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Zebra mussels and Eurasian watermilfoil reporting patterns in Minnesota

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A B S T R A C T

Recognizing common reporting patterns of aquatic invasive Zebra mussels (*Dreissena polymorpha*, ZM) and Eurasian watermilfoil (*Myriophyllum spicatum*, EWM) helps to better understand invasions. We hypothesize that confirmed invasions may be confounded by human population density, leading to overrepresentation of invasions in highly populated areas and underrepresentation in less populated areas. Here we recognize dispersal patterns of confirmed ZM and EWM invasions in Minnesota, USA, using spatial clustering and directionality tests, while adjusting for human density. By 2015, 125 (0.68%) and 304 (1.65%) of 18,411 Minnesota waterbodies were reported to have ZM and EWM, respectively. A multivariate multinomial model of the scan test was used to identify clustering of invasions. The resulting 23 clusters included 13 with either or both ZM and EWM, and most clusters (11/13) occurred in areas with >10 people per square kilometer. Whereas, among the 10 clusters without invasion, nine were from less populated areas. The standard deviation ellipse and the spatiotemporal directionality tests indicated a northwestern trend of invasions, which is in the same direction as the I-94 interstate highway connecting urban centers. Results suggested that confirmed ZM and EWM invasions are potentially confounded by human densities, which is explained by varying human impact on either or both dispersal and reporting of invasions. Considering this impact of human density, we suggest that a combination of passive and targeted surveillance, where the magnitude of efforts are stratified by the human densities, may provide insight into the true invasion status and its progression in the Great Lakes region.

Introduction

Aquatic invasive species (AIS) disrupt the stability of ecosystems and are difficult to eradicate (Pysek and Richardson, 2010). The state of Minnesota, including its Lake Superior drainage basin, has experienced numerous AIS incursions and spends over 10 million dollars each year on activities intended to prevent, control, or manage AIS (Invasive Species Program, 2016; MN Statute 477A.19, 2016). Eurasian watermilfoil (*Myriophyllum spicatum*) and Zebra mussels (*Dreissena polymorpha*) are AIS of concern for Minnesota and were first reported in the state in 1987 and 1989, respectively. The official records of confirmed aquatic invasions are publicly available from the Minnesota Department of Natural Resources (MNDNR). Despite efforts focused on control and prevention, new cases of zebra mussel and Eurasian watermilfoil invasions keep accumulating every year (http://www.dnr.state.mn.us/invasives/ais/infested.html. Cited January 21, 2018).

The initial introduction of zebra mussel into the Great Lakes region of North America has been attributed to the unintentional transport in the ballast water of transatlantic ships (Carlton, 2008; Brown and Stepien, 2010). According to genetic diversity analyses, the ancestral locations of zebra mussels may have varied across Eurasia suggesting multiple independent translocations of zebra mussels into North America (Brown and Stepien, 2010). Zebra mussels are rapidly propagating bivalves that disrupt the stability of the food web in aquatic ecosystems, affecting both pelagic and benthic species (Karatayev et al., 2015). Removal of zebra mussels colonizing public water supplies and industrial facilities pipes is expensive (Connelly et al., 2007).

Eurasian watermilfoil, an invasive aquatic macrophyte, was likely introduced into North America through the aquarium trade (Les and Mehrhoff, 1999). Asia is the likely source of Eurasian watermilfoil based on genetic analysis (Moody et al., 2016). Eurasian watermilfoil grows rapidly, limiting the ability to implement effective removal or control strategies upon establishment in a waterbody (Lodge et al., 2006; Roley and Newman, 2008). Dense vegetation of Eurasian watermilfoil outcompetes native macrophytes and interrupts recreational activities (Cheruvelil et al., 2002). Understanding the dispersal patterns common to both zebra mussels and Eurasian watermilfoil,

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such as the clustering of confirmed invasions, may support recognizing the drivers behind both the spread of the invasions and potential bias in public reporting.

Public observation of new AIS invasions plays a major role in data collection in Minnesota (http://www.dnr.state.mn.us/invasives/report_invasives.html. Cited January 22, 2018). There is no active systematic surveillance for AIS with the objective of early detection although some of the invasions were discovered during surveys by the MNDNR. In the absence of active surveillance, AIS invasions are primarily recorded based on public reports and subsequent confirmation by the MNDNR (http://www.dnr.state.mn.us/invasives/report_invasives.html Cited January 22, 2018). We hypothesize that the confirmed invasions may be confounded by human population density, leading to overrepresentation of invasions in highly populated areas and underrepresentation in less populated areas. Briefly, a confounder is a factor associated with both the exposure and the output of interest, which may distort the magnitude of the relationship between exposure and output (Jolley et al., 1992; Szklo and Nieto, 2007). For example, consider the exposure of interest as the presence of invaded waterbodies in the area and the output as new invasions in neighboring waterbodies. Having a large human population may result in high frequency boater traffic between waters, increasing the exposure levels, as well as the possibility of higher frequency observations due to the increased traffic. A similar phenomenon related to a terrestrial invasive species has been explained by Aikio et al. (2010). Therefore, it is important to adjust for confounding by human population density when analyzing the publicly reported data.

Thus, the objective of this study was to identify clustering patterns of confirmed zebra mussels and Eurasian watermilfoil invasions, while accounting for the potential confounding by human population density. To that end, estimates of spatial or spatiotemporal clustering patterns and the directionality of AIS reporting using geostatistical methods would help to quantify the dispersal dynamics. Recognition of the common dispersal patterns would contribute to better understanding of the invasions and generating hypotheses on the mechanisms of spread and underlying risk factors, similar to the role of infectious disease spatial dynamics in epidemiological studies (Ward and Carpenter, 2000; Elliott and Wakefield, 2001). Understanding the human influence on reported invasions would guide the implementation of active surveillance efforts and encourage passive surveillance and public reporting through educational activities in the Great Lakes region.

Methods

Data

The units of analysis here were waterbodies ($n = 18{,}411$), mainly lakes and ponds ($n = 18{,}253$) and a few river locations ($n = 148$). Locational data for waterbodies were extracted from the spatial layer referred to as "MNDNR Hydrography," which is available from the Minnesota GIS Commons (MNGSC Hydro, 2015). Waterbodies were represented by their centroids regardless of the size.

AIS presence data were obtained from the MNDNR's publicly available online database. The invasions are reported to the MNDNR by the public and MNDNR confirms the newly reported invasions prior to adding them to their online database (http://www.dnr.state.mn.us/invasives/ais/infested.html. Cited June 22, 2015). When long rivers were confirmed with invasions, several Minnesota counties were included in the data records. Therefore, invaded riverine locations were represented by the rivers' midpoint within each county, according to the data records. The number of new cases and the cumulative number of cases confirmed by the MNDNR were used for the analysis (Fig. 1). The temporal data only includes the year in which the invasion was confirmed. By the end of 2015, the number of waterbodies invaded by zebra mussels and Eurasian watermilfoil were 125/18,411 (0.68%) and 304/18,411 (1.65%), respectively (Fig. 2). The confirmed presence of the AIS was used here to define a case regardless of the magnitude of infestation. This study considers all lakes, ponds, and certain riverine locations, as the waterbodies at risk for invasions regardless of their size, because the invaded waterbodies ranged between 0.006 km^2 to ~82,000 km^2 (i.e. Lake Superior). Geographical locations were mapped using ArcMap 10.3 (ESRI, 2016). The waterbodies were categorized based on the invasion status into four invasion categories: 1) reported with both zebra mussels and Eurasian watermilfoil (EWM+/ZM+; $n = 21$), 2) reported only with zebra mussels (EWM−/ZM+; $n = 104$), 3) reported with Eurasian watermilfoil only (EWM+/ZM-; $n = 283$), and 4) as of 2015, not reported with either of the AIS (ZM-/EWM-; $n = 18{,}003$).

Human population density data were obtained from the LandScan Global Population Database of 2011 census, assuming 2011 is a representative year for population density between the study period 1987 to 2015 (Bright et al., 2013). To facilitate interpretation of the results, maps of selected major roads and major river centerlines were incorporated at the completion of analysis. The road map of 2012, available through Minnesota Geospatial Commons and originated from the Minnesota Department of Transportation was used to extract major roads (MNGSC Roads, 2012). As defined in the metadata of the spatial layer, U.S. road classes including interstate highways, freeways, arterials, and major collectors were considered as major roads in the analysis (MNGSC Roads, 2012). The major river centerlines were extracted from the "MNDNR Hydrography" spatial layer available from Minnesota Geospatial Commons (MNGSC Hydro, 2015). The rivers longer than 200 km were considered as the major rivers.

Data analysis

Techniques for detection of directionality and spatial clustering (Levefer, 1926; Kulldorff, 2009; Jung et al., 2010; Wang et al., 2015), were used to quantify the pattern of confirmed AIS dispersal in Minnesota. The multivariate multinomial model of the scan statistics test was used to detect spatial clusters. To further examine the hypothesis that known invasions are confounded by the urban centers, directionality of the confirmed invasions was detected using the standard deviation ellipse and the spatiotemporal directionality tests as explained below.

Global cluster analysis

The intent of clustering analysis is to test whether the invaded locations are spatially grouped compared to the null hypothesis of random distribution across the geographical space. The global cluster analysis only detects the tendency to cluster and does not point out where the clusters are located. The global cluster analysis based on the Cuzick and Edwards test was performed using the ClusterSeer v.2.05. software for each AIS data set separately (Cuzick and Edwards, 1990; Jacquez et al., 2012; https://www.biomedware.com/). The Cuzick and Edwards's test compares observed number of AIS invaded locations whose nearest neighbor is also a case, among the k nearest neighbors, with the number of paired cases that would be expected under the null hypothesis of random spatial distribution (Cuzick and Edwards, 1990). The test was run from the first up to tenth k neighborhood level. Significance of the clustering was determined at the p value 0.05. A detailed description regarding the cluster analysis using the Cuzick and Edwards test is described elsewhere (Cuzick and Edwards, 1990).

Multivariate multinomial local cluster analysis

To locate statistically significant local clusters, a purely spatial multinomial model of the scan statistics was performed using the SaTScan software (Kulldorff et al., 2007; Kulldorff, 2009; Jung et al., 2010). The purely spatial multinomial cluster analysis detects any spatial aggregation of the four invasion categories (i.e. EWM−/ZM−; EWM+/ZM−; EWM−/ZM+; EWM+/ZM+) regardless of the time (Jung et al.,