there may be differences between eels' interactions with the invasive rusty crayfish and the native spinycheek crayfish (*O. limosus*). Because eel populations are in decline, this project has conservation and restoration implications on two accounts. If eels can act as a native biological control to stop the spread of rusty crayfish, that could motivate increased eel restoration efforts in the future. A harmful invasive species could be controlled while also increasing eel populations.

METHODS

Study Sites

Stream surveys were conducted to quantitatively sample for eels, other fish, and crayfish at several tributaries to the Hudson River, NY. The streams surveyed were the Fall Kill in Poughkeepsie, Crum Elbow Creek in Hyde Park, Indian Brook in Garrison, Furnace Brook in Croton-on-Hudson, the Landsman Kill in Rhinebeck, and the Saw Kill in Annandale-on-Hudson (Fig. 1). Surveys were conducted from June-September, 2009, except the eel survey of Furnace Brook and the surveys on the Saw Kill, which were conducted in June-July of 2008.

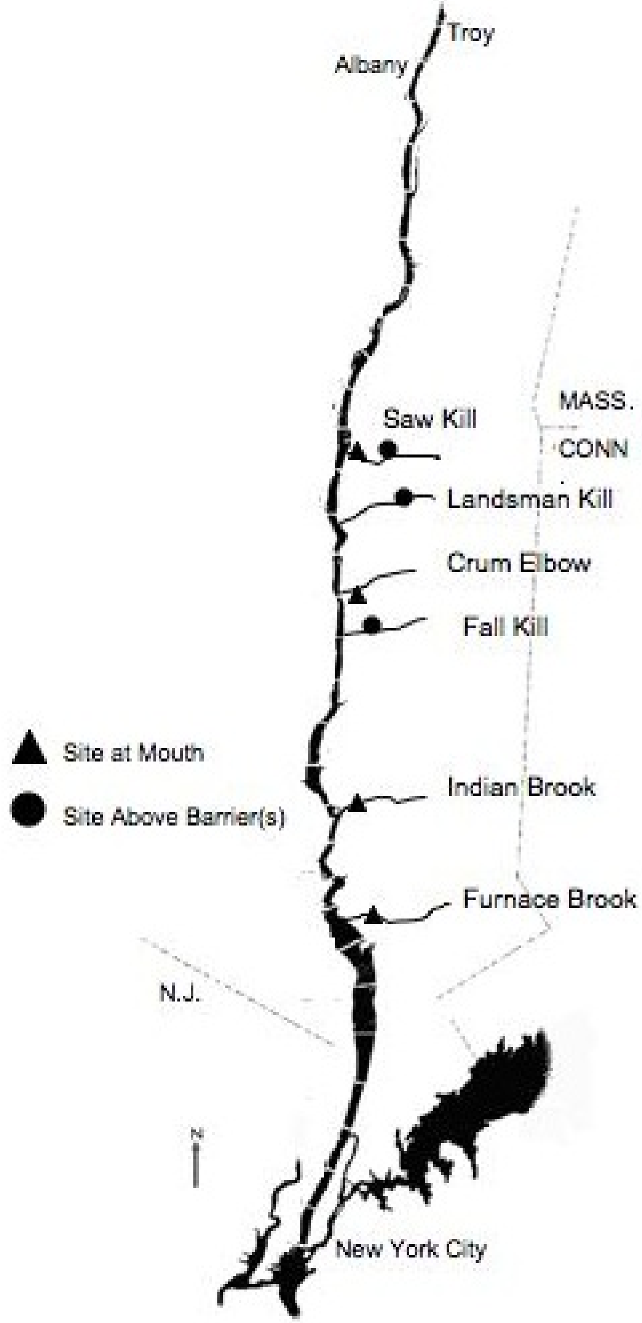

Figure 1: Map of the lower Hudson River with the tributaries sampled. Triangles are sample sites at the mouth of a stream, circles are sample sites above barrier(s). Map adapted from NYSDEC.

Survey sites were located along different parts of the stream: some were at the mouth of the stream, and some were above barriers that restrict upstream eel migration, such as dams and waterfalls (Fig. 1; Table 1). The Fall Kill is an urban stream, and the sample site was upstream of one small waterfall. The site at Crum Elbow was at the mouth of the stream, where there is a marina. The site at Indian Brook was at the mouth of the stream, in a rural area at the Constitution Marsh Audubon Center and Sanctuary. The site at Furnace Brook was rural and above one dam that was breached; therefore, eels were still able to migrate upstream. The site at the Landsman Kill was above two waterfalls. Two sites on the Saw Kill were sampled. One was at the mouth of the stream, with no barriers separating it from the river. The second was above two waterfalls and one dam. The dam, however, has an eel ladder to allow upstream migration by eels (Schmidt et al. 2009).

Stream Surveys

A Smith-Root backpack electroshocker was used to quantitatively sample for eels. A reach of the stream was shocked for three passes (average reach length=59 m; range=20-84 m). A block net was put at the downstream end of the reach so any fish not caught sampling would not leave the sampling area. Eels were sedated with clove oil, measured for total length, and released back into the stream after recovery. During the triple pass shocking, other non-target species were also caught. These fish were identified, counted, and released back into the stream.

There is no standard method to quantitatively sample crayfish (Rabeni et al. 1997; Price & Welch 2009). Therefore, a combination of two methods (electroshocking and hand-netting) was used to get a more representative sample. At each stream, hand-netting was done for three ten-minute periods, and electroshocking was done for three ten-minute periods. Hand-netting consists of one person flipping rocks and disturbing the substrate, while another person holds a net downstream so that any crayfish under the rocks will flow into the net.

Shelter Experiments

Experimental Animals and Set Up

Shelter competition experiments were done to see if an eel or a crayfish would outcompete the other for shelter. All eels used in laboratory experiments were caught by electroshocking in the Saw Kill at the mouth of the stream. All rusty crayfish (*Orconectes rusticus*) used were caught using a minnow seine at Webatuck Creek, in the Housatonic watershed. All spinycheek crayfish (*O. limosus*) used were caught electroshocking and hand-netting in the Fall Kill, above the first waterfall. Crayfish were kept in 38 L holding tanks with abundant shelter (rocks) and fed guinea pig food daily. Ammonia levels were checked daily and the water was changed if ammonia was detectable. New eels were caught for each experiment, and the water was changed between experiments.

Experimental tanks were 110 L tanks, filled 20 cm high, which is approximately half full. The water level was kept low to prevent eels and crayfish from escaping the tanks. All tanks were oxygenated with aerators. The experimental room was on a 12:12

light:dark cycle. A blue nightlight with a 0.5-watt bulb was used to simulate moonlight. Shelters were made with PVC tubing cut in half lengthwise. The PVC tube was glued to a piece of tile to weigh down the shelter, so eels could not flip it over.

Shelter Preference

To assess shelter use alone, data were used from preliminary shelter size preference experiments. One individual was put in a tank with five shelter size options: 1.3 cm, 2.5 cm, 3.8 cm, 5.1 cm, and 7.6 cm (numbers represent the diameter of the PVC). These preliminary experiments showed that 5.1 cm shelter size was appropriate for all size classes of both eels and crayfish used in this study. Observations were made starting after the first night; both eels and crayfish are nocturnal, and this delay allowed them to acclimate to the shelter. Observations were made during the daytime because shelter use should be greatest during the day for nocturnal animals. Starting at 9:15 AM, records were taken of which individual was in the shelter every 30 minutes for a total of eight observations per day. This was repeated after the second night, for a total of sixteen observations per experimental replicate. Observations in which an individual was in any of the shelter sizes were combined to measure shelter use when not paired with another individual.

Shelter Competition

Each tank contained one shelter (5.1 cm), one eel, and one crayfish of either species. Observations were taken similarly to the shelter preference experiments.

Data Analysis

To represent shelter use by an individual, data were analyzed using the percent of observations in which an individual, either eel or crayfish, was in the shelter. Eels paired with the invasive rusty crayfish and eels paired with the native spinycheek crayfish were analyzed separately. At each observation for the shelter competition experiments, there were four possible results for which animals were in the shelter: eel alone, crayfish alone, both (sharing), or no one. T-tests were used to compare means of shelter use between eels and both species of crayfish. All data were analyzed using JMP 7.0 (SAS Institute, Inc.).

RESULTS

Stream Surveys

Sites at the mouth of the stream had significantly more eels than sites above barriers, and sites above barriers had significantly more crayfish than sites at the mouth ($P<0.05$; Fig. 2; Table 1). On average, 93 (±SE 21) eels and 0.75 (±SE 0.5) crayfish were caught at sites at the mouth; at the sites above barriers, only 2 (±SE 1) eels, but 27 (±SE 5) crayfish were caught.

Table 1: Summary of sites and data from stream surveys. Reach measurements were not recorded for the Saw Kill (NR).

Stream	**Location**	**Reach Length (m)**	**Reach Width (m)**	**Reach Area (m^2)**	**Total Number of Eels**	**Total Number of Crayfish**	**Density of Eels (indv/m^2)**	**Density of Crayfish (indv/m^2)**
Furnace Brook	Above One Breached Barrier	20	10	200	46	1	0.23	0.005
Indian Brook	Mouth	82.2	5.4	443.88	70	2	0.16	0.005
Crum Elbow	Mouth	46.6	9.9	461.34	141	0	0.31	0
Saw Kill	Mouth	NR	NR	NR	116	0		0
Landsman Kill	Above Two Waterfalls	84.1	6.1	513.01	2	17	0.004	0.03
Fall Kill	Above One Waterfall	61.3	6	367.8	4	31	0.01	0.08
Saw Kill	Above Three Waterfalls and One Dam	NR	NR	NR	0	34	0	

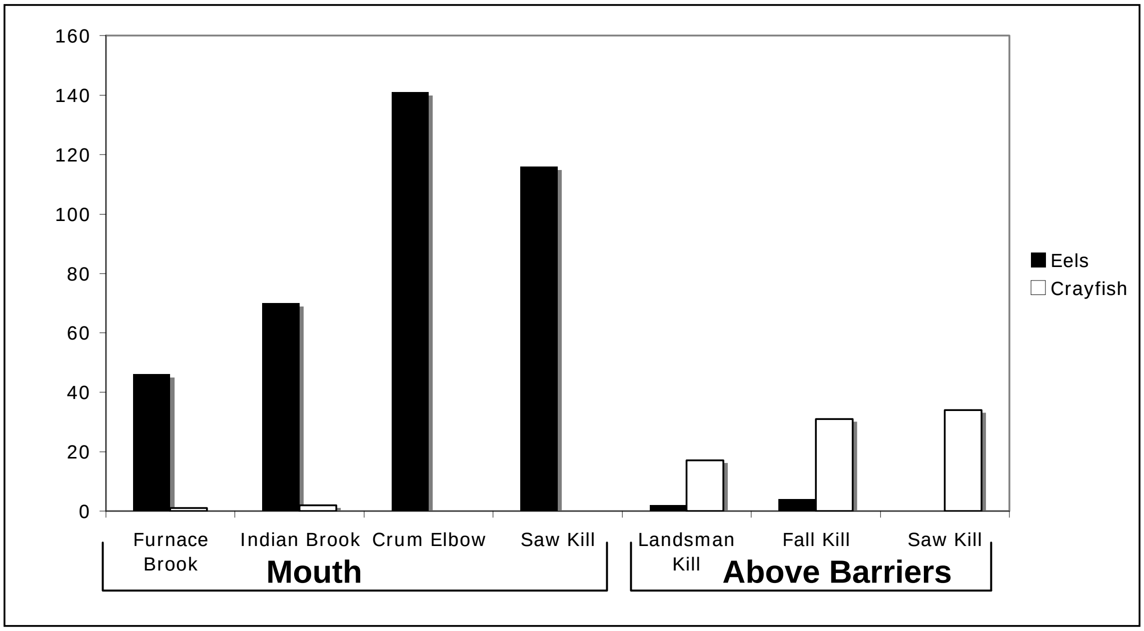

Figure 2: Sites at the mouth of the stream had an order of magnitude more eels than sites above barriers. Sites above barriers had very few or no eels and an abundance of crayfish. Black bars show the number of eels, and white bars show the number of crayfish (all native).

All crayfish caught during stream surveys were the native spinycheek crayfish. The one exception, a single *Cambarus bartonii*, the Appalachian brook crayfish also native to the Hudson River watershed, was caught at Indian Brook by hand-netting. More crayfish were caught by electroshocking than by hand-netting. Average catch per unit effort (CPUE) at sites that had more than two crayfish caught was 15 crayfish/hr by hand-netting and 33 crayfish/hr by electroshocking. There was not a significant difference in the size of crayfish caught between the two methods ($P>0.05$).

Eels and crayfish were not found together in high numbers in streams sampled (R^2=0.66, P<0.05; Fig. 3). Sites that had an abundance of crayfish had very few eels, and sites that had an abundance of eels had very few crayfish.

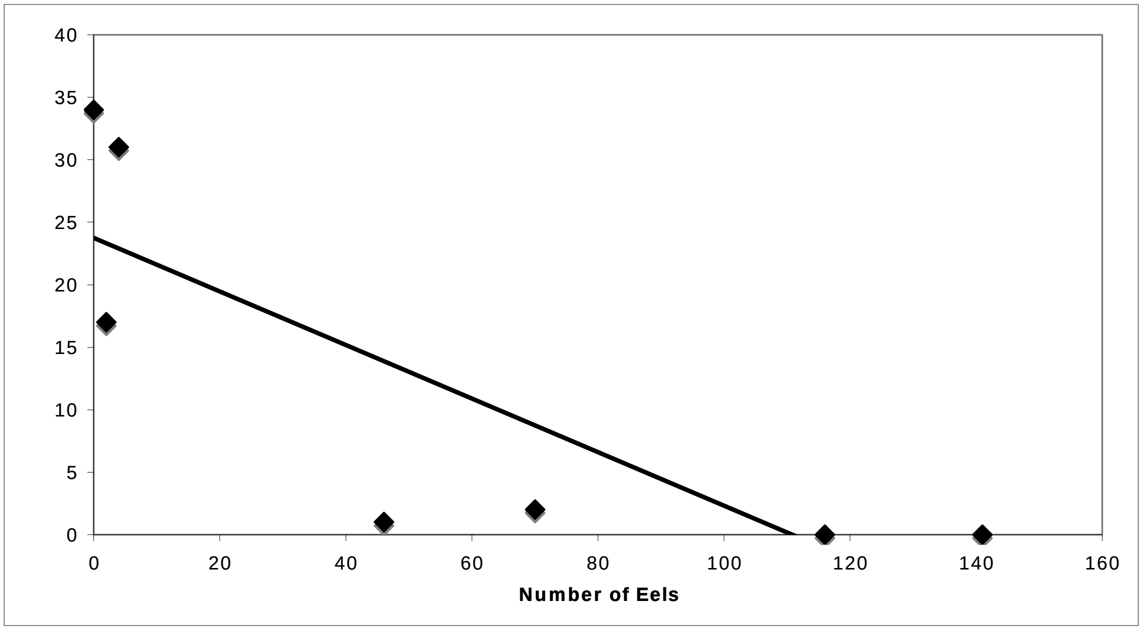

Figure 3: There was a significant negative relationship (R^2=0.66, P<0.05) between the number of eels present and the number of crayfish (of all species) present.

Shelter Use Alone

Spinycheek crayfish spent significantly less time in shelter when paired with an eel than when alone (P=0.01). Spinycheek crayfish unpaired with an eel spent an average of 65% (SE ±16) of observations in shelter, whereas spinycheek crayfish paired with an eel were never observed in the shelter alone. Shelter use by rusty crayfish, however, was not different when paired with an eel or not (P>0.05).

Shelter Competition

Eels spent more time in shelter than crayfish when the two species were paired in a tank. Eels paired with rusty crayfish spent an average of 69% (SE ±8.4) of observations in the shelter alone, while the rusty crayfish spent an average of 18% (SE ±7.7) of observations in the shelter alone ($P<0.05$; Fig. 4a). Eels paired with spinycheek crayfish spent an average of 77% (SE ±7.8) of observations in the shelter alone, while the spinycheek crayfish was never observed in the shelter alone ($P<0.05$; Fig. 4b).

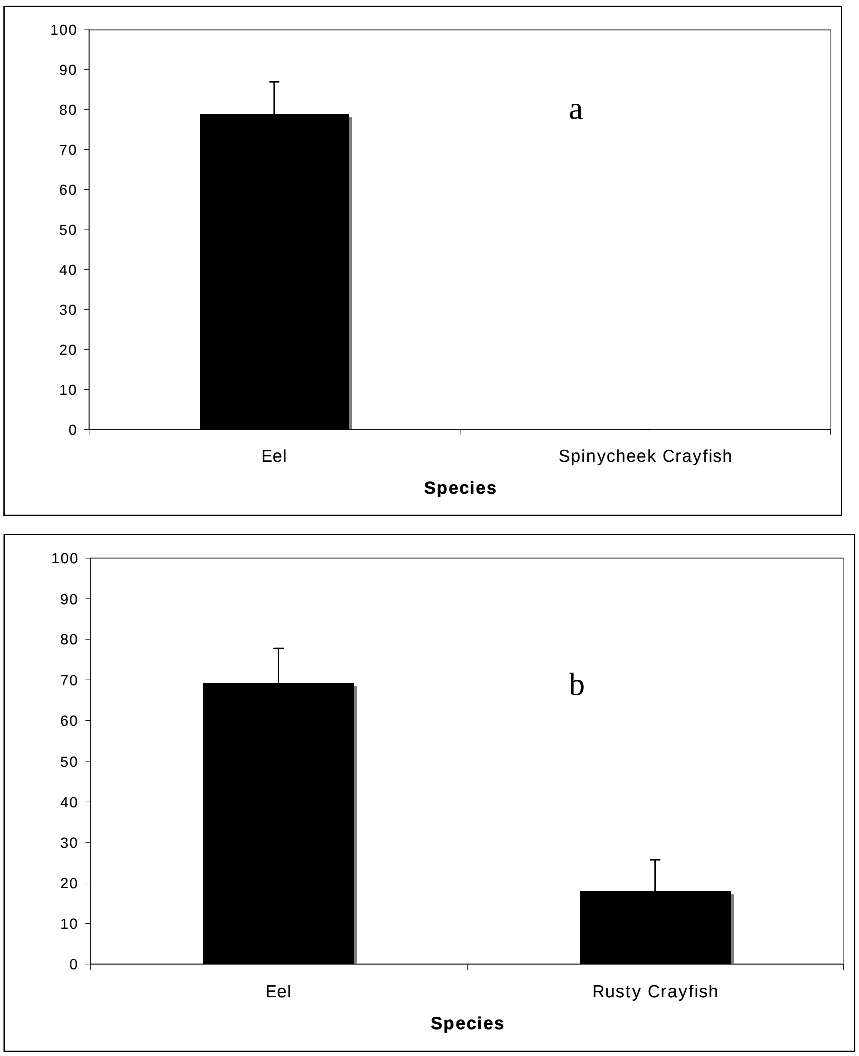

Figure 4: The average percent of observations (± SE) each species was in the shelter alone for **a**: pairings between eels and the invasive rusty crayfish, and **b**: pairings between eels and the native spinycheek crayfish. In both treatments, eels were observed in the shelter more often ($P<0.05$). Note that the spinycheek crayfish was never observed in the shelter alone.

There was a negative trend between size difference and the time rusty crayfish spent in shelter (Fig. 5). Rusty crayfish were only observed in the shelter alone when there was a small size difference between the eel and the crayfish.

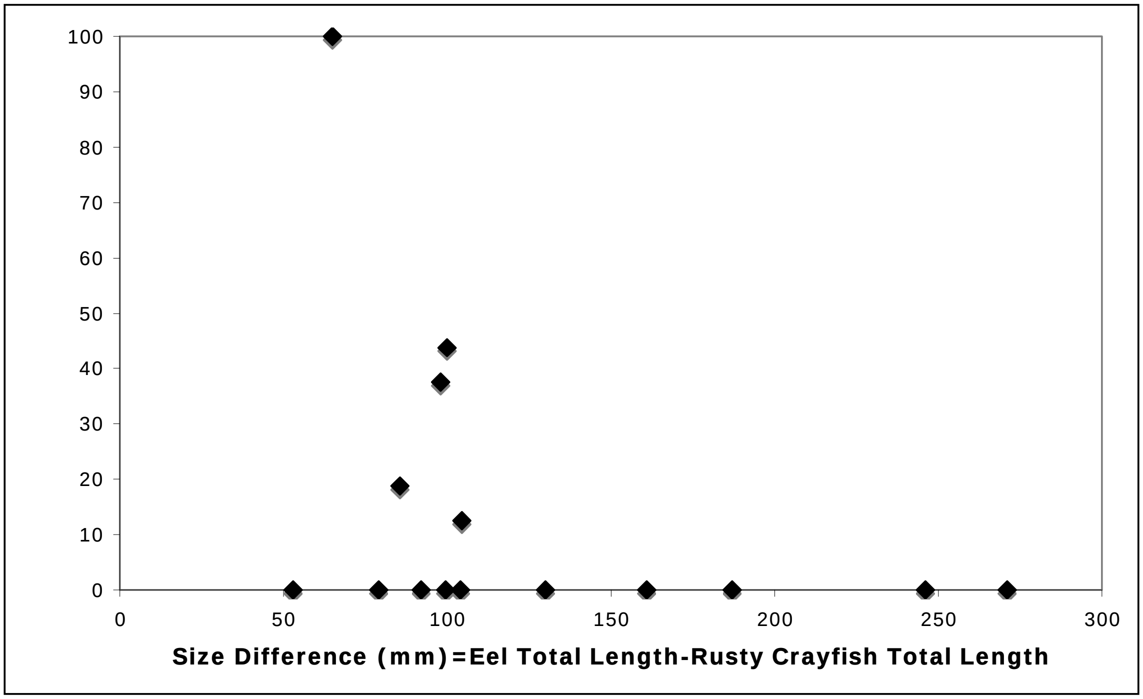

Figure 5: The relationship between shelter use by rusty crayfish and the size difference between eel total length and crayfish total length. Only when the size difference is small can rusty crayfish outcompete eels for shelter. Spinycheek crayfish, however, never outcompete eels for shelter. The linear relationship is not significant, ($P=0.23$) but it shows a negative trend.

An eel and a crayfish occasionally would share the shelter. Within an experimental period, spinycheek crayfish were observed more frequently sharing shelter than rusty crayfish (65% versus 22%; $P<0.05$). However, rusty crayfish shared shelter in more experimental replicates (7 out of 16 experiments) than spinycheek crayfish

(3 out of 15). In other words, rusty crayfish were more likely to share shelter, but spinycheek crayfish spent more time sharing shelter.

DISCUSSION

Eels and crayfish were not found together in high densities. This allopatric pattern was similarly observed in lakes of Sweden (Svardson 1972). Dense eel populations may be reducing crayfish populations through predation and competition. Crayfish are known to comprise a large portion of the diet of larger eels (Facey & LaBar 1981; Lookabaugh & Angermeier 1992; Machut 2006), especially in areas that have an abundance of eels. While field survey data cannot prove a causal relationship between the densities of eels and crayfish, it is possible that predation and competition is driving the relationship. Machut (2006) found crayfish in 58% of large eels (>400 mm) that had food in their stomachs in tributaries to the Hudson River. However, sites at the mouth of the stream and above barriers may be different in some other way not quantified in this study, such as algal or invertebrate abundance, that may affect population densities of eels and crayfish.

The field surveys also show the important impact of barriers on both eel and crayfish populations, supporting previous studies (Machut et al. 2007). Sites at the mouth of a stream have extremely high densities of eels because most of them cannot migrate above barriers. Crayfish populations are significantly lower at sites that have high numbers of eels possibly because eels eat crayfish and outcompete them for shelter. Covich et al. (2008) also show the importance of barriers in population dynamics of diadromous fish and their prey. They found that sites with predatory fish (including

American eels) had low numbers of shrimp, whereas sites above steep barriers and with no predatory fish had an abundance of shrimp. Covich et al. argue that the shrimp take refuge from fish predators in headwater sites that are above barriers, which is likely what is also happening between eels and crayfish in the tributaries sampled here.

Eels usually outcompete crayfish for shelter in the lab. In interactions between eels and the native spinycheek crayfish, eels always outcompete the crayfish for shelter, while the native crayfish did use the shelter not in the presence of an eel. In interactions between eels and the invasive rusty crayfish, eels outcompete the crayfish for shelter in the vast majority of cases (Fig. 4). Rusty crayfish are more aggressive than spinycheek crayfish, and the dominant crayfish outcompetes the subordinate crayfish for shelter (Klocker & Strayer 2004). Taking all three species into account, eels are the most competitive, rusty crayfish are less so, and spinycheek crayfish are the least competitive for shelter. Individuals who are outcompeted for shelter could be forced into less ideal shelters, become more vulnerable to predators, and possibly shift their behavior and feeding (Werner & Hall 1977).

Importantly, when the rusty crayfish is large and the eel is small, the rusty crayfish sometimes outcompetes the eel for shelter. The relationship is size dependent for the invasive species, but not for the native species (Fig. 5). However, at the same size difference between eels and crayfish, some rusty crayfish were observed in the shelter and some eels were observed in the shelter. It is unclear what conditions affect a large rusty crayfish's ability to outcompete eels for shelter. In laboratory experiments, glass eels were preyed upon by large crayfish, both native and non-native (C.L. Turrin, Cary

Institute of Ecosystem Studies REU, unpublished data). Therefore, large rusty crayfish can both prey upon eels and outcompete them for shelter.

Eel restoration efforts focused on lessening the impact and spread of the invasive rusty crayfish should focus on larger eels, instead of focusing on glass eels or elvers that may be vulnerable to predation or competition by rusty crayfish. In the future, the possibility of native species acting as biological controls should be considered as an important factor in controlling the impact and spread of harmful invasive species. Anthropogenic influences such as overfishing and man-made barriers can lessen the ability of native species to act as biological controls, and the benefits of these native species should be taken into account when designing policy.

Rusty crayfish have not invaded the tributaries sampled, which all had eels present. Only native species of crayfish were caught. It is possible that the presence of eels is preventing the invasion of rusty crayfish in the streams sampled. DeRivera et al. (2005) found that the native blue crab, *Callinectes sapidus*, controls the range of the invasive European green crab, *Carcinus maenas*, in eastern North America. They found a similar negative relationship between the abundances of the two crabs. From a combination of lab and field experiments, the authors conclude that predation on the invasive crab by the native crab provides a control on the spread of the invasive species. Predation was the only interaction DeRivera et al. formally investigated, although they do state that both crabs live in the same shelter and that other factors, such as competition, could contribute to the negative relationship in densities.

If rusty crayfish were to invade a stream with an established population of eels with varying sizes, eels could act as a native biological control by preying upon rusty crayfish and outcompeting them for shelter. It is possible that the presence of eels in the tributaries sampled, particularly the abundance of eels found at sites at the mouth of a stream, prevents successful colonization of rusty crayfish in those areas because not enough crayfish survive and reproduce. It is also possible, however, that rusty crayfish have simply not been introduced to those streams. If rusty crayfish were to invade a stream that did not have eels present, they could both displace the native crayfish species and prevent the establishment of eels by preying upon incoming migratory glass eels. Native species can have important effects on invasion success. Through predation and/or competition, a native species can lessen the negative impacts associated with an invasive species. In the future, native species should be considered as key candidates for biological controls, and the importance of native species on invasion should be considered for fisheries management to prevent overfishing of native predators.

ACKNOWLEDGEMENTS

First and foremost I would like to thank my advisors, Catherine O'Reilly and Dave Strayer. Thank you to the many other people without whom this project would not have been possible: Courtney Turrin, Bob Daniels, Bob Schmidt and interns, Chris Bowser and interns, Dan Miller, Vassar URSI students, Hannah Shapero, Wyatt Shell, Philip Pardi, Felicia Keesing, Philip Johns, Bill Perry, Maureen O'Callaghan-Scholl, Dwane Decker and the high school summer interns: Aidan Mabey, Preston Kemeny, Ian Hetterich, and Haley Van Vlack. Thank you to the Polgar Fellowship and Committee: Sarah Fernald, David Yozzo, and Helena Andreyko for funding this project.

REFERENCES

Capelli, G.M. 1982. Displacement of northern Wisconsin crayfish by *Orconectes rusticus* (Girard). Limnology and Oceanography 27: 741-745.

Carlsson, N.O.L., O. Sarnelle, and D.L. Strayer. 2009. Native predators and exotic prey – an acquired taste? Frontiers in Ecology and the Environment, doi: 10.1890/080093.

Covich, A.P., T.A. Crowl, C.L. Hein, M.T. Townsend, W.H. McDowell. 2008. Predator–prey interactions in river networks: comparing shrimp spatial refugia in two drainage basins. Freshwater Biology, doi:10.1111/j.1365-2427.2008.02121.x

Daniels, R.A. 1998. Changes in the distribution of stream-dwelling crayfishes in the Schoharie Creek system, eastern New York State. Northeastern Naturalist 5: 231-248.

DeRivera, C. E., G.M. Ruiz, A.H. Hines, and P. Jivoff. 2005. Biotic resistance to invasion: native predator limits abundance and distribution of an introduced crab. Ecology 86: 3364-3376.

Facey D.E. and G.W. LaBar. 1981. Biology of American eels in Lake Champlain, Vermont. Transactions of the American Fisheries Society 110: 396-402.

Feunteun, E. 2002. Management and restoration of European eel population (*Anguilla anguilla*): an impossible bargain. Ecological Engineering 18: 579-591.

Gruner, D.S. 2005. Biotic resistance to an invasive spider by generalist insectivorous birds on Hawaiin Islands. Biological Invasions 7: 541-546.

Gurevitch, J. and D.K. Padilla. 2004. Are invasive species a major cause of extinctions? Trends in Ecology and Evolution 19: 470-474.

Haro, A.J., W. Richkus, K. Whalen, A. Hoar, W.D. Busch, S. Lary, T. Brush, and D. Dixon. 2000. Population decline of the American eel: Implications for research and management. Fisheries 25: 7-16.

Keane R..M, and M.J. Crawley. 2002. Exotic plant invasions and the enemy release hypothesis. Trends in Ecology and Evolution 17:164–170.

King, R.B., J.M. Ray, K.M. Stanford. 2006. Gorging on gobies: beneficial effects of alien prey on a threatened vertebrate. Canadian Journal of Zoology 84: 108-115.

Klocker, C.A. and D.L. Strayer. 2004. Interactions among an invasive crayfish (*Orconectes rusticus*), a native crayfish (*Orconectes limosus*), and native bivalves

(Sphaeriidae and Unionidae). Northeastern Naturalist 11: 167-178.

Kolar, C.S., and D.M. Lodge. 2002. Ecological predictions and risk assessment for alien fishes in North America. Science 298: 1233-1236.

Lookabaugh, P.S. and P.L. Angermeier. 1992. Diet patterns of American eel, *Anguilla rostrata*, in the James River drainage, Virginia. Journal of Freshwater Ecology 7: 425-434.

Machut, L.S. 2006. Population dynamics, *Anguillicola crassus* infection, and feeding selectivity of American eel *(Anguilla rostrata)* in tributaries of the Hudson River, New York. Master's Thesis. SUNY College of Environmental Science and Forestry, Syracuse, NY.

Machut, L.S., K.E. Limburg, R.E. Schmidt, and D. Dittman. 2007. Anthropogenic impacts on American eel demographics in Hudson River tributaries, New York. Transactions of American Fisheries Society 136: 1699-1713.

Mack R.N., D. Simberloff, W.M. Lonsdale, H. Evans, M. Clout and F. Bazzaz. 2000. Biotic invasions: causes, epidemiology, global consequences and control. Ecological Applications 10: 689-710.

Olden, J.D., J.M. McCarthy, J.T. Maxted, W.W. Fetzer and M.J. Vander Zanden. 2006. The rapid spread of rusty crayfish (*Orconectes rusticus*) with observations on native crayfish declines in Wisconsin (U.S.A.) over the past 130 years. Biological Invasions 8: 1621-1628.

Perry, L.G., S.M. Galatowitsch, and C.J. Rosen. 2004. Competitive control of invasive vegetation: a native wetland sedge suppresses *Phalaris arundinacea* in carbon-enriched soil. Journal of Applied Ecology 41: 151-162.

Price J.E. and S.M. Welch. 2009. Semi-quantitative methods for crayfish sampling: sex, size, and shelter bias. Journal of Crustacean Biology 29: 208-216.

Rabeni C.F., K.J. Collier, S.M. Parkyn, and B.J. Hicks. 1997. Evaluating techniques for sampling stream crayfish *(Paranephrops planifrons)*. New Zealand Journal of Marine and Freshwater Research 31*:* 693-70.

Rahel, F.J. 2007. Biogeographic barriers, connectivity and homogenization of freshwater faunas: it's a small world after all. Freshwater Biology 52: 696-710.

Rahel, F.J., and J.D. Olden. 2008. Assessing the effects of climate change on aquatic invasive species. Conservation Biology 22: 521-533.

Santos, A.F.G.N., L.N. Santos, E. Garcia-Berthou, and C. Hayashi. 2009. Could native predators help to control invasive fishes? Microcosm experiments with the Neotropical characid, *Brycon orbignyanus*. Ecology of Freshwater Fish 18: 491-499.

Schmidt, R.E., C.M. O'Reilly, and D. Miller. 2009. Observations of American eels using an upland passage facility and effects of passage on the population structure. North American Journal of Fisheries Management 29: 715-720.

Svardson, G. 1972. The predatory impact of eel (*Anguilla anguilla* L.) on populations of crayfish (*Astacus astacus* L.). Rep. Institute of Freshwater Research Drottningholm 52: 149-191.

Torchin, M.E., and C.E. Mitchell. 2004. Parasites, pathogens, and invasions by plants and animals. Frontiers in Ecology and the Environment 2: 183-190.

Werner E.E., and D.J. Hall. 1977. Competition and shelter shift in two sunfishes (Centrarchidae). Ecology 58: 869-876.