AQUATIC INVASIVE SPECIES

Aquatic Nuisance Species-Evaluating the Ecological and Economic Value of the 100th Meridan Initiative

Final Report

Abstract

Private and public investments in prevention of the introduction and spread of invasive species are rare. This results in part from the lack of rigorous cost-benefit analyses. To remedy this situation with respect to the westward spread of zebra mussel in the US, we are addressing several questions in a step-wise manner: What is the probability of boaters accidentally moving live zebra mussels from the heavily invested Midwest to the western US? Results in a paper in review suggest that although this probability is low, it is important and poses a serious threat. Does the western US provide suitable habitat for zebra mussels? Results in a published paper suggest that parts of the Colorado, Columbia, and Sacramento-San Joaquin river systems do provide suitable habitat. What environmental and financial goods and services are at risk in these river basins, and what would be the financial impact if zebra mussels established? On-going analyses suggest that zebra mussels could substantially impact the infrastructure that exists in the Columbia and Colorado Rivers, including hydropower dams, water supplies and fish ladders (potentially causing damage to native salmonids). In just the Columbia River Basin we estimate a mean annual welfare loss of roughly $1.55 million. Finally, given what is at risk, what investments would it be prudent to make in prevention and possibly in control should zebra mussel become established in one or more locations in the west? On-going analyses will provide some possible answers to this final question.

Introduction

Estimates of the cost of zebra mussels to power plants and other water intake facilities in the Great Lakes region alone have been estimated to be at least $30 million per year. These costs do not include the on-going extirpation of native mussels and other undesirable environmental changes. For the foreseeable future, all these costs will be recurring annually and growing as zebra mussels inevitably spread in the Midwest and eastern US. Despite these impacts, concern for these issues among the public and policy makers is often quite low (Bossenbroek et al. 2005).

However, the opportunity exists to prevent such costs in the western US, where zebra mussels have not yet invaded. The 100th Meridian Initiative already provides the skeleton infrastructure needed to stop or slow the spread of zebra mussels into the western US, but the funding devoted to the effort is grossly inadequate to the need, and no guidance currently exists about how best to allocate funding to alternative methods of prevention and control. Specifically, then, robust numbers are needed on the likely financial impact of zebra mussel on water users if zebra mussel invaded the western US. Additional research would then be required to provide quantitative information on the cost effectiveness of specific alternative prevention and control options (e.g., education, inspections, boat washing, etc), so that government and private dollars may be invested appropriately.

In this project, we have used state of the art methods for bioeconomic risk analyses to integrate the best ecological, economic, and social information available to define optimal expenditures for prevention and control, providing guidance on the most cost effective allocation of those resources. Given time and funding constraints, we focused primarily on market values (much more easily attainable from existing sources than non-market values) and largely on two important western waterways. Market values provide a rough lower bound on the economic losses that would be suffered in the region if zebra mussels invaded. We have relied entirely on existing data, much of which, however, required great effort to obtain, transform into appropriate

parameters, and analyze. To identify potential habitat for zebra mussel, we conducted a niche modeling analysis covering all of the US. However, we focused our most intensive effort—including both environmental and economic analyses—on the Colorado River and the Columbia River.

Narrative Report

Our proposal focused on three central questions: 1) In what parts of the Columbia and Colorado river and reservoir systems are zebra mussels likely to thrive if they are introduced from infested eastern waters? 2) For those parts of the target river systems that meet the ecological requirements of zebra mussel, what a) environmental goods and services, and b) financial and commercial goods and services are at risk? 3) What are the costs and how effective are different prevention strategies? For the 100th Meridian Initiative, what is the most cost-effective level of investment in prevention and control? We highlight the status of our work under each issue below.

1) Probability of transport to the West and suitability of habitat in the Columbia and Colorado rivers.

Forecasting the introduction of zebra mussels into western waters requires an understanding of the probabilities of introduction and the habitat requirements of zebra mussels. Our modeling of the spread of zebra mussels to western rivers is based on gravity models, which are frequently used by geographers. Our gravity models estimate recreational boater movement patterns based on the distance to and attractiveness of different bodies of water. A global analysis of transport of ballast-vectored species like zebra mussels was in part inspired and supported by this project (Drake and Lodge 2004).

The mechanistic basis underlying gravity models was explored in order to assess the recreational boater pathway (Leung et al. 2006). We used production constrained gravity models to describe movement of recreational boaters between lakes – potentially the most important pathway of overland dispersal for many aquatic organisms including zebra mussel. We show that, despite their simplicity, gravity models are able to capture important characteristics of the recreational boater pathway. To assess our model we compared observed data based on creel surveys and mailed surveys of recreation boaters to the model output. Specifically, we evaluated four metrics of pathway characteristics: boater traffic to individual lakes, distances traveled to these lakes, Great Lakes usage and movement from the Great Lakes to inland waters. These factors influence the propagule pressure (hence the probability of establishment of invasive populations) and the rate of spread across a landscape. The Great Lakes are of particular importance because they are a major entry point of non-indigenous species from other continents, hence will act as the origin for further spread across states. The model output fit well with empirical observations suggesting that gravity models are generally useful for modeling invasion pathways between non-contiguous locations (Leung et al. 2006).

Based on our understanding of the mechanisms of spread, we constructed a gravity model to explore the movement patterns of recreational boaters on a national scale (Bossenbroek et al. in review). To quantify the potential spread of zebra mussels throughout the U.S. we developed a production-constrained gravity model. Our model was developed using 4-digit USGS Hydrologic Units (HUCS) to create 210 watersheds in the continental U.S. For each watershed we estimated the number of boaters and the attractiveness of each watershed based on lake surface area, rivers, and the amount of shoreline of the Great Lakes or oceans. We also estimated the attractiveness of oceanic Great Lakes shorelines based on two surveys of recreational boaters in Wisconsin and Oregon. To estimate the parameters of our model, we compared our model results with survey data collected via the 100th Meridian Initiative. Our model results are consistent with the observed slow range expansion of zebra mussels in recent years, and suggest that zebra mussel range expansion to western North American waterways via transient recreational boating activity is likely to be very slow. While we cannot provide an estimate of absolute probability, we do provide probabilities relative to those for eastern watersheds.

We also contributed to an assessement of the current and past distribution of zebra mussels at several scales, which quantified the slow range expansion and the low occurrence of long-overland dispersal events (Johnson et al. 2006). At the continental scale, we combined data from states for which more than 10 invaded lakes had been reported by 2003 to assess national trends. We found that only six states had more than 10 inland invasions observed, and they account for 97% of the 293 lakes reported to be invaded in the U.S. For the four states surrounding Lake Michigan, <8 % of suitable lakes greater than 25 ha had been invaded by 2003. Although the number of invaded lakes has increased over time, the rate of invasions has decreased. This analysis also suggests that up to one-third of the US lakes invaded by zebra mussels were invaded via downstream dispersal from already invaded lakes.

Zebra mussels have the ability to spread through streams, which we analyzed so that we could predict the likelihood that lakes will become infested if they are downstream of an infested lake (Bobeldyk et al. 2005). To examine this potential mechanism of spread, we (1) assessed populations of zebra mussels in 2000 and 2003 in over a dozen coupled lake-stream systems of the St. Joseph River basin (Indiana and Michigan, USA) and (2) examined the interconnectedness of lake-stream systems by evaluating all invaded inland lakes and reservoirs in the U.S. To assess if connectedness, as opposed to mere proximity, is related to the pattern of zebra mussel invaded lakes we identified all lakes within 1 km of a zebra mussel invaded lake and classified each lake as either “not connected”, “downstream” of an invaded lake, or “upstream” of an invaded lake. Our results suggest that when a lake contains zebra mussels, its outflowing stream and nearby downstream lakes are likely to be invaded by mussels. Though invaded, streams rarely had adult zebra mussels more than a couple of kilometers downstream of a source lake. Also, being connected downstream from a zebra mussel source was a good indicator of whether a lake is invaded. Over 90% of the lakes analyzed that were downstream of an invaded lake were also invaded. On the other hand, only 7% (6 of 84) of the lakes that were within 1 km of an invaded lake but not connected were invaded. These results will enable predictions of how quickly zebra mussels would spread at a local-scale when new basins, such as the Colorado and Columbia river basins, become invaded.

We have also assessed the ability of zebra mussels to become established in western rivers once transported there. We have done this at two different scales. On a national scale, we have predicted the suitable habitat for zebra mussels based on eleven environmental and geologic variables using a genetic algorithm for rule-set production (GARP; Drake & Bossenbroek 2004). GARP analysis, often called ecological niche modeling, estimates the potential suitable habitat of a species based on the available environmental variables and the current distribution of a species. Using this tool, we developed three models, the first using all the available variables and the second using only variables we thought were biologically relevant. Our third model was the same as the second with the removal of elevation as a variable. The results of the second model appeared to be driven mostly by elevation. For all three models, our results suggest that much of the western United States may not be as susceptible to zebra mussel invasion as previously thought. Our results, however, do predict that the river basins on which we have focused in this project are at significant risk (Drake & Bossenbroek 2004).

On a more localized scale, we collected more detailed water quality parameters from state and federal sources for the western rivers in order to predict the potential densities of zebra mussels if they were to become introduced into these systems (Bossenbroek et al. in review). Using a previously published model, we compared the data from the western rivers to water bodies with reported zebra mussel density. Water chemistry data for these water bodies were retrieved from the Washington Department of Ecology database (**http://www.ecy.wa.gov/database.html (http://www.ecy.wa.gov/database.html)**) for Lake Roosevelt and the EPA STORET database (**http://www.epa.gov/STORET (http://www.epa.gov/STORET)**) for the other water bodies. Based on these data and model, density predictions suggest that both Lake Mead (Colorado River) and Roosevelt Lake (Columbia River) could support substantial population densities of zebra mussels (Bossenbroek et al in review). Lake Mead would have considerably higher densities of zebra mussels than

Roosevelt Lake. Lake Mead would have the potential of maximum population densities reaching the 100,000s m-2, whereas Lake Roosevelt would most likely maintain more moderate populations in the 1000s m-2.

Our research on the dispersal and potential habitat of zebra mussels suggests that there is appropriate habitat in the Columbia and Colorado rivers. The dispersal of zebra mussels to this area via recreational boats has a low but non-trivial probability. Such transport has been observed multiple times for the Colorado and Columbia rivers, although whether the zebra mussels discovered were alive has not been ascertained.

2) Environmental and financial goods and services that are at risk in the river basin portions that are inhabitable by zebra mussel.

If zebra mussels become established in the Columbia and Colorado rivers they could cause significant impacts on the ecology and economy of these regions. We have accumulated data on the native biota found in the focal river basins and determined that for those taxonomic groups, such as freshwater mussels, that have been substantially impacted by zebra mussels in eastern waters, there are very few species of concern in the western United States. One major concern in the Columbia Basin, however, is the potential risk to the native salmonid species that pass through fish ladders. If fish ladders become encrusted with zebra mussels, salmonids could be damaged by rubbing against the sharp shells of zebra mussels.

Industries that would be most affected in the Columbia and Colorado river basins would be hydropower, agriculture (due to the reliance on irrigation) and water supply for household and industrial consumption. In Year 1, project postdoc Jon Bossenbroek undertook two trips to meet with individuals and organizations that were identified as stakeholders within the Colorado and Columbia river Basins. These trips laid the groundwork for identifying the scope and specific impacts that zebra mussels could have on these river systems. Compared to the Midwest, the west is more dependent on surface water supplies for power, drinking water and irrigation. This dependence highlights the importance of understanding the probability and impacts of a zebra mussel invasion. The leg work of these trips inspired our colleague Stephen Phillips, of the Pacific States Marine Fisheries Commission, to conduct a detailed assessment of the potential impacts of zebra mussels on the hydroelectric power dams of the Columbia River (Phillips et al. 2005). This analysis estimates “that the one-time cost for installing zebra mussel control systems at hydroelectric projects could range from the hundreds of thousands of dollars to over a million dollars per facility.”

To assess the economic impacts on the Colorado and Columbia river basins, we are assessing the potential costs at two scales: local and regional. At the local scale, we are building a Real Options model to account for various types of uncertainty, including the variability in zebra mussel populations. We have reported a preliminary exploration of this approach (Saphores & Shogren 2005). Following that work, we consider a situation where an exotic species (here zebra mussels) may invade an area and cause damages. In this situation, a resource manager needs to decide how to spend scarce resources on prevention (to keep the invader out), monitoring (to detect the invader quickly if it successfully settles in the area of interest), and control (to reduce its biomass), in order to limit damage costs caused by the invader. Her objective function is therefore to minimize the expected value of prevention, monitoring, control, and damage costs.

We focus here on the case where, if the invader successfully establishes in the area of interest, it cannot be eradicated; indeed, the only reliable way to get rid of zebra mussels may be to sufficiently lower a reservoir level, short of using harmful chemicals that may eradicate aquatic life. It thus makes sense to stop prevention efforts once the invader has successfully arrived. Moreover, if technology and the economy are in a steady state, there is no reason for prevention costs to vary over time.

We apply our model to the control of zebra mussels in Lake Roosevelt. We model prevention and monitoring efforts for the whole lake, but we analyze the control decision for different types of water intakes. This allows us to derive simple decision rules that help managers of various facilities when to take action to decrease the

density of zebra mussels after a successful invasion. Our approach also allows us to compare the value of monitoring and prevention, and to compare it to a pure adaptation strategy. In economic terms, an adaptation strategy entails no attempt to control the arrival of zebra mussels; instead, various facilities simply adapt (with increased costs, changes in practices, etc) to function in the presence of zebra mussels, assuming their arrival cannot be prevented.

At the regional scale, we estimate the impacts of a zebra mussel invasion on different economic sectors using computable general equilibrium modeling (CGE) so that we may capture both primary and secondary (indirect) effects. The data for the Columbia River basin (Washington, Oregon, and Idaho) was purchased from IMPLAN, and the model constructed. We are working with an existing model of the Colorado River basin to update it and extend it for our purpose. The goal of the CGE method is to estimate ranges in the expected increases in costs due to full infestation of zebra mussels in the river basins for agriculture, electricity generation, water-intensive industries, and municipalities.

Thus far, we have results for the Columbia Basin. In the Columbia Basin, the economy consists of households and producing sectors, linked to one another and the rest of the world through commodity and factor markets. The rest of the world includes both domestic trade (with the lower 48 states) and foreign trade. Zebra mussels are introduced to the model as affecting the production process of waters users of the Columbia River. Water of the Columbia River provides important inputs to several economic sectors of production. To evaluate the potential consequences of a zebra mussel invasion on industries of the Columbia River Basin, we engaged in an exhaustive literature search for enumerations on the costs of zebra mussel invasions. Lacking well defined spread, growth and abundance models of zebra mussel population dynamics following establishment, the analysis was limited to a binary problem: no zebra mussels or a “full” zebra mussel invasion (defined to be sector specific magnitudes of impacts from zebra mussel invasions observed elsewhere). Our search found observed costs of zebra mussel invasions for irrigated agriculture, independent power producers, municipal and industrial water users, federal power generation facilities and state and municipal power generation facilities. The impacts of zebra mussels are modeled through functions that relate invasions to an increase in the unit costs of effected industries. Zebra mussels cover surfaces and clog intake pipes for industries dependent on water of the Columbia River Basin, resulting in costly cleaning and reduced capacity. For each of the key industrial sectors potentially impacted by a zebra mussel invasion we detail the methodology employed to generate the changes in unit costs following an invasion.

The consequences of invasion-induced increased unit costs of affected sectors are evaluated using household welfare measures, calculated in relation to the benchmark equilibrium of (non-invaded) 2001 data. We employed a method that generated unbiased and asymptotically consistent estimators of welfare changes. To examine the sensitivity of the results to the precision of the cost impacts, three alternative specifications were made (high, medium and low precision), with altered low, central, and high cost impacts. For each level of unit cost precision, cost impacts were drawn at random to create an impact scenario. Following a random draw, the model is run using that scenario and equivalent variations are calculated. Repeating this process 10,000 times for each level of precision creates a distribution of welfare effects in terms of equivalent variations.

Our results indicate that a zebra mussel invasion of the Columbia River Basin would result in a mean annual welfare loss of roughly $1.55 million, with differential impacts across households. Households with annual incomes of $50-$75 thousand bear the largest proportion of mean welfare losses, while those households with smallest incomes have the smallest mean welfare change. Per household costs range from a low of $0.15 per household (for households with incomes less than $10 thousand) to a high of $2.35 per household (for households with incomes greater than $150 thousand). These results are a lower bound on the total potential costs of zebra mussels because they are derived from analyses based on market values only (and do not include environmental costs).

3) Cost-effective levels of investment in prevention and control for the 100th Meridian Initiative.
Based on the answers we've obtained to the first two questions in our study we have determined that the likelihood of a zebra mussel introduction into the Columbia and Colorado Rivers is low relative to eastern waters, but non-trivial. Likewise, the overall economic impact, based solely on estimates of market costs, is lower than some have expected. Our final goal is to combine the results of the first 2 questions to determine what it is worth spending to prevent an introduction of zebra mussels into the western waters. To achieve this goal we will attempt to develop at least a range of probabilities of introduction into the Colorado and Columbia Rivers. Given a range of probabilities and our estimated economic impact we will use bioeconomic models to determine cost-effective levels of investment in prevention and control.

Our bioeconomic models will enable mangers to find the appropriate balance between urgency and neglect. For example, investment in preventing an invasion may reduce the need for investment in control. Prevention (what economists call mitigation or self-protection) refers to management actions to reduce the probability of an invasion (e.g. education, quarantines, transport regulations). Control (what economists call adaptation or self-insurance) refers to management actions to reduce the effects of an invasion once it has occurred. The desirability of prevention efforts depends upon expected costs if an invasion occurs, which in turn requires ecological forecasts of the future likelihood and costs of an invasion. In this conceptual framework, the level of risk society should accept occurs when the projected damages are less than the costs associated with prevention and control (Finnoff et al. 2005). Our framework incorporates risk assessment and risk management, includes uncertainty distributions, and optimizes prevention and control options. The application of this framework is on-going and expected to reach completion within the next six months

Lay Summary
Invasive zebra mussels, which have spread throughout much of the eastern half of the U.S., clog intake pipes of power plants and water intake facilities. Some estimates of the current cost of this problem are upwards of $30 million per year, but the mussels and their damage are still spreading. Efforts to prevent zebra mussels from moving westward, such as the 100th Meridian Initiative, are poorly funded. In this project, we are using state of the art methods to integrate the best ecological, economic, and social information available to define optimal expenditures for prevention and control during the westward spread of zebra mussel.

To accomplish this goal, we are addressing several questions in sequence: What is the probability of boaters accidentally moving live zebra mussels from the heavily invested Midwest to the western US? Results suggest that although this probability is low relative to eastern waterways, it is important and poses a serious threat. Does the western US provide suitable habitat for zebra mussels? Parts of the Colorado, Columbia, and Sacramento-San Joaquin river systems do provide suitable habitat. Specifically, both Lake Mead of the Colorado River and Roosevelt Lake of the Columbia River provide water quality in which zebra mussels might thrive. We predict that Roosevelt Lake would have higher population densities than Lake Mead. What environmental and financial goods and services are at risk in these river basins, and what would be the financial impact if zebra mussels established? Zebra mussels could substantially impact the infrastructure that exists in the Columbia and Colorado Rivers, including hydropower dams, water supplies and fish ladders (potentially causing damage to native salmonids). In just the Columbia River basin we estimate a mean annual welfare loss to society of roughly $1.55 million. Finally, given what is at risk, what investments would it be prudent to make in prevention and possibly in control should zebra mussel become established in one or more locations in the west? We plan to answer this final question in the next six months.

International Applications
The science and policy of invasive species are extremely timely and important environmental and economic topics. Invasive species are increasing rapidly *worldwide*, are one of the top causes of global biodiversity loss and changes in ecosystem function, and are economically expensive (e.g., they are estimated to cost the US alone as much as $137 billion/yr). Forecasting the location of new invasions and developing risk analysis

frameworks to make policy decisions will allow us to respond most effectively to these environmental challenges. Thus, our continuing project will have rapid and important consequences on the science and policy of invasive species. Project personnel have already begun communicating results with international constituencies including researchers and managers in Australia and China. In October 2003, David Lodge, Reuben Keller and Brian Leung spoke at a Victorian state government Department of Conservation and Natural Resources seminar in Melbourne, Australia. Research Assistant Professor Leung presented the project to a workshop organized by the Great Lakes Commission, as specified in the proposal. David Lodge presented "Managing Invasive Species: A U.S. Perspective" to a gathering of Victoria state government officials on November 5, 2003. On the same trip, Lodge also spoke on November 6th at the University of Melbourne, and at the Marine Laboratory, CSIRO in Hobart, Australia.

In June 2004, Lodge was a plenary speaker at the Beijing International Symposium on Biological Invasions. During the same trip to China, he was also a speaker and workshop participant on Biocomplexity as part of a NSF delegation of ecologists. The delegation visited and Lodge spoke in an initial workshop in Beijing, and in a workshop at the Institute of Hydrobiology, Wuhan. This project was a component of each of these presentations.

Media Coverage

- *BioScience* news article (*BioScience* 54:615-621)
- *The Scientist* (**http://www.biomedcentral.com/news/20040322/03 (http://www.biomedcentral.com/news/20040322/03)**);
- *China Daily*, 5/04
    - **http://www.chinadaily.com.cn/english/doc/2004-05/29/content_334747.htm (http://www.chinadaily.com.cn/english/doc/2004-05/29/content_334747.htm)**
    - **http://www.chinadaily.com.cn/english/doc/2004-05/29/content_334764.htm (http://www.chinadaily.com.cn/english/doc/2004-05/29/content_334764.htm)**
    - **http://www.chinadaily.com.cn/english/doc/2004-05/29/content_334765.htm (http://www.chinadaily.com.cn/english/doc/2004-05/29/content_334765.htm)**
- *Notre Dame Magazine*, Winter 2003/04 (**www.nd.edu/~ndmag/w0304/ness.html (http://www.nd.edu/~ndmag/w0304/ness.html)**);
- We have provided a progress report to Robert Pittman of the US Fish & Wildlife Service. This report will be posted on the 100th Meridian Initiative web site (**http://www.100thmeridian.org/ (http://www.100thmeridian.org/)**);
- Lodge is quoted in a *National Geographic* story on species invasions that will be published in the March issue.
- Bossenbreok is quoted in "Researchers Studying Zebra Mussel Threat to Columbia Bain", Columbia Basin Bulletin, Jan14, 2005 (**http:www.cbbulletin.com/Archive/01142005/default.aspx (http://www.cbbulletin.com/Archive/01142005/default.aspx)**)

Partnerships With Other Institutions/Individuals

1) This project is a cooperative one with the US Fish and Wildlife Service, under a contract for $40,000 7/1/03-6/30/05. This leverages Sea Grant funding and influence because the USFWS leads the 100th Meridian Initiative, and will therefore be in a position to use project recommendations most quickly and effectively.

2) Our economist collaborators, Jason Shogren and David Finnoff, are operating under a subcontract from the University of Notre Dame to the University of Wyoming.

3) We have extended the project, via subcontract, to McGill University, because former Notre Dame Research Associate Professor Brian Leung left Notre Dame to become a faculty member at McGill.

4) We have added a collaborative partnership with economist Jean-Daniel Saphores at UC-Irvine because of his expertise with Real Option models.

5) We have extended the project to the University of Toledo, because former Notre Dame Postdoc Jon Bossenbroek left Notre Dame to become a faculty member at UT.

6) The Western Regional Panel of the Aquatic Nuisance Species Task Force has been supportive of our project from the beginning. Lodge will present an update to the panel in September 2006.

Publications (including reference cited above; reprints are provided of the 2 of these manuscripts that have appeared in print).

Barbier , E.B. and J.F. Shogren.2004. Growth with Endogenous Risk of Biological Invasion.Economic Inquiry **42**: 587-601.

Bobeldyk, A. M., J. M. Bossenbroek, M. A. Evan-White, D. M. Lodge, and G. A. Lamberti. 2005. Secondary spread of zebra mussels (*Dreissena polymorpha*) in lake-stream systems. Ecoscience **12**:414-421.

Bossenbroek, J. M., L. E. Johnson, B. Peters, and D. M. Lodge. in review. Forecasting the Westward Expansion of the Zebra Mussel in the United States. Conservation Biology.

Bossenbroek, J. M., J. McNulty, and R. P. Keller. 2005. Can ecologists heat up the discussion on invasive species risk? Risk Analysis **25**:1595-1597.

Drake, J. M., and J. M. Bossenbroek. 2004. The potential distribution of zebra mussels (*Dreissena polymorpha*) in the United States. BioScience **54**:931-941.

Drake JM, Lodge DM 2004. Global hot spots of biological invasions: evaluating options for ballast-water management. Proceedings of the Royal Society of London Series B **271**: 575-580.

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Johnson, L. E., J. M. Bossenbroek, and C. E. Kraft. 2006. Patterns and pathways in the post-establishment spread of non-indigenous aquatic species: The slowing invasion of North American inland lakes by the zebra mussel. Biological Invasions **8**:475-489.

Leung, B., J. M. Bossenbroek, and D. M. Lodge. 2006. Boats, pathways, and aquatic biological invasions: Estimating dispersal potential with gravity models. Biological Invasions **8**:241-254.

Leung, B., J. M. Drake, and D. M. Lodge. 2004. Predicting invasions: propagule pressure and the gravity of Allee effects. Ecology **85**:1651-1660.

Leung, B., D. Finnoff, J. F. Shogren, and D. Lodge. 2005. Managing invasive species: Rules of thumb for rapid assessment. Ecological Economics **55**:24-36.

Phillips, S., T. Darland, and M. Sytsma. 2005. Potential economic impacts of zebra mussels on the hydropower facilities in the Columbia River Basin. Pacific States Marine Fisheries Commission, Portland, OR.

Saphores, J. D. M., and J. F. Shogren. 2005. Managing exotic pests under uncertainty: optimal control actions and bioeconomic investigations. Ecological Economics **52**:327-339.

Presentations at conferences:

Bossenbroek, J.M., D.M. Lodge, J.M. Drake and B. Leung. 2004. Assessing the Potential Ecological and Economic Impacts of Zebra Mussels to Western River Systems. American Fisheries Society – Western Division Annual Meeting. March 2004, Salt Lake City, Utah.

Bossenbroek, J.M., D.M. Lodge, J.M. Drake and B. Leung. 2004. The Role of Habitat Suitability and Dispersal Potential in Limiting the Range of an Aquatic Invasive Species. 19th Annual Symposium of the International Association for Landscape Ecology. April 2004, Las Vegas, Nevada.

Bossenbroek, J.M., B. Leung, D.M. Lodge, and J.M. Drake. 2004. Habitat suitability and dispersal potential: Keys to understanding the range of an aquatic invasive species. Ecological Society of America Annual Meeting – Portland, OR.

Bossenbroek, J.M. 2005. Using gravity models to predict pathways of aquatic invasive species. 20th Annual Symposium of the International Association for Landscape Ecology. March 2005, Syracuse, New York.

Bossenbroek, J.M**.**, Finoff, D. C., Saphores, J. D., Lodge, D.M. 2005. Evaluating the 100th Meridian Initiative: What is it worth to keep zebra mussels out of the Columbia River? Estuarine Research Federation Biennial Conference. October 2005. Norfolk, VA.

Bossenbroek, J.M. 2006. The importance of stream connections for the dispersal of aquatic invasive species. 21st Annual Symposium of the International Association for Landscape Ecology. March 2006, San Diego, California.

Bossenbroek, J.M. 2006. The importance of stream connections for the dispersal of aquatic invasive species. IAGLR. May 2006, Windsor, Ontario.

Undergraduate/Graduate Students

This project partially supported graduate student Jody Murray.

Related Projects

EPA STAR program on Exploratory Research to Anticipate Future Environmental Issues, Biopollution. $450,000 for April 2001-July 2005. Lodge, P.I., with co-investigator Greg Dwyer. Predicting the identity, spread, and impact of future nonindigenous species in the Great Lakes.

USDA (Ottawa National Forest). $95,000 for Sept 2001-. Lodge, P.I. Monitoring and control of rusty crayfish.

National Science Foundation, Integrated Challenges for Research in Environmental Biology. $2,989,645 for September 2002-August 2007. Lodge, P.I., with the following Co-PIs or senior collaborators: Gary Lamberti (UND), Mark Lewis (U. Alberta), Hugh MacIsaac (U. Windsor), Jason Shogren (U. Wyoming), and David Finoff (U. Central Florida). Ecological forecasting and risk analysis of nonindigenous species: strategic optimization using a bioeconomic approach.

NOAA National Sea Grant. Lodge is unfunded Co-investigator for 2003-2005. One of 12 Co-investigators, with P.I. Doug Jensen, Minnesota Sea Grant. A National ANS Outreach Campaign for the Aquarium Industry and Hobbyist Consumers: A collaborative effort involving the Pet Industry Joint Advisory Council, the US Fish and Wildlife Service and the Great Lakes Sea Grant Network.

Great Lakes Protection Fund, Lodge participated in project led by William Weeks, Sommer Barnard Ackerson, Attorneys, “Risk Management and Risk Financing as Tools for Preventing Biological Pollution.” 2003-2004.

USDA ERS. $25,000 for 06/01/04-05/31/06. Shogren PI with participation from B. Leung and D. Finnoff. Integrating economics and biology for bioeconomic risk assessment/ management of invasive species.

USDA NRS/PREISM $250,000 for 01/01/07 – 12/31/08. Bossenbroek PI with Co-PIs Finoff and Louis Iverson of the US Forest Service, along with Senior Personnel Patrick Lawrence of Univ. of Toledo, Davis Snydor of the Ohio State Univ. and Anatha Prasad of the USFS. Evaluating the economic costs and benefits of slowing the spread of the emerald ash borer in Ohio and Michigan.

Graphs, figures, photos

We include a reprint of the Drake & Bossenbroek 2004 paper on potential habitat for zebra mussels throughout the United States. The figures in that paper illustrate the potential vulnerability of the Columbia, Colorado, and Sacramento-San Joaquin river systems to invasion. We also include the manuscript "Forecasting the Westward Expansion of the Zebra Mussel in the United States" (in review at Conservation Biology), which received mostly positive reviews. The figures in that paper illustrate the relative probability of zebra mussels being transported to the western U.S. and the potential abundances of zebra mussels in Lake Mead and Roosevelt Lake.

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Research Information

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- Initiation Date: December 16, 2003
- Completion Date: May 31, 2006
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Topics

- AQUACULTURE (/topic_aquaculture.php)
- AQUATIC INVASIVE SPECIES (/topic_ais.php)
- CLIMATE CHANGE (/topic_climate.php)
- COASTAL RESTORATION (/topic_coastal.php)
- GREAT LAKES ECOSYSTEMS (/topic_glecosystems.php)
- GREAT LAKES LITERACY (/education.php)
- MEDICINE DISPOSAL (http://web.extension.illinois.edu/unusedmeds/)
- NATURAL LAWN CARE (/l2l.php)
- NUTRIENTS (/topic_nutrients.php)
- RECREATION AND FISHERIES (/topic_recreation.php)
- RESILIENT COMMUNITIES (/topic_resilient.php)
- WATER RESOURCES (/topic_water.php)

Products

- AQUACULTURE (/products_aquaculture.php)
- AQUATIC INVASIVE SPECIES (/products_ais.php)
- CLIMATE CHANGE (/products_climate.php)
- COASTAL RESTORATION (/products_coastal.php)
- EDUCATION (/products_education.php)
- FISH CONSUMPTION (/products_fishcon.php)
- GREAT LAKES HEALTH (/products_glhealth.php)
- LAND USE PLANNING (/products_landuse.php)
- MEDICINE DISPOSAL (/products_gros.php)
- PROGRAM (/products_program.php)
- NATURAL LAWN CARE (/products_lawncare.php)
- WATER RESOURCES (/products_water.php)

Resources

- ABOUT US (/about.php)
- CHICAGO WATER WALK APP (http://www.chicagowaterwalk.org/)
- FUNDING (/funding.php)
- NEWSROOM (/newsroom)

- OTHER WEBSITES (/other_sites.php)
- PEOPLE (/staff.php)
- PHOTOS (http://iisg.photoshelter.com/)
- SOCIAL SCIENCE (/glssn.php)
- TEACHERS (/education.php)

Careers

- TEACHER TRAINING (/education.php)
- FELLOWSHIPS (/fellowships.php)
- INTERNSHIPS (/internship.php)
- SOCIAL SCIENCE (/glssn.php)

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Sea Grant (http://www.seagrant.noaa.gov/)

NOAA (http://www.noaa.gov/)

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