GREAT LAKES FISHERY COMMISSION

2003 Project Completion Report[1]

Predicting the identity, spread, and impact of future nonindigenous species in the Great Lakes

by:

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Abstract

The goal of this project was to develop techniques for predicting future invasions of nonindigenous species in the North American Great Lakes from ships' ballast water and other vectors. Specifically we (1) identified and quantified organisms introduced in ballast water; (2) used theoretical models to identify conditions conducive to establishment and to determine how risk changes with the number of organisms introduced based on the number required to establish a self-sustaining population; and (3) we related different stages of the invasion process to characteristics of different aquatic species and screened species from different regions that are likely to be introduced to the Great Lakes. (1) was accomplished by sampling ballast tanks from ships entering the Great Lakes, processing samples to separate viable propagules from detritus and sediment, and identification and enumeration of organisms. (2) was accomplished by modeling the representative species spiny water flea (*Bythotrephes longimanus*) and Eurasian ruffe (*Gymnocephalus cernuus*) using population viability analysis (PVA) techniques. (3) was accomplished using multivariate statistical techniques including discriminant analysis, categorical and regression trees, and logistic regression. This study will produce the most highly resolved species list for ballast water introductions in the Great Lakes. Additionally, our study (along with an ongoing study in Canada) is the first to quantify the propagule pressure of resting eggs from ballast tank sediments. These results are providing important information for developing ballast water policy, managing the risk of future invasions, and understanding the population dynamics of currently invading species.

Final Report for Great Lakes Fisheries Commission

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Date of Report: December 18, 2003
Title: Predicting the Identity, Spread, and Impact of Future Nonindigenous Species in the Great Lakes
Investigators: Dr. David M. Lodge
Institution: University of Notre Dame, University of Chicago
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The grant from GLFC was used in conjunction with a grant from EPA R-82889901-0, which ends in July, 2004. Thus the project continues until that time. This report describes the latest progress towards the project goals and was also submitted to the EPA as an annual report.

Objective(s) of the Research Project: The overall objective of our research was to develop techniques for predicting future invasions of nonindigenous species Our model system is aquatic organisms introduced to the North American Great Lakes in ballast water from ships, though we are also considering trade in aquatic plants and pets, too. Specific goals are to:

1) Identify and quantify organisms introduced in ballast water;
2) Use theoretical models to identify conditions conducive to establishment and determine how risk changes with the number of organisms introduced based on the number required to establish a self-sustaining population;
3) Relate different stages of the invasion process to characteristics of different aquatic species and screen species from different regions that are likely to be introduced to the Great Lakes.

Objective (1) will be accomplished by sampling ballast tanks from ships entering the Great Lakes, processing samples to separate viable propagules from detritus and sediment, and identification and enumeration of organisms. Objective (2) will be accomplished through mathematical modeling of representative species using population viability analysis (PVA) techniques. Objective (3) will be accomplished using multivariate statistical techniques including discriminant analysis, categorical and regression trees, and logistic regression. These results will be applied to species lists for regions of concern to highlight species requiring special attention.

Progress Summary/Accomplishments:

Progress toward (1): Sample collection and isolation of organisms is complete. Summary statistics for collected samples have been compiled. Specific taxonomic identifications are underway. Active subcontracts or partnerships with taxonomic specialists are with James Vancil (aquatic ecologist, Knoxville, Tennessee) for species identification of adult invertebrates and Timothy Wood (Wright State University) for species identification of bryozoan resting stages (statoblasts).

A large number of invertebrate resting stages were isolated during the completion of objective (1). Therefore, we conducted a pilot study to determine the feasibility of extracting DNA from batches of resting eggs using a combination of molecular techniques (denaturing gradient gel electrophoresis and gene sequencing) and statistical analyses (bootstrap) to isolate and identify organisms based on sequences of mitochondrial (COI) and nuclear ribosomal (18S) genes. Results from this pilot study indicate that this approach is feasible. Using these data, Drake and Lodge obtained a doctoral dissertation improvement grant from NSF to carry out further analyses using these methods. We have determined that this work should be carried out under the direction of Greg Dwyer at the University of Chicago (a co-PI on the EPA grant) in order to capitalize on facilities and on-site genetic expertise available there. Using funds allocated to Dwyer from EPA grant R-82889901-0 (originally earmarked for hiring a postdoctoral researcher), we have arranged the necessary personnel for completing this further investigation. Thus, objective (1) is near completion.

The practical importance of these results is twofold. First, we believe that when complete our analysis will be the most highly resolved species list for ballast water introductions in the Great Lakes. Second, our study (along with an ongoing study in Canada) is the first to quantify the propagule pressure of resting eggs from ballast tank sediments. A tentative inference from these results is that release of sediments may be even more important than the release of ballast water in initiating invasions. Consider, for example, that collected sediments contained more propagules per volume by two or three orders of magnitude than ballast water. This is particularly important because ships declared NOBOB (no ballast on board) are not as strictly regulated as ballasted ships, though they are the most likely to introduce resting eggs. Our quantification of these two sources will assist managers and policy makers in developing crucial ballast water management approaches.

Progress toward (2): We have selected two invasive species, representing two life histories, for analysis. First, population viability analyses for the predatory zooplankter *Bythotrephes longimanus* are presently being validated with a bootstrap technique and results are being prepared for publication. In addition to its usefulness for assessing invasion risk, this analysis is the first to model population growth as a non-homogeneous birth-death process, a modeling framework that allows us to distinguish "windows" of high invasion risk (midsummer) from times when invasion risk is negligible (winter). Breakpoints between these times are quantitatively analyzed with our technique. We are presently extending these techniques to another species of considerable concern, *Cercopagis pengoi.* Second, we have completed a population viability analysis for an introduced fish, Eurasian ruffe (*Gymnocephalus cernuus*). This analysis found no evidence for Allee effects (inverse density dependence) in ruffe. An integro-difference model to integrate spatial spread with ruffe life history is also under development. We hope that this model will indicate if local intervention in population growth (*e.g.* harvesting) can be a useful tool for managing this invasive species.

A general model relating the chance of invasion to propagule pressure for parasitized species was developed and published earlier this year (Drake 2003) under the auspices of this grant. Finally, to facilitate the application of scientific theory to ballast

water policy, we developed a general model that related the chance of invasion to the volume of ballast water discharged and organism body size for sexually reproducing organisms. This model expands a previously published model that related minimal patch size for persistence to population growth rate. A known allometric relation between organism body size and population growth rate was used to generalize this model for ballast water policy. The results of this research have been submitted for publication. Two other projects have been partially supported by this grant. First, a global model of ballast water introduction hotspots was developed based on patterns of shipping traffic (manuscript submitted). Second, we conducted an experiment with the laboratory model organism *Daphnia magna* to test the premise that environmental variation increases the chance of extinction, a theoretical prediction that is central to population viability analysis (manuscript submitted).

Progress toward (3): We are continuing work toward statistical models identifying potentially invasive fishes from a list of 1,487 fish stocks from Chinese waters. When this analysis is complete we intend to assess risk from other temperate regions of Asia. We have developed a statistical model relating economic damages of mollusks to their individual lifetime fecundities. We are presently preparing these results for publication. Finally, consistent with our proposed schedule, we are conducting a similar analysis for macrophytes, including the aquatic weed Eurasian watermilfoil (*Myriophyllum spicatum*).

Conclusions:
Together, these three components of our research are providing important information for developing ballast water policy, managing the risk of future invasions, and understanding the population dynamics of currently invading species. As reported previously, our progress toward goal one was hampered by the quality of data that could be obtained by hatch-out experiments. However, we believe we will be able to overcome these obstacles using an approach combining molecular and statistical analyses. Methods for this analysis have been worked out and additional funds have been obtained from the NSF to purchase additional materials and supplies. Our progress toward goal two has now exceeded the pace anticipated in the original proposal. Several models have been published or submitted for publication. Additional models are ready for use with data from our sampling project. Our progress toward goal three is mixed. We have been extremely successful in developing models to predict risk of invasion of fishes and moderately successful for mollusks. We will not be able to conduct similar analyses, however, for phytoplankton and zooplankton because data on historical introductions are insufficient. An analysis for macrophytes is underway.

Publications/Presentations:
Publications:
Drake, J.M. and J.M. Bossenbroek. The potential distribution of zebra mussels (*Dreissena polymorpha*) in the U.S.A. (submitted to *BioScience*)

Clark, J.S., S.R. Carpenter, M. Barber, S. Collins, A. Dobson, J. Foley, D.M. Lodge, M. Pascual, R. Peilke, Jr., W. Pizer, C. Pringle, W.V. Reid, K.A. Rose, O. Sala, W.H. Schlesinger, D. Wall, and D. Wear. 2001. Ecological forecasts: an emerging imperative. *Science* 293:657-660.

Drake, J.M. and D.M. Lodge. Effects of environmental variation on extinction and establishment. *Ecology Letters* 7:26-30

Drake, J.M and D.M. Lodge. Hotspots for biological invasions determined from global pathways for non-indigenous species in ballast water. In press *Proceedings: Biological Sciences*.

Drake, J.M., M. Lewis, and D.M. Lodge. Is dilution a solution to exotic species invasions? A recommendation for provisional ballast water standards (submitted to *Ecological Applications*).

Drake, J.M. (2003) The paradox of the parasites: implications for biological invasion. *Proceedings of the Royal Society of London, Series B, Supplement (Biology Letters)* (published online DOI 10.1098/rsbl.2003.0056)

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

Leung, B., D.M. Lodge, D. Finnof, J.F. Shogren, M.A. Lewis, G. Lamberti. 2002. An ounce of prevention of a pound of cure: bioeconomic risk analysis of invasive species. *Proc. R. Soc. Lond. B* 269:2407-2413.

Drake, J.M. (2003). Allee effects and the risk of biological invasion. In press *Risk Analysis*.

Leung, B., J.M. Drake, and D.M. Lodge. (2003) Predicting invasions: propagule pressure and the gravity of Allee effects. In press *Ecology*.

Sakai, A.K., S.G. Weller, F. W. Allendorf, J. S. Holt, D. M. Lodge, J. Molofsky, K. A. With, S. Baughman, R. J. Cabin, J.E. Cohen, N.C. Ellstrand, D. E. McCauley, P. O'Neil, I.M. Parker, and J. N. Thompson. 2001. The population biology of invasive species. *Annual Review of Ecology and Systematics* 32:305-332.

Presentations:

Drake, J.M., M.A. Lewis, and D.M. Lodge. 2003. Policy Recommendations for Ballast Water Standards. 12th annual Aquatic Nuisance Species conference, 2003, Windsor, Ontario (presentation).

Drake, J.M., D.M. Lodge, N.Yan. "Allee effects and the success of colonizing species: *Bythotrephes longimanus* in North America" Ecological Society of America, annual conference 2002, Tucson, Arizona.

Drake, J.M., D.M. Lodge, K.L.S. Drury, G. Dwyer. "Predicting invasion success: Deriving standards for ballast water from theoretical models" 11th annual Aquatic Nuisance Species conference, 2002, Washington D.C.

Drake, J.M., D.M. Lodge, K.L.S. Drury, G. Dwyer. "Predicting invasion success: Applying probabilistic models of population growth to invading species". International Association of Great Lakes Research annual conference 2001, Green Bay, Wisconsin.

Drake, J.M., D.M. Lodge, K.L.S. Drury, G. Dwyer. "Predicting the success of invading species: applying stochastic models of population growth and the role of Allee effects". Society for Conservation Biology annual conference 2001, Hilo, Hawaii.

Drake, J.M., D.M. Lodge, "Estimating the Risk of Invasion by *Bythotrephes* with Theoretical Models." Presented at University of Notre Dame, All University Symposium on Research in the Environmental Sciences. 13 November 2002. (poster)

Drake, J.M., D.M. Lodge, N. Yan. "Why it takes more than one *Bythotrephes* to cause an

invasion." Presented at "Risk Assessment for Invasive Species: Perspectives from Theoretical Ecology" a joint workshop of the Ecological Society of America and the Society for Risk Analysis, New Mexico State University, Las Cruces, New Mexico, 21-23 October 2001. (poster)

Leung, B., D. M. Lodge, D. Finnoff, J. F. Shogren, M. A. Lewis, G. Lamberti. "Biological Invasions: Prediction, Risk and Action". 2002 University of Alberta Mathematical Biology Seminar Series. Edmonton, Alberta, Nov 18, 2002 (Invited).

Leung, B., D. M. Lodge, D. Finnoff, J. F. Shogren, M. A. Lewis,G. Lamberti. "Bioeconomic risk analysis of invasive species: Strategic optimization using dynamic programming" Ecological Society of America (ESA). Tucson, Arizona Aug 7, 2002

Leung, B., D. M. Lodge, D. Finnoff, J. F. Shogren, M. A. Lewis, G. Lamberti. "Bioeconomic risk analysis of invasive species: Strategic optimization using dynamic programming". 2002 University of Alberta Mathematical Biology Seminar Series. Edmonton, Alberta, Apr 15, 2002. *Invited*.

Lodge, D.M. 2003.Invited symposium speaker, EPA Environmental Research Seminar, Chicago, 6/03.

Lodge, D.M. 2003. Invited speaker, Univ of Wyoming Bioinvasions Workshop, 6/03.

Lodge, D.M. 2003. Invited speaker, Society of Conservation Biology symposium on Values and Ecosystem Management of the Great Lakes, Duluth, 6/03.

Lodge, D.M. 2003. NSF Workshop on China-US ecological cooperation, Arizona State Univ, 4/03.

Lodge, D.M. 2003. Invited speaker, symposium on invasive species, Illinois State University, 4/03.

Lodge, D.M. 2003. Great Lakes Panel of the Aquatic Nuisance Species Task Force, Ann Arbor, 12/02.

Lodge, D.M. 2003. International Joint Commission Symposium on Invasive Species, Ann Arbor, 9/03.

Lodge, D.M. 2001. Invited presentation, AAAS symposium on "Stopping the invasions."

Lodge, DM. 2001. Progress in invasion biology: understanding the occurrence and impact of nonindigenous species. Invited symposium presentation, Ecological Society of America (ESA).

Lodge, D.M. 2002. Invited seminar, NOAA Pacific Northwest Science Center, NIMFS, Seattle.

Lodge, D.M. 2002. Invited seminar, NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, MI.

Lodge, D.M. 2002. Invited seminar, Dept. of Fisheries and Wildlife, Colorado State University.

Lodge, D.M. 2002. Invited seminar, Nicholas School of the Environment, Duke University.

Lodge, D.M. 2002. Using ecological models to forecast establishment, spread, and impact of nonindigenous species. Invited symposium presentation, Ecological Society of America (ESA).

Lodge, D.M. 2002. Risks, uncertainties, and values in prevention and management of nonindigenous species. Invited talk, Maryland Sea Grant meeting on Management of Invasive Species in Chesapeake Bay. Baltimore, MD.

Lodge, D.M. 2002. Invited presentation to Great Lakes Panel of the Aquatic Nuisance Species Task Force, Ann Arbor.
Lodge, D.M. 2002. Invited presentation, Mayor Daley's "Great Lakes—Great Ideas" Great Lakes Mayors' Initiative.

Future Activities:
During the next phase of this project we plan to complete the molecular/statistical analysis of resting eggs with additional support obtained from the NSF (doctoral dissertation improvement grant to Drake and Lodge). These results will be used as initial conditions in models for establishment and spread. We will use existing statistical models to extrapolate from our samples to estimate the total number of organisms and total number of species introduced to the Great Lakes in ballast water and sediments each year. Finally, we will conduct a sensitivity analysis on our predictive models for invasive fishes and complete screening of possible invasive fishes from different regions of the world. We will submit for publication our analysis for mollusks and complete our analysis of macrophytes. Though we have presented preliminary results and professional meetings and have completed some publications, more extensive publications of our analysis will be the focus of our final year of research. In particular, we are pursuing the publication of a book-length monograph summarizing the results of this study.

Supplemental Keywords:
Risk Assessment: exposure, risk, risk assessment, effects, ecological effects, sensitive populations, dose-response, animal, organism, population, stressor, susceptibility, cumulative effects
Ecosystem Protection: ecosystem, aquatic, habitat
Risk Management: life-cycle analysis,
Public Policy: public policy, decision making, conservation,
Scientific Disciplines: biology, ecology, limnology
Methods/Techniques: modeling, monitoring, analytical, surveys
Geographic Areas: Great Lakes, Midwest
Sectors: business, transportation

Relevant Web Sites: N/A