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Evaluating the potential of ecological niche modelling as a component in marine non-indigenous species risk assessments

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ABSTRACT

Marine biological invasions have increased with the development of global trading, causing the homogenization of communities and the decline of biodiversity. A main vector is ballast water exchange from shipping. This study evaluates the use of ecological niche modelling (ENM) to predict the spread of 18 non-indigenous species (NIS) along shipping routes and their potential habitat suitability (hot/cold spots) in the Baltic Sea and Northeast Atlantic. Results show that, contrary to current risk assessment methods, temperature and sea ice concentration determine habitat suitability for 61% of species, rather than salinity (11%). We show high habitat suitability for NIS in the Skagerrak and Kattegat, a transitional area for NIS entering or leaving the Baltic Sea. As many cases of NIS introduction in the marine environment are associated with shipping pathways, we explore how ENM can be used to provide valuable information on the potential spread of NIS for ballast water risk assessment.

1. Introduction

Marine ecosystems are affected by human activities in the sea such as stocking, aquaculture and shipping. These processes often cause invasions of non-indigenous species (NIS) worldwide, alter native communities and lead to the global decline of biodiversity. Frazier et al. (2013) described the invasion of NIS as one of the major environmental stressors for marine ecosystems, which often results in broad economic and ecological damage. Examples of severe invasions with socio-economic consequences are problems in water management systems following mass settlement of the European zebra mussel *Dreissena polymorpha* in the United Kingdom (Oreska and Aldridge, 2011) and Canada (Colautti et al., 2006), or the collapse of the fisheries in the Black Sea following the introduction of the western Atlantic comb jelly *Mnemiopsis leidyi* (Knowler and Barbier, 2000).

According to Kaluza et al. (2010), 90% of world trade is carried out by sea, and global shipping is one of the most important transport networks. Bulk dry carriers and oil tankers are two examples for large amounts of ballast water exchange across biogeographic regions, promoting the spread of biological invasions. In a ranked list of the 50 most trafficked ports worldwide, six of the top twenty are located in northern Europe (Kaluza et al., 2010), e.g. Europoort Rotterdam (Netherlands), Antwerp (Belgium), Le Havre (France), Hamburg (Germany), Bremerhaven (Germany) and St. Petersburg (Russia). This makes the region enclosing the North and Baltic Sea one of the most significant potential hot spots for biological invasions worldwide (Drake and Lodge, 2004). In the Baltic Sea, an increase in NIS number during the past century can be correlated with the number of ships entering the region with larger volumes of ballast water (Leppäkoski and Olenin, 2000). Similar patterns were observed from the estuaries of North America (Ruiz et al., 1997), and also in the Mediterranean Sea (Gollasch, 2006).

More than 150 NIS have been reported for the North and the Baltic Sea to date (Gollasch et al., 2009). In Europe, more than 1000 species (Vila et al., 2010) and worldwide around 10,000 are estimated to be in transit with ballast water (Bax et al., 2003). Introduced species are often locally distributed and frequently overlooked in the initial stage, but many of them are able to spread successfully over larger areas, such as *Marenzellaria* spp. (Gollasch and Nehring, 2006) or the Chinese Mitten Crab *Eriocheir sinensis* (Therriault et al., 2008).

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The International Maritime Organization (IMO) recognizes the role of ballast water as a vector for NIS and developed the International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWMC, 2004; IMO, 2004). This convention states that by 2019 at latest all ships have to comply with the Ballast Water Performance Standard. In situations where ballast water does not pose any risk for the environment, i.e. for certain ships on certain routes, an exemption from the Ballast Water Management Convention (BMWC) may be granted on the basis of a risk assessment (RA). Such RAs determine the probability that organisms from the donor port survive in the recipient port, and they are based on three principal methods (IMO, 2007):

(1) Environmental matching. Here, RAs compare the environmental conditions in the donor and recipient ports, to determine if these are sufficiently different so that any species found in the donor port is unlikely to survive and establish reproductive populations in the recipient port. This RA method is usually based on salinity criteria and requires clear definitions of seawater and freshwater, together with detailed studies on salinity gradients in estuary ports and ballast water uptake in these ports (Dragsund et al., 2005).
(2) Biogeographic matching. This method compares the distribution of non-native species, and if there are overlapping species in donor and recipient ports, the conditions may be similar enough for more species of the donor port to survive in the recipient region (Pikkarainen, 2010; David et al., 2013a).
(3) Species-specific RAs. This method considers information about individual species in the donor port and the environmental conditions in the recipient port.

The first generation of non-indigenous species-specific RAs combine biological with environmental parameters, but typically use only salinity data and few occurrence records for a limited number of species (see for example David et al., 2013b). Other studies that include more than one environmental parameter use statistical correlation models for making detailed distribution predictions. But such studies only investigate single species (e.g. Herborg et al., 2007; Ba et al., 2010; Kotta et al., 2013). In the present study, we designed an approach that combines data-access with species distribution modelling methods (SDM) such as ecological niche modelling (ENM) to analyze the habitat suitability of large numbers of species under a wide range of environmental conditions. ENM employs environmental variables associated with occurrence data of a species to predict spatial distribution patterns, using a correlative approach. SDMs have been used in a wide range of contexts in recent years, including policy support, for example in conservation decision making (Schwartz, 2012; Guisan et al., 2013) or marine ecosystem management (Reiss et al., 2014).

Here we investigate 18 non-indigenous species (Table 1) belonging to four different ecological categories (zoobenthos, zooplankton, phytobenthos and phytoplankton) to answer the following questions: (1) Is salinity, the current standard environmental parameter in non-indigenous species RAs, the most important and/or the only factor determining the distribution of the species? (2) Can we identify hot- and cold spots in habitat suitability in the Baltic Sea for a large number of non-indigenous species? (3) Can we use model-based evidence to distinguish between natural *versus* ship-facilitated spread of non-indigenous species along shipping routes? (4) Finally, how can SDM approaches be integrated into existing ballast water risk assessments?

2. Material and methods

2.1. Study area

The study was carried out in Northern Europe (Fig. 1), a global hot spot for biological invasions (Drake and Lodge, 2004; Kaluza et al., 2010). This study area includes the semi-enclosed Baltic Sea, which differs from the fully marine areas of the North Atlantic and North Sea by a strong salinity gradient from around 30-20 PSU in the Skagerrak, to 20-15 PSU in the Kattegat, down to 10 PSU at the mouth of the Baltic Sea and to nearly freshwater conditions in the Gulf of Finland and the Bothnian Bay. Olenin and Leppäkoski (1999) stated that this relatively young brackish-water body (around 10,000 years old) is mostly open for species that are oligohaline (0.5-5 PSU), mesohaline (5-18 PSU) or euryhaline (adapted to all salinities). An important environmental factor in this area is sea surface temperature, which can become low in the northern and northeastern parts of the Baltic during the winter months (November–April: mean 1–3 °C, 1952–2008) (Feistel et al., 2008). The Bothnian Bay/Sea as well as parts of the Gulf of Finland are often covered with ice for several months of the year.

2.2. Species data

We use the term non-indigenous species to refer to species or subspecies transported intentionally or accidentally by a human mediated vector into habitats outside its native range, natural past or present distribution (ICES, 2005). Invasive species are defined here as NIS that have the ability to spread causing damage to the environment, the economy and health. We selected 18 NIS according to the following criteria: (i) species with native ranges in the Atlantic or the Pacific, (ii) species that have invaded Northern Europe in the last 100 years (Table 1) and (iii) species for which we were able to obtain more than 50 environmentally unique occurrence points (Table 2). In addition, eight of the species have a broad salinity tolerance (Tables 1 and 2, in bold). The species were grouped into four categories, i.e. zoobenthos (ZB), phytobenthos (PB), zooplankton (ZP) and phytoplankton (PP), and all species of a category were modelled using the same environmental parameters. The invasion status of the species (Table 1: unknown, non-established or established) strongly depended on the area of interest (from the DAISIE database, www.europe-aliens.org). All scientific names used in this study conform to the nomenclature of the World Register of Marine Species, WoRMS (Appeltans et al., 2014).

Occurrence points for each species were extracted from GBIF (Global Biodiversity Information Facility; http://gbif.org) during June–September 2013 (Supplement A). The taxonomic data refinement workflow (DRW) was used to carefully check the synonyms, download, visualize, filter and integrate occurrence records for all species (Mathew et al., 2014). For many species, numerous distribution records exist in the literature, but these are not digitized. We manually geo-referenced additional occurrence data from these sources (Supplement B). In addition, complementary data sets were obtained from scientific networks and environmental agencies (Supplement C) (Table 1).

2.3. Environmental data

Global marine layers used in our study came from Bio-Oracle (http://www.bio-oracle.ugent.be/) with a resolution of 5 arc-minutes (Tyberghein et al., 2012), and were used to study abiotic factors such as annual mean sea surface temperature (SST in °C), mean surface salinity (SSS in PSU) and mean photosynthetically available radiation (PAR in Einstein/m2/day). Those data are built