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Invasive Species Research to Meet the Needs of Resource Management and Planning

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Abstract: *As zebra mussels* (Dreissena polymorpha) *continue to spread among inland lakes of the United States and Canada, there is growing interest from professionals, citizens, and other stakeholders to know which lakes are likely to be colonized by zebra mussels. Thus, we developed a classification of lake suitability for zebra mussels on the basis of measured or estimated concentrations of dissolved calcium in lake water and applied the classification to >11,500 lakes in Wisconsin and the Upper Peninsula of Michigan. The majority of lakes (58%) were classified as unsuitable (<10 mg/L Ca) for survival and reproduction of zebra mussels, 27% were identified as suitable (≥21 mg/L Ca), and 15% were classified as borderline suitable (≥10 and <21 mg/L Ca). Of the 77 inland lakes with confirmed zebra mussel records for which data on dissolved calcium were available, our method classified 74 as suitable and 3 as borderline suitable. To communicate this lake-specific suitability information and to help prioritize regional efforts to monitor and prevent the expansion of zebra mussels and other invasive species, we developed a web-based interface (available from http://www.aissmartprevention.wisc.edu/). Although we are still uncertain of how access to suitability information ultimately affects decision making, we believe this is a useful case study of building communication channels among researchers, practitioners, and the public.*

Keywords: calcium concentration, communication, conductivity, GIS, invasive species, suitability, zebra mussel

Investigación de Especies Invasoras para Satisfacer las Necesidades del Manejo y Planificación de Recursos

Resumen: *A menudo que continua la expansión de almejas* (Dreissena polymorpha) *hacia los lagos interiores de Estado Unidos y Canadá, hay un creciente interés entre profesionales, ciudadanos y otros actores para saber que lagos tienen probabilidad de ser colonizados por las almejas. Por lo tanto, desarrollamos una clasificación de la idoneidad de lagos para almejas con base en las concentraciones, medidas o estimadas, de calcio disuelto en el agua y aplicamos la clasificación a >11,500 lagos de Wisconsin y la Península Superior de Michigan. La mayoría de los lagos (58%) fueron clasificados como no idóneos (<10mg/L Ca) para la supervivencia y reproducción de almejas, 27% fueron identificados como idóneos (≥21 mg/L Ca) y 15% fueron clasificados como idóneos marginales (≥10 y ≥21 mg/L Ca). De los 77 lagos interiores con registros confirmados de almejas y con datos disponibles de calcio disuelto, nuestro método clasificó 74 como idóneos y 3 como idóneos marginales. Para comunicar esta información sobre idoneidad de lagos específicos y para ayudar a priorizar esfuerzos regionales para monitorear y prevenir la expansión de almejas y otras especies invasoras, desarrollamos una interfaz basada en la web (disponible en http://www.aissmartprevention.wisc.edu/). Aunque aun estamos inciertos de la manera en que esta información sobre idoneidad afecta la toma de decisions, consideramos que es un caso de estudio útil para la construcción de canals de comunicación entre investigadores, practicantes y el público.*

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Introduction

Communication of environmental science research findings to natural resource managers and civil society has been limited (e.g., Opdam et al. 2001; McNie 2007; Knight et al. 2008). The extent and forms of involvement needed from researchers to inform management of natural resources remains unclear. Often a disproportionately large amount of time is invested in refining research techniques compared with time invested in communicating results to parties other than scientists (Knight et al. 2008).

One of the proposed strategies for bridging the gap between scientists and practitioners is a "policy-focused assessment" (Scheraga & Furlow 2001) in which scientists work with practitioners to identify information needs and useful mechanisms for communicating research results. Management of non-native invasive species is an example of a complex situation that requires diverse forms of scientific input at different stages of the management process (Buckley 2008). Invasive species are an increasingly important driver of global environmental change (Mooney & Cleland 2001), yet invasive species research is not often conducted with the aim of direct translation into management practices. Thus, it can be difficult for practitioners to apply research findings to efforts to prevent and control establishment or expansion of invasive species (Leung et al. 2005; Lodge et al. 2006).

Since its appearance in Lake St. Clair, near Detroit (U.S.A.), over 20 years ago, zebra mussel (*Dreissena polymorpha*) has been one of the most intensively researched invasive species (Hebert et al. 1989). The strong interest in this invader stems in part from its major economic effects, primarily through the clogging of water intake pipes and other infrastructure (Connelly et al. 2007), and dramatic effects on the structure and function of aquatic ecosystems, such as aquatic food webs and energy flow (reviewed by Strayer [2009] and Higgins and Vander Zanden [2010]).

We worked closely with staff of the Wisconsin Department of Natural Resources (hereafter state agency) to prioritize research plans for and disseminate research results on zebra mussels and other invasive species of interest to the wider community of stakeholders. Through these discussions, we decided that forecasting the spread of invasive species on the basis of environmental suitability would allow practitioners to more effectively allocate their efforts to prevent and detect new introductions early on (Vander Zanden & Olden 2008). We assessed and mapped the suitability of lakes in Wisconsin and the Upper Peninsula of Michigan for zebra mussels. The map is designed to be used by practitioners to prioritize locations for field surveys and efforts to prevent introductions. In contrast with previous spatially extensive studies on the potential distribution of zebra mussels (e.g., Strayer 1991; Drake & Bossenbroek 2004; Whittier et al. 2008), we provide lake-specific classification of invasion potential and an avenue through which to communicate research results to practitioners.

Methods

Lake Calcium Concentrations

The concentration of dissolved calcium in a body of water affects the reproductive success of zebra mussels (Sprung 1987) and thus functions as a physiological constraint to the distribution of this species. First, we compiled the findings from 7 studies of the effects of calcium concentration on adult and larval zebra mussels (Sprung 1987; Strayer 1991; Ramcharan et al. 1992; Mellina & Rasmussen 1994; Hincks & Mackie 1997; Allen & Ramcharan 2001; Jones & Ricciardi 2005). From the results of these studies, we determined the mean and 95% lower and upper confidence intervals (CIs) of calcium that zebra mussel can tolerate. We classified lakes with calcium concentrations below 95% CI as unsuitable for mussels, lakes with calcium concentrations between 95% CIs as borderline suitable for mussels, and lakes with calcium concentrations at or above the upper 95% CI as suitable for mussels.

Second, we assembled data on calcium concentrations in 1207 lakes in Wisconsin and 149 lakes in the Upper Peninsula of Michigan from various sources (Supporting Information). This represents < 10% of the total number of lakes in Wisconsin and the Upper Peninsula. The sources from which we obtained the calcium data also contained data on the conductivity of most lakes in Wisconsin. Calcium accounts for over half of the cations in the majority of lakes on both noncalcareous and calcareous substrates in Wisconsin (Rodhe 1949; Gorham et al. 1983); thus, conductivity is expected to be correlated positively with calcium concentration. We conducted a linear regression of observed calcium concentration on conductivity for 433 Wisconsin lakes (of 1207 lakes) for which both calcium and conductivity data were available (Linthurst et al. 1986; Kratz et al. 1997; USGS 2009; see Supporting Information). Our regression model for predicting dissolved calcium concentration on the basis of conductivity included only lakes with calcium concentration values that fell below the "suitable" threshold. Values above this threshold were considered strongly indicative of physiological suitability, thus, we deemed prediction of calcium concentration unnecessary. Because we assembled the subset of 433 lakes used to derive the linear-regression equation from 3 different sources (Supporting Information), we performed an analysis of covariance to test whether the slopes of the calcium-conductivity regressions were significantly different before pooling the data. We used Pearson product–moment correlation tests to compare the predicted and observed calcium concentrations.

Using the regression model, we estimated calcium concentrations for 10,501 Wisconsin lakes not included in model building for which conductivity data were available. We log-transformed all values prior to analysis. We performed all statistical analyses in SAS 9.2 (SAS Institute, Cary, North Carolina).

In summary, we classified 11,857 lakes into 1 of the 3 categories of suitability for zebra mussels on the basis of lake calcium concentrations that we measured (1207 lakes in Wisconsin and 149 lakes in Michigan) or estimated (10,507 lakes in Wisconsin). We assessed the sensitivity of this classification (Fielding & Bell 1997) by comparing it with the known zebra mussel presence records in Wisconsin (93 lakes; Wisconsin Department of Natural Resources 2010).

Communicating the Suitability Estimates

We created a map of lakes suitable for colonization by zebra mussels in ArcGIS 9.2 (ESRI, Redlands, California) by integrating the lake classification results with shapefiles of lakes downloaded from the state agencies of Michigan and Wisconsin (Michigan Center for Geographic Information 2009; Wisconsin Department of Natural Resources 2009). We made the map and underlying data accessible online via an interface (www.aissmartprevention.wisc.edu) that allows users to visualize and download data in a tabular or GIS (shapefile) format. Managers of invasive species at the county and state levels provided feedback on data format and functionality in initial versions of the interface.

Results

Previous publications suggest that the mean calcium concentration below which zebra mussels cannot survive is 15.4 mg/L (Table 1). We classified lakes with calcium concentrations $\leq$ 10 mg/L as unsuitable for zebra mussel, lakes with calcium concentrations between 10 and 21 mg/L as borderline suitable, and lakes with calcium concentrations $\geq$ 21 mg/L as suitable.

Slopes of calcium-conductivity regressions did not differ significantly among 3 sources of data on 433 Wisconsin lakes ($p = 0.18$). The intercepts did, however, differ significantly ($p < 0.001$) (Fig.1). Because we did not identify an interaction of conductivity and source of data (but a main effect of data source existed), we pooled the data from the 3 sources. The following linear regression equation was derived from the pooled data: $\ln(\text{calcium}) = -2.89329 + 1.13039 \times \ln(\text{conductivity})$. The relation between predicted and observed calcium concentrations for 1186 lakes was significant ($r = 0.90$, $p < 0.001$) (Fig.1).

Of the 11,857 lakes (10,501 with predicted and 1356 with observed calcium values), 58% were unsuitable for zebra mussels (6848 lakes), 16% were borderline suitable (1853 lakes), and 26% were suitable (3156 lakes). Most of the suitable lakes were in eastern Wisconsin, whereas most of the borderline suitable and unsuitable lakes were in north-central and northeastern Wisconsin. Overall, 14% of lakes in the Upper Peninsula of Michigan and 66% of Wisconsin lakes were included in the analyses. Due to lack of conductivity or calcium concentration data, we omitted about 6900 lakes, of which 13% are located in the Upper Peninsula of Michigan and 87% in Wisconsin. Of the omitted lakes in Wisconsin, 17% were $\geq$ 10 ha.

No calcium or conductivity data were available for 10 of the 93 inland lakes in Wisconsin and the Upper Peninsula of Michigan in which zebra mussels are present. Of the 77 lakes that contain zebra mussels that we were able to classify, 74 were classified as suitable, and 3 were classified as borderline suitable. None were classified as unsuitable, which renders our classification highly sensitive to known presence of zebra mussels.

The online interface allows users to view and download regional or county data on lake suitability for zebra mussels (Fig. 2). The option to download classification results in table format allows a diverse group of users to access the information because it does not require software that many users are unlikely to own (e.g., ArcGIS). Users can download information by Lake Identifier (a unique numeric code), location, suitability class, and calcium concentration. A description of methods and background information can also be downloaded from the same interface.

Table 1: Calcium concentrations reported in the literature as limiting zebra mussel (*Dreissenapolymorpha*) growth (in the native range) or distribution (in areas where the species is not native) and thresholds* derived for classifying suitability of lakes in Wisconsin and Upper Peninsula of Michigan for zebra mussels.

	Location	*Calcium concentration (mg/L)*	*Study*
Invaded range	Canada	8	Jones & Ricciardi 2005
	U.S.A.	16	Allen &Ramcharan 2001
	Canada	8.5	Hincks & Mackie 1997
	Canada and U.S.A.	15	Mellina & Rasmussen 1994
Native range	Europe	28	Ramcharan et al. 1992
	Europe	20	Strayer 1991
	Europe	12	Sprung 1987
Mean		15.4	
SD		7.0	
95% CI		5.2	
Lower 95% CI		10.2	
Upper 95% CI		20.5	

**Threshold levels of Ca: <10 mg/L Ca, unsuitable; ≥10 and < 21 mg/L Ca, borderline suitable; ≥21 mg/L Ca, suitable.*

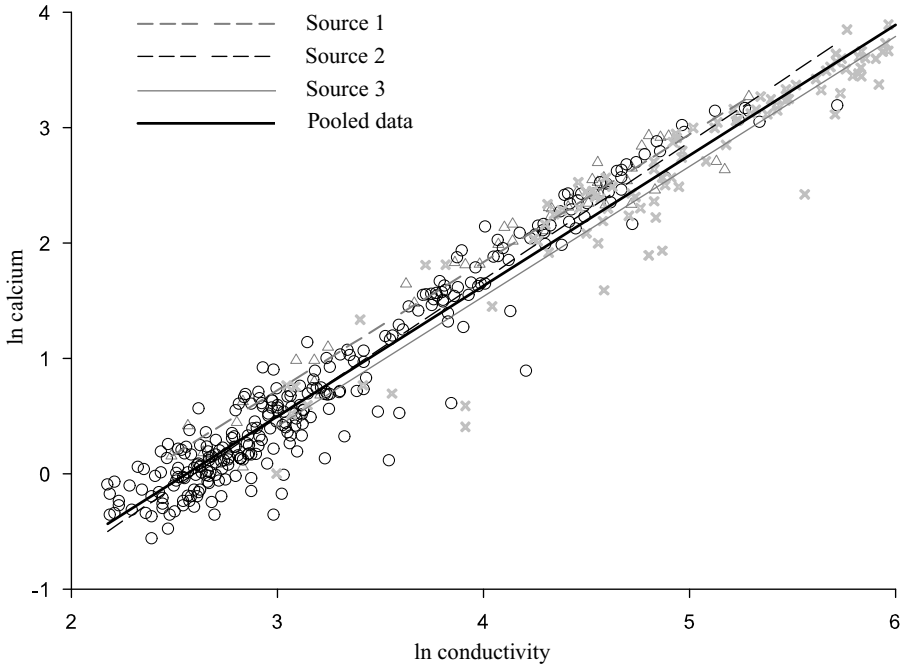

Figure 1. Linear regressions of conductivity and calcium concentration in 433 Wisconsin lakes (data from Linthurst et al. 1986, source 1; Kratz et al. 1997, source 2; and http://waterdata.usgs.gov/nwis, source 3).

Discussion

Our goal was to estimate whether many thousands of lakes across an extensive region were suitable for colonization by zebra mussels. Our physiological threshold-based approach is less sophisticated than other empirical methods that estimate invasion probability, but perhaps more useful for management planning in the early stages of a potential regional invasion because it is easier to prevent the colonization of than to eradicate an invasive species (Kolar & Lodge 2001). Previous studies in which the potential distribution of zebra mussels was assessed on the basis of calcium concentration and other environmental parameters at an ecoregional extent identified Wisconsin and the Upper Peninsula of Michigan as regions with highly variable calcium concentrations (Drake & Bossenbroek 2004; Whittier et al. 2008). Accordingly, predictions of the potential distribution of zebra mussels have high uncertainty at the extent of individual lakes. Thus, a finer-resolution approach is needed that generates predictions for individual lakes. In this work, given the large number of lakes and limited financial resources, the state agency was interested in focusing efforts to prevent and monitor establishment of zebra mussels on the subset of lakes most suitable for zebra mussels. Our relatively simple but quick approach for classifying lakes on the basis of dissolved calcium was viewed by collaborators and practitioners as an acceptable trade-off between the need to refine suitability classification and the need to provide a useful product. This simplified way of assessing lake suitability may not be applicable to other aquatic invasive species (Olden & Jackson 2002).

We worked closely with state agency staff to identify gaps in information about potential invasions by zebra mussels and participated directly in the state agency's efforts to reach out to various stakeholders. Periodic meetings and interactions among scientists and stakeholders helped us fine-tune the final interface to better serve the community of users. Outreach efforts were organized by the state agency and were designed to inform us of information needs, disseminate research results, publicize accessibility of information from our research, and initiate discussions among stakeholders about the regional spread of aquatic invasive species.

Our assessment of suitability of lakes for zebra mussels was based exclusively on environmental suitability. Suitability is only one of several issues when considering probability of invasion. Other important aspects are the likelihood of dispersal and introduction and the potential for undesired effects (MacIsaac et al. 2004; Lockwood et al. 2005; Vander Zanden & Olden 2008; Leprieur et al. 2009). Nonetheless, determining suitability is useful for prioritizing management efforts (i.e., inspections of boats, monitoring of lakes and boat landings, and efforts to prevent colonization), particularly when combined with other information, such as road and boat access to lakes, lake popularity, and connectivity of lakes. The strength of our approach is the simplicity of our classification. The web-based interface and data (http://www.aissmartprevention.wisc.edu/) were envisioned as a channel for direct transfer of information from scientists to stakeholders. Within 6 months of the official release of the website (30 September 2010), the site had 1.6 million hits from 1900 unique visitors. Lake

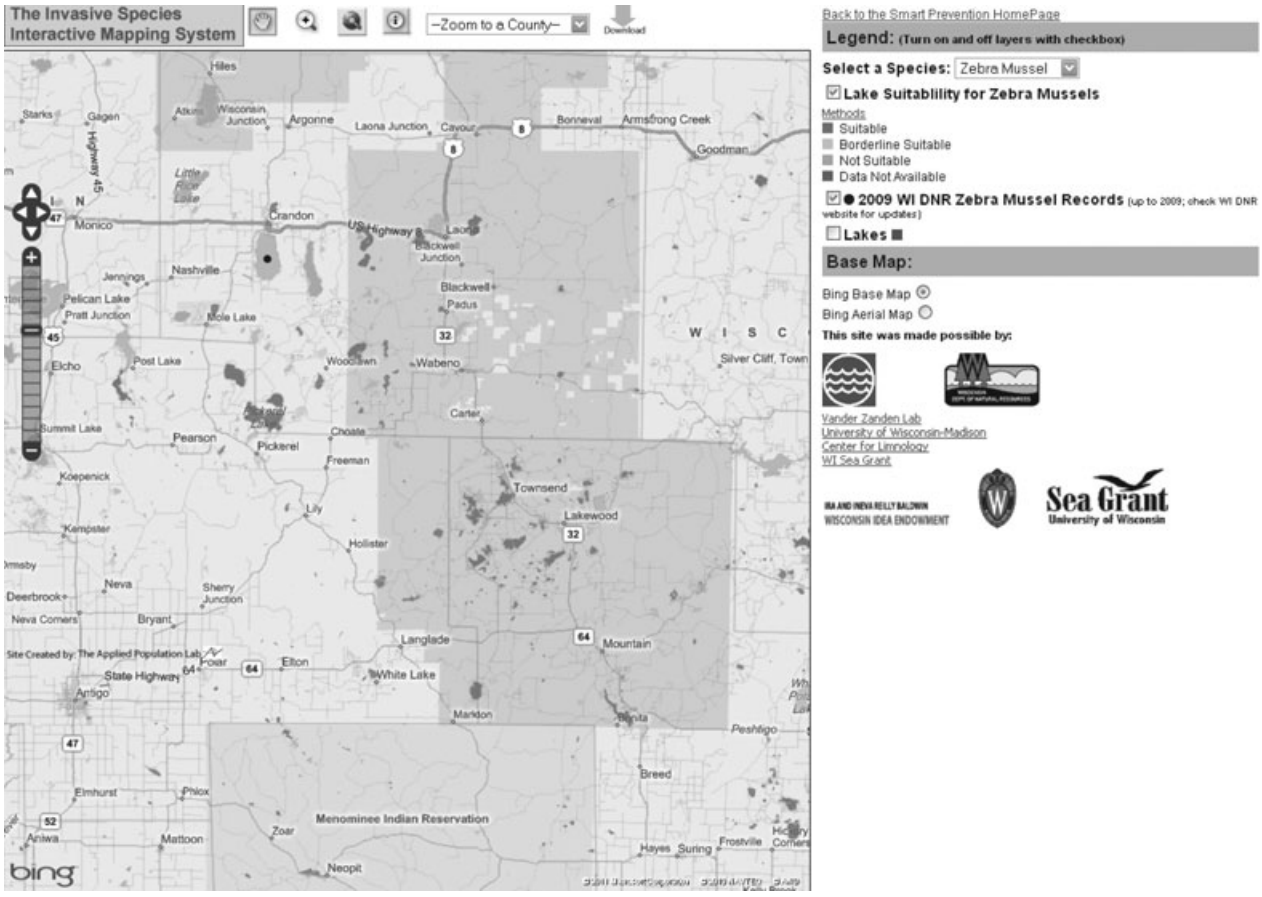

Figure 2. View of the online interface for mapping lake suitability for zebra mussels, showing options such as data download, zoom, and map layers that can be displayed (base map from Microsoft Bing Maps Platform (http://www.bing.com).

suitability for other invasive species has been added as research results become available. On the website, we also provide information regarding the methods and assumptions involved in generating the classification as a means of communicating uncertainties associated with the classification scheme to users (Duncan 2006). We expect the interface will increase public involvement in management of lakes and community-based monitoring, which should help increase regional and local knowledge of aquatic invasive species. Knowing which lakes are most suitable for zebra mussels allows limited resources to be directed toward monitoring and inspection of those locations.

In general there is agreement that communication of scientific results from researchers to managers helps inform the decision-making process. Scientists may not make decisions about management and policy, but they can reach out to and build partnerships with stakeholders to improve the flow of information (Roux et al. 2006). Our experience has been that this interaction can shape the nature of the research itself and direct scientist's efforts to conducting management-relevant research.

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Supporting Information

Sources of lake characteristics (calcium concentration and conductivity values) are available online (Appendix S1). The authors are responsible for the content and functionality of these materials. Queries (other than absence

of the material) should be directed to the corresponding author.

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