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PRIMARY RESEARCH PAPER

Identifying high-risk areas for introduction of new alien species: the case of the invasive round goby, a door-knocker for Norway

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Abstract Identifying new areas of colonisation by alien species is important for early detection and management. Door-knocker species pose problems for traditional predictive models because of lacking presence–absence data, but habitat suitability modelling might overcome this. We here identify the most likely areas for introduction and first establishment of the invasive round goby *Neogobius melanostomus* to Norway, where it has not yet been registered. We implemented knowledge on dispersal pathways and the species' biology in a simplified suitability model based on spatial data representing the most relevant environmental variables: distance to international harbours in Norway, distance to the closest population in neighbouring country, salinity, wave exposure, depth and water temperature. The results suggest that there are many potential localities for introduction and first establishment and reveal several hotspots of such areas, especially in less-exposed coastal brackish areas of southern Norway. Especially the region around the Oslo Fjord stands out as being associated with higher risk. Our results could guide future monitoring programmes and increase the chance of early detection of this potential new invader. The study illustrates how spatial analyses can be used to identify the most likely areas for future invasion by an aquatic door-knocker species despite lacking presence–absence data.

Keywords Brackish · Door-knocker · Suitability modelling · Fish · *Neogobius melanostomus* · Atlantic Ocean

Introduction

With increasing globalisation, trade and transport, the spread of alien species has seen an enormous increase (Perrings et al., 2005; Ricciardi, 2007; Hulme, 2009). The spread of alien species and the negative impact they can have on native marine ecosystems are pressing issues (Katsanevakis et al., 2014). For marine alien species, accidental introduction through shipping is the most important pathway of introduction (e.g. Nunes et al., 2014). Ballast water and fouling spread alien species over long distances (Ruiz et al., 2000; Nunes et al., 2014) and further spread are often difficult to stop. The risk that an alien species is introduced and establishes in a new area increases with the number of individuals introduced, i.e. propagule pressure (e.g. Lockwood et al., 2005). It also depends on species characteristics and how suitable the new environment is regarding biotic and abiotic factors (Blackburn et al., 2011).

To mitigate the spread and impact of alien species, management actions as early as possible in the

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invasion process are clearly desirable as these are more cost-efficient (Leung et al., 2002; Hulme, 2006). Early detection is therefore crucial (e.g. Lehtiniemi et al., 2015). With the increasing rate of human-mediated biological invasions, the need for predictive models in the assessment of invasion risk is urgent (Lockwood et al., 2005). Species distribution models based on presence–absence data can yield knowledge on which factors explain species distributions and predict areas where new establishments are likely (Elith et al., 2006). This approach has proven useful in the context of established alien species (e.g. Kotta et al., 2016; Florin et al., 2018). However, in the case of door-knocker species, i.e. alien species that are not yet introduced or established in a region but are expected to be so in the near future, presence–absence data are either very limited or non-existing for the country or region in question. This limits the use of predictive models and model validation. Habitat suitability-type models represent a highly useful alternative given their ability to identify potential areas at risk for future invasion (e.g. Morisette et al., 2006; Crall et al., 2013; Shafer et al., 2016). In this study we exemplify how such models can be used to pin-point the most relevant areas for introduction of a door-knocker fish species to facilitate early detection.

The aim of our study was to identify the most likely areas for future invasion by an aquatic door-knocker species whilst lacking presence–absence data. The round goby, *Neogobius melanostomus* (Pallas, 1814), is a small benthic fish that has invaded freshwater and brackish ecosystems in North America and Eurasia during the last three decades, likely via ship ballast water. The round goby has not yet been registered in Norway but is listed as a door-knocker species with severe impact (Norwegian Biodiversity Information Centre, 2018). Thus, our objective was to identify the most likely areas for introduction and first establishment of the round goby in Norway, given already established populations in nearby Sweden, using habitat suitability modelling and hotspot analysis. This should be particularly helpful to focus monitoring and mitigating actions. To do this we combined literature review and spatial modelling using available data on environmental factors. We hypothesise that factors explaining round goby occurrence in the Baltic Sea (Kotta et al., 2016; Florin et al. 2018) also are relevant for Norway. In the Baltic Sea, round goby occurrence was related to both human factors (shipping) and natural environmental conditions (Kotta et al., 2016; Florin et al., 2018).

Materials and methods

Study species

The round goby, native to the Ponto-Caspian region (Black Sea, Caspian Sea and Azov Sea with tributaries), has in the last decades invaded aquatic ecosystems in North America and Eurasia. In 1990 it was discovered both in the Laurentian Great Lakes and the Baltic Sea (Gulf of Gdansk) (reviewed in Corkum et al., 2004; Kornis et al., 2012). Since then, it has rapidly expanded its distribution and has established numerous large populations in North America and Europe in both fresh water and brackish ecosystems. The main vector of introduction is most likely ship traffic and evidence strongly suggests that it has been repeatedly spread via ballast water from ships (Brown & Stepien, 2009; Kornis et al., 2012; Kotta et al. 2016). After being introduced, the round goby has a high potential for further spread by means of natural dispersal (Kornis et al., 2012; Azour et al., 2015). Other possible vectors are regional boat traffic, canals and anglers using it as bait (Kornis et al., 2012; Hirsch et al., 2016a). In Europe it has invaded the Baltic Sea and several rivers of continental Europe (Roche et al., 2013; Kotta et al., 2016; Puntila et al., 2018). It is also found in brackish waters along the Danish coast, on the Swedish west coast and the Netherlands (van Beek, 2006; Azour et al., 2015; Kotta et al., 2016). The first year after an introduction, populations are generally characterised by low numbers of individuals and a limited distribution. This initial lag phase is then followed by population growth and colonisation of new shallow areas as seen in the Baltic Sea (Sapota, 2004; Sapota & Skora, 2005; Thorlacius & Brodin, 2018). Along the Danish coast the distribution of round gobies has expanded at a rate of 30 km per year (Azour et al., 2015). The rapid and successful invasion by the species is likely explained by many factors, including a wide salinity and temperature tolerance, a broad diet, high genetic variation and rapid adaptation to local conditions (reviewed in Kornis et al., 2012).

The round goby spawns multiple times in spring–summer and has paternal care of eggs in a nest site (Meunier et al., 2009; Kornis et al., 2012). It can occur at very high densities and often becomes the dominant fish species in nearshore benthic habitats (e.g. Sapota & Skora, 2005; Karlson et al., 2007). Longevity is up to 6 years and it can reach a total length of 25 cm. It is characterised as aggressive and highly competitive (Balshine et al., 2005), and there are many studies reporting negative impact on native species, mainly through predation, food competition, interference competition and displacement (reviewed in Poos et al., 2010; Kornis et al., 2012; Hirsch et al., 2016b). Even though its biology is quite well studied, there are many uncertainties regarding the spread and ultimate distribution, its ecological effects and economic consequences (Kornis et al., 2012; Hirsch et al., 2016b).

Study area

The Norwegian coastline is approximately 24,000 km long, including its many fjords, bays and islands (Fig. 1). Facing Skagerrak, the North Sea, the Norwegian Sea and the Barents Sea this is a very different ecosystem compared to the brackish Baltic Sea ecosystem, both regarding biotic and abiotic conditions. A major difference is the higher salinity that by and large is euhaline (> 30 PSU).

Variables and data

Since the round goby is not yet recorded in Norway, the corresponding lack of presence–absence data prevented us from developing explanatory and predictive models. As an alternative, we developed a simplified habitat suitability model. We combined available spatial data related to (1) the pathways of introduction,

Fig. 1 Overview of the study area (Norway). Norwegian harbours with international ship traffic are marked, as well as the closest known round goby population (Gothenburg, Sweden)

considering shipping and secondary dispersal from neighbouring country being the most important dispersal pathways (Kornis et al., 2012; Kotta et al., 2016) and (2) environmental conditions increasing the probability of survival and successful reproduction. Here, knowledge on the species biology is relevant and we included environmental variables known to be most suitable for the establishment and proliferation of the species (reviewed in Kornis et al., 2012; Kotta et al., 2016; Florin et al., 2018). We focused on the following factors:

Shipping

As a proxy of propagule pressure (Lockwood et al., 2005), distance to port was found to be an important predictor of round goby occurrence in the Baltic Sea (Kotta et al., 2016). The species was particularly more likely to occur close to large cargo ports (Kotta et al., 2016). Hence, we included distance to all Norwegian harbours with international ship traffic (the Norwegian Coastal Administration 2019). We considered areas in the vicinity of these harbours (radius 10 km) to be of particular interest (Fig. 2a).

Dispersal from neighbouring country

The closest known population of round gobies is in Gothenburg, Sweden (Fig. 1), where the species was established by around 2010 (Kullander et al., 2012). We identified the area where propagule pressure by this additional dispersal pathway is conceivable in 2020 (Fig. 2b). This was based on the distance from Gothenburg, time since establishment

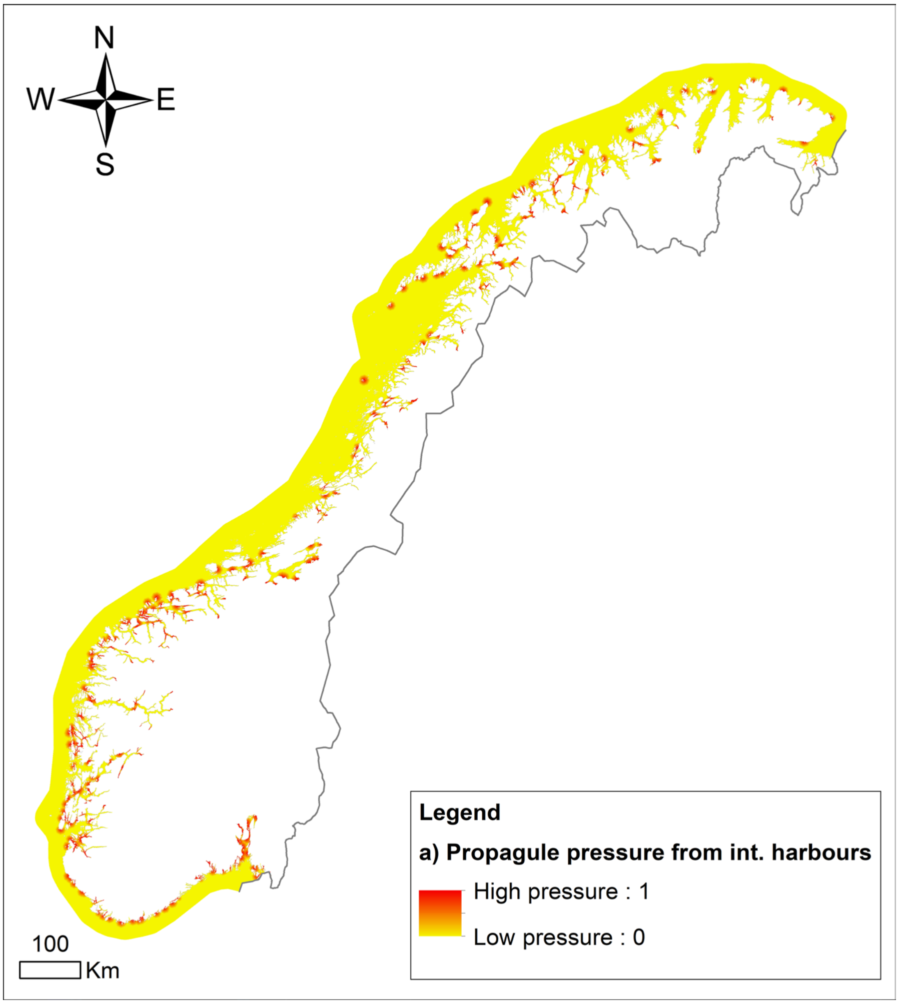
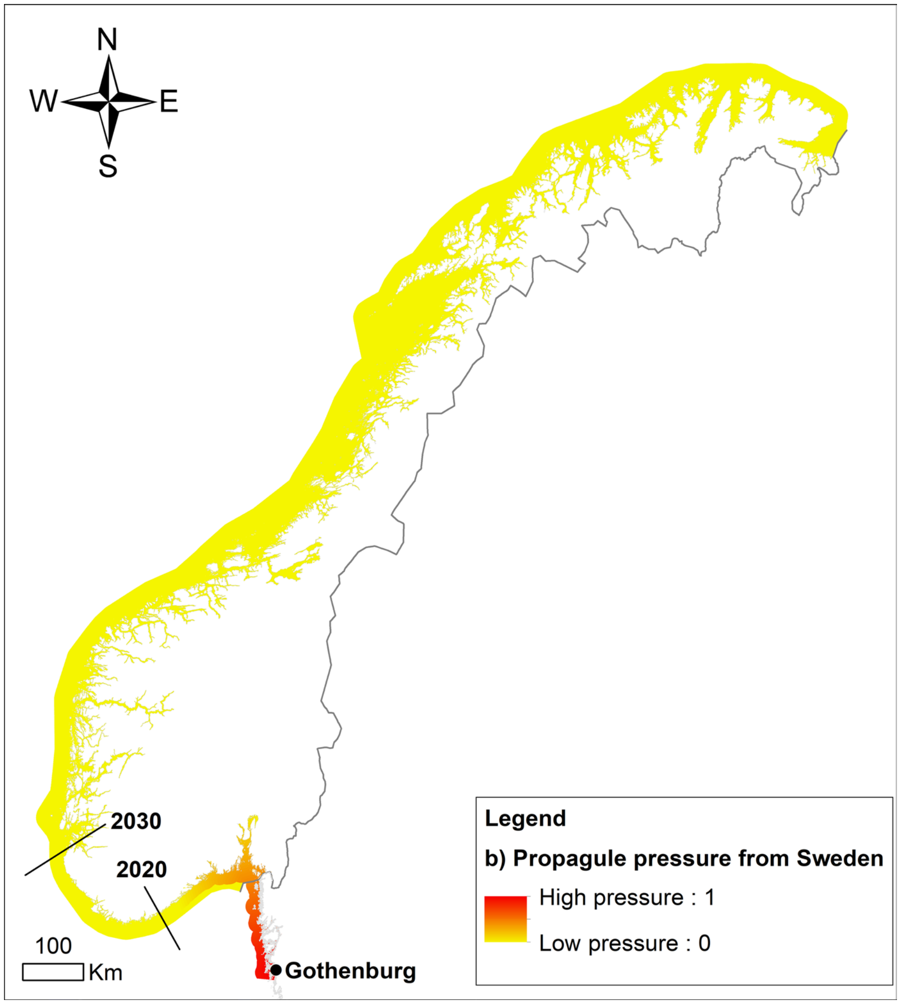


Fig. 2 Possible areas for first introduction of the round goby *Neogobius melanostomus* to Norway through two important dispersal pathways; (**a**) shipping, map showing international harbours (+ 10 km radius), and (**b**) secondary dispersal from Sweden, i.e. within reach by migrating fish from the established population in Gothenburg at a rate of 30 km year^{-1} from 2010, bars showing potential invasion front in 2020 and in 2030. Colours from yellow to red indicate increasing propagule pressure on a relative scale from 0–1

Fig. 2 (continued)



and a reported dispersal rate of 30 km yr^{-1} along the Danish coast (Azour et al., 2015). We also forecasted the potential invasion front for 2030.

Wave exposure

The distribution of round gobies in the Baltic Sea was primarily related to local hydrological conditions, namely low wave exposure, both on a regional and a local scale (Kotta et al., 2016; Florin et al., 2018). In our model we used average wave height from April to August 2019 (EU Copernicus Marine Service Information, 2019a, b) as a proxy for wave exposure and hypothesised that the probability of round goby presence should be negatively related to wave height.

Salinity

The round goby has a broad salinity tolerance, from freshwater to marine. Different populations are adapted to different salinities depending on the origin of the population (Hempel & Thiel, 2015; Green et al., 2019, 2021). Round gobies thrive in the brackish Baltic Sea with a salinity spanning from 2 to 8 PSU (Kotta et al., 2016; Green et al., 2019) and are established along parts of the Danish coast with salinity between 10 and 17 PSU (Behrens et al., 2017). Even if round gobies have been found in high oceanic salinities, for example, 29 PSU outside Gothenburg (Gothenburg University, 2016), there is no known established population in such high oceanic salinities. It has therefore been suggested that the salinity tolerance for the species is <30 PSU (Kornis et al., 2012).

Experiments on juveniles from a brackish population found almost 100% survival in a broad range of salinities (01–30 PSU), although food intake and growth were reduced at 30 PSU (Hempel & Thiel, 2015). In adults, there was a reduced physiological performance and lower survival in higher salinities (25 and 30 PSU). Yet, a substantial proportion (60–70%) did survive these high salinities (Behrens et al., 2017). Knowledge on how reproduction is affected by high salinity is poor. Sperm are motile at a salinity of 30 PSU (Green et al., 2019), but it is unclear whether the gobies can successfully reproduce and produce offspring in such high salinities. Based on our current knowledge on salinity tolerance and the known dispersal pathways of the species, brackish areas should be particularly likely for introduction and first establishment of the round goby in Norway, whilst high salinities probably will limit its distribution. In our model we used modelled salinity data at 3-m depth April to August from the "NordKyst-800 m model" (Albretsen et al., 2011; Norwegian Meteorological Survey, 2019).

Temperature

The round goby has a broad temperature tolerance and a high level of thermal resilience (Wellband & Heat, 2017; Christensen et al., 2021). It may tolerate temperatures between 0 and 30 °C (Kornis et al., 2012) but seems to prefer relatively warm water as its energetic optimum temperature was estimated to 26 °C (Lee & Johnson, 2005). Warmer water temperatures should also allow a longer breeding season. Moreover, in substrate brooding fish, the reproductive rate increases with temperature, mainly due to faster embryo development during the parental care phase, as shown in the sand goby, *Pomatoschistus minutus* (Pallas, 1770) (Kvarnemo, 1994). Due to the Gulf Stream, Norwegian Sea temperatures are in general warmer than would otherwise be the case for such northern latitudes. Given the broad temperature tolerance, Norwegian water temperatures should not be limiting for round goby survival, but higher sea surface temperatures should be associated with improved reproductive and living conditions. In our model we used modelled sea temperature data at 3-m depth from April to August derived from the "NordKyst-800 m model" (Albretsen et al., 2011; Norwegian Meteorological Survey, 2019).

Depth

The round goby is a benthic shallow water species, which in marine habitats mainly occurs at depths down to 20 m (Kullander et al., 2012). In the southern Baltic Sea (Sweden) it was most abundant at depths < 10 m (Florin et al., 2018). It is found in shallow water during the reproductive season and migrates to deeper waters over winter (Sapota, 2004; Gertzen et al., 2016; Christoffersen et al., 2019; Behrens et al., 2021). In our model we used Bathymetric data (Norwegian Mapping Authority 2019).

For the variables showing temporal change (temperature, salinity, wave height) data were limited to spring–summer (April–August) in order to focus on the crucial time period when the round goby occur at shallower depths to reproduce. Omitting winter should not be a problem since coastal sea water temperatures wintertime in Norway are higher than at the western coast of Sweden and much higher than in the Baltic Sea (Reynolds et al., 2008) where the gobies do occur.

Spatial data representing all the variables within the study area (defined by 12 nautical miles from the Norwegian coast) were reprojected to ETRS_1989_UTM_Zone_33N, resampled to a raster data resolution of 50 × 50 m and normalised using the ArcGIS Pro Fuzzy Membership geoprocessing tool (ESRI, 2021a). This tool transforms each input variable raster dataset into a scale ranging from 0 up to 1, indicating the strength of a membership in a fuzzy set, based on the applied Fuzzy membership function type (e.g. the Linear membership function) and threshold values regarding the species physiological tolerance and preferences (Table 1). A normalised value of 1 indicates full membership (suitable), with membership decreasing to 0 (not suitable), indicating it is not a member of the fuzzy set. Since most of the environmental variables are ordered data we used the Linear membership function where a positive slope is given by a minimum threshold value less than the maximum threshold value (e.g. for temperatures ranging from 0 to 25 °C) and where a negative slope is given by a minimum threshold value greater than the maximum threshold value (e.g. for wave height ranging from 0 to 1 m). Hence, this procedure normalises the variables to the same scale and approximates how each variable is related to risk/suitability (Table 1).

Table 1 Variables used in the analyses to identify the most likely areas for introduction and first establishment of the round goby *Neogobius melanostomus* in Norway

Variable	Unit	Data range (min–max)	Model thresholds (min–max)	Relation to risk/suitability	Weight	Data source
Dispersal pathway/Propagule pressure						
Distance to international port (in Norway)	km	–	0–10	Decrease with distance	1/6	Norwegian coastal administration
Distance to nearest population (Gothenburg, Sweden)	km	–	180–300	Decrease with distance	1/6	NINA
Abiotic environment						
Salinity	PSU	16–34.5	0–30	Decrease over 15	1/6	IMR/NIVA/MET
Wave height	m	0–1.8	0–1	Decrease over 0	1/6	COPERNICUS
Water depth	m	0.5–2000	0.5–30	Decrease over 15	1/6	Norwegian mapping authority
Water temperature 3-m depth (April–August)	°C	5–15.6	0–25	Increase with temp	1/6	IMR/NIVA/MET

All variables were given equal weights. The variables were beforehand delimited to the coastal zone and normalised to a common scale (0–1) within a relevant threshold range according to introduction pathway and round goby habitat requirements, as well as their estimated relation to risk/suitability. E.g. sites with salinities of up to 15 PSU would have been given a value of 1, whilst salinities > 15 PSU were given successively lower values in a linear manner from 1 (salinity of 15 PSU) down to 0 (salinity 30 PSU and higher), i.e. decreasing suitability with higher salinity. The spatial (pixel) resolution of all variables are 50 × 50 m

Spatial modelling

Traditionally, habitat suitability models help to map and interpret known and potential species distributions. Such models can range in complexity from the simple habitat suitability index (HS*i*) approach to sophisticated regression-based machine learning methods that create complex relationships to capture detailed nuances in the spatial patterns in the data (Gregr et al., 2019). Choosing the most appropriate model approach depends on available data, the study context and intent (Segurado & Araújo, 2004) and aspects that highly influence the model complexity (Merow et al., 2013).

Being empirically restricted by the lack of presence–absence data, the objective of this study was to estimate a relative likelihood (or risk proxy) for introduction and establishment of the round goby in Norwegian coastal waters. We therefore modelled a simplified habitat suitability index (HS*i*) limited to the dispersal areas where the round goby in theory can be introduced (areas near harbours and/or currently within reach from the nearest population in Sweden). This was performed in ESRI ArcGIS Pro 2.4.2 (ESRI, 2021b). The HS*i* reflects the relative likelihood of round goby presence within 50 × 50 m pixels in these areas. HS*i* is derived from distance to the potential introduction point, as well as the suitability of the abiotic variables (salinity, temperature, wave height, depth) according to current knowledge about the round goby's tolerances and preferences (Table 1).

There are generally two types of methods to model HS*i*, either through data-driven methods (based on presence/absence data or presence only data) or expert-based methods using multi-criteria evaluation methods (MCE). We used a simple MCE method, the Weighted Linear Combination (WLC), where the normalised environmental variables and propagule pressure proxy variables are multiplied by equal fraction weights defined as $\frac{1}{n}$ (where n is the total number of variables) and summarised into a composite HS*i* raster dataset. This operation was done with the ArcGIS Pro 2.4.2 Raster Calculator. WLC is given by

$$\mathrm{HS}_i = \sum_{j=1}^{n} W_j * X_{i,j} \text{where} \sum_{j=1}^{n} W_j = 1,$$

where HS_i is the suitability score for pixel i, W_j is the fraction weight of variable j, X_{ij} is the value of pixel i under variable j and n is the total number of variables.

WLC is one of the most frequently used MCE aggregation techniques in GIS and is often applied in suitability modelling (Hanssen et al., 2018). WLC scales the normalised variables to a common range where suitable and unsuitable areas are continuous measures (Sposito et al., 2013). The derived HS*i* is a numerical index (ranging from 0 to 1), which in this case approximates the relative likelihood (or risk) for introduction and establishment of the round goby in Norway. Finally, as the round goby is a shallow water species, we extracted the HS_i pixels within the shallow coastal zone (0.5–30 m depth).

This type of model is sensitive to how variables are weighted. In our model all variables were given equal weights, however, with more detailed knowledge regarding the importance of the factors and potential spatial and temporal variation regarding the importance, the model could be further refined with differential weights to the variables.

Hotspot analysis

To identify spatially significant clusters of high risk (hotspots) and low risk (coldspots) at a local/regional scale we converted the risk raster dataset to a risk point cloud and used the Hotspot Analysis tool (Getis-Ord GI* statistic) in ArcGIS Pro 2.4.2 (Getis & Ord, 1992; Ord & Getis, 1995; ESRI, 2021c). For the conceptualisation of spatial relationships, we used a fixed distance band of 1.5 km to resemble a useful local/regional scale for the study. The result was converted to a hotspot raster dataset based on the correspondent confidence level bin values (− 3 to + 3).

Results

There are several areas in Norway where introduction is possible due to the main dispersal pathways of shipping and secondary dispersal from Sweden (Fig. 2). This means that these areas could be subjected to some level of propagule pressure today. Harbours with international traffic are spread along the coast (Figs. 1, 2a), whilst introduction by secondary dispersal from Sweden is, so far, only relevant in the southern part as seen by the potential invasion front by 2020 (Fig. 2b). Hence, our results indicate that, in addition to areas near harbours, the round goby, in theory, could already have been introduced by unaided dispersal from Sweden to the southeastern part of Norway. With time the area of potential invasion from Sweden will increase, given the round goby's rate of dispersal (Azour et al., 2015), as illustrated by the potential invasion front by 2030 (Fig. 2b).

The distribution of suitable habitat conditions varies and depends on which abiotic variable we look at (Fig. 3). Suitable habitat due to lower salinity is found near river outlets and estuaries. Low wave exposure is found in fjords and on leeward side of islands. Shallow areas are found near the coast, and water temperature is warmer in the south. Combining all variables in a WLC to yield the habitat suitability index (HS*i*) within the possible introduction areas, the model pinpointed several sites, spread along the coast, where both introduction is possible and the conditions seem suitable or at least acceptable for the species (Fig. 4).

The relative likelihood (risk) (approximated by the HS*i*) of first establishment varied spatially. Higher-risk localities are typically found in sheltered areas as compared to more-exposed coast (Fig. 4). The model also suggests that the relative risk varies on a larger scale, generally ranging from higher risk in the southeastern part to lower risk in the northern part. These results are further illustrated by cluster analysis of the individual HS*i* pixels. This analysis identified hotspots for first establishment, i.e. regions with significant clusters of high-risk areas for first establishment (Fig. 5). Such hotspots were prevalent in many places, particularly in southern Norway. Notably the Oslo Fjord region stands out as a hotspot associated with higher risk. Here, the distance to the round goby population in Gothenburg is short, there are many harbours with international traffic and there are several areas with suitable abiotic conditions, that is, sheltered, brackish, shallow and relatively warm. The analysis also identified significant coldspots, that is, clusters of areas where introduction is possible, but establishment is not likely because of less suitable environmental conditions and lower propagule pressure. These coldspots were largely located to exposed coastal areas even though there are exceptions (Fig. 5).

Discussion

An urgent challenge in invasion biology is to predict the distribution and potential spread of alien species.

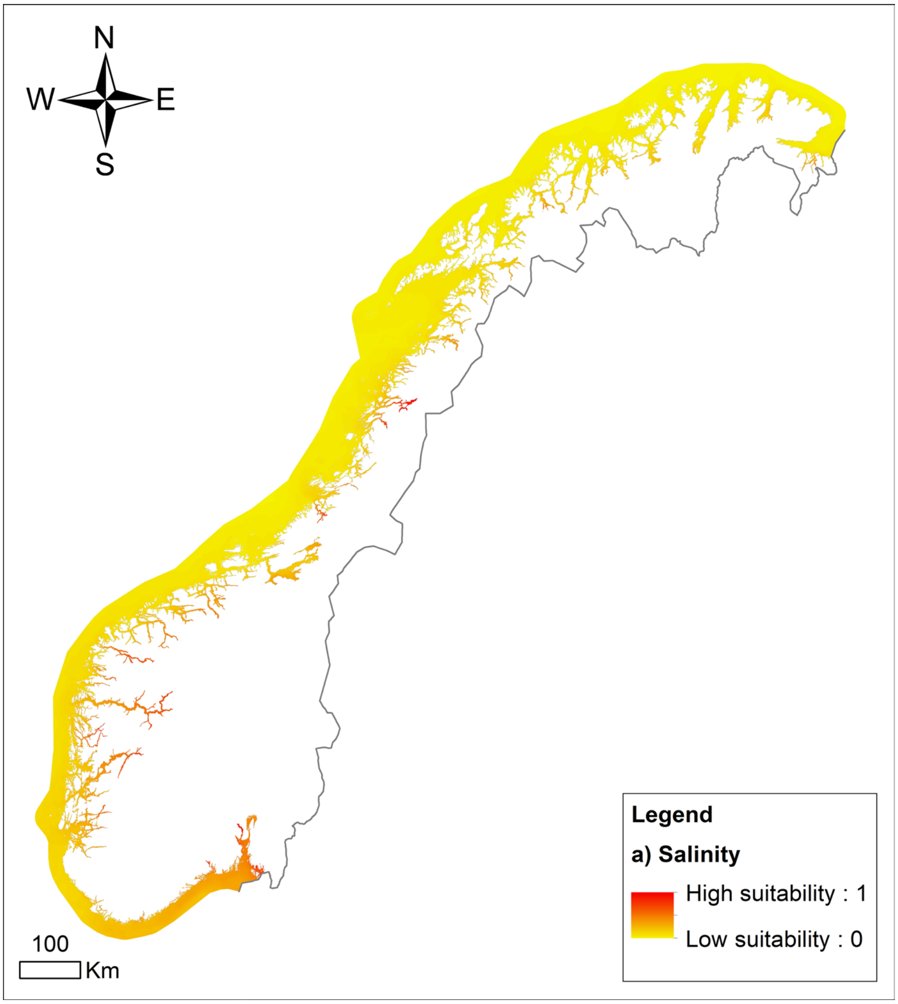


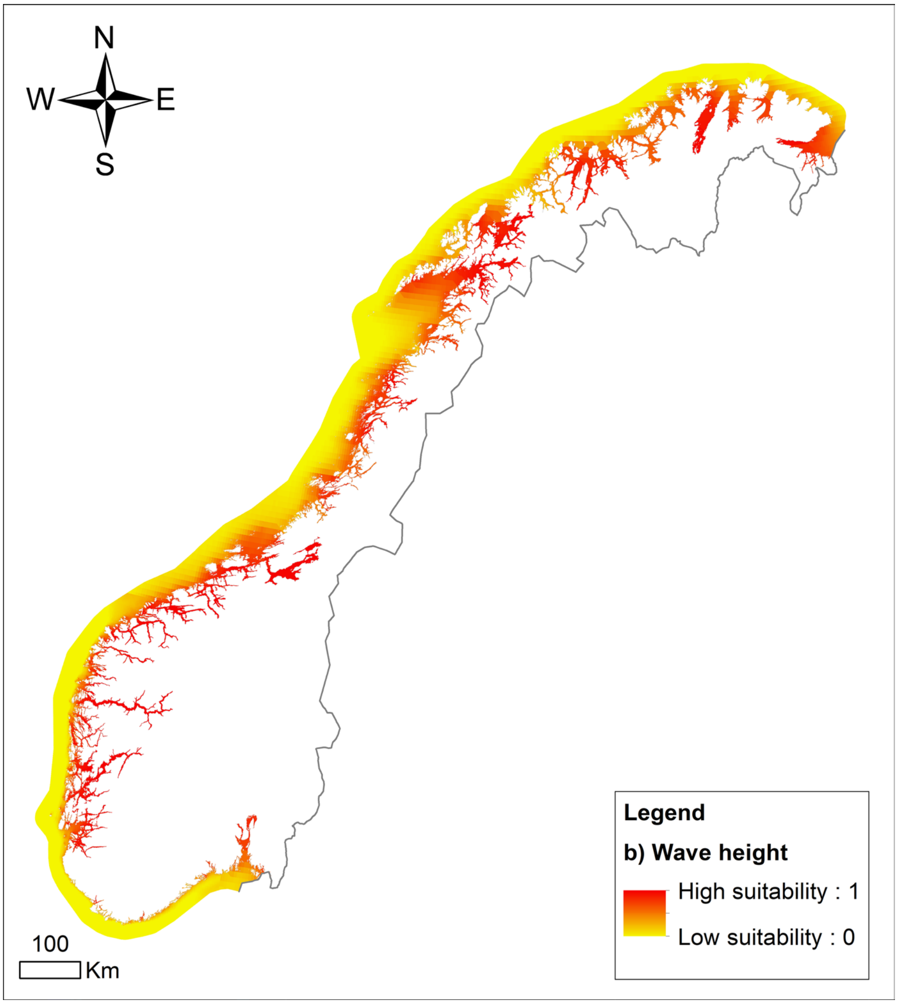
Fig. 3 Distribution of environmental variables relevant for the establishment of the round goby *Neogobius melanostomus* in coastal and estuarine areas in Norway. The figure shows estimated habitat suitability based on (**a**) salinity at 3-m depth, (**b**) wave height, (**c**) water depth and (**d**) water temperature at 3-m depth. For **a**, **b** and **d**, averaged data from April to August 2019 were used. All variable values were normalised to a common scale (0–1) using the ArcGIS Fuzzy Membership algorithm and threshold values (Table 1) (Colours indicate suitability from yellow (low suitability) to red (high suitability)

We have shown how the risk of a future potential invasion by an aquatic door-knocker species can be analysed spatially without absence–presence data. This should be applicable to other door-knocker species, in any region. According to our results there are many areas in Norway where introduction and establishment of round gobies are possible.

For alien species with shipping as a vector, like the round goby, there are numerous potential introduction points via harbours. In addition, the closest population of round gobies is only 180 km from the border between Norway and Sweden, from which the gobies most likely can disperse in the coastal zone. The Swedish population have a long enough invasion history to expect fish to be dispersing to new areas (Sapota, 2004; Sapota & Skora, 2005; Azour et al., 2015; Thorlacius & Brodin, 2018). Our estimates identified an area along the southern Norwegian coast which could, in theory, be reached by migrating fish today. This area is, of course, subject to uncertainty. It is, for example, unknown whether the dispersal rate along the more saline Swedish west coast would be lower than the recorded rate along the Danish coast (Azour et al., 2015; Behrens et al., 2017). On the other hand, it is possible that the Baltic current (along the Swedish west coast) and the Jutland current (northwards from Skagen) might facilitate a northward migration pattern. Hence, this dispersal pathway should not be underestimated. Taken together, there should be some propagule pressure from both ship traffic and secondary dispersal to the Norwegian coast today, although the level is not known.

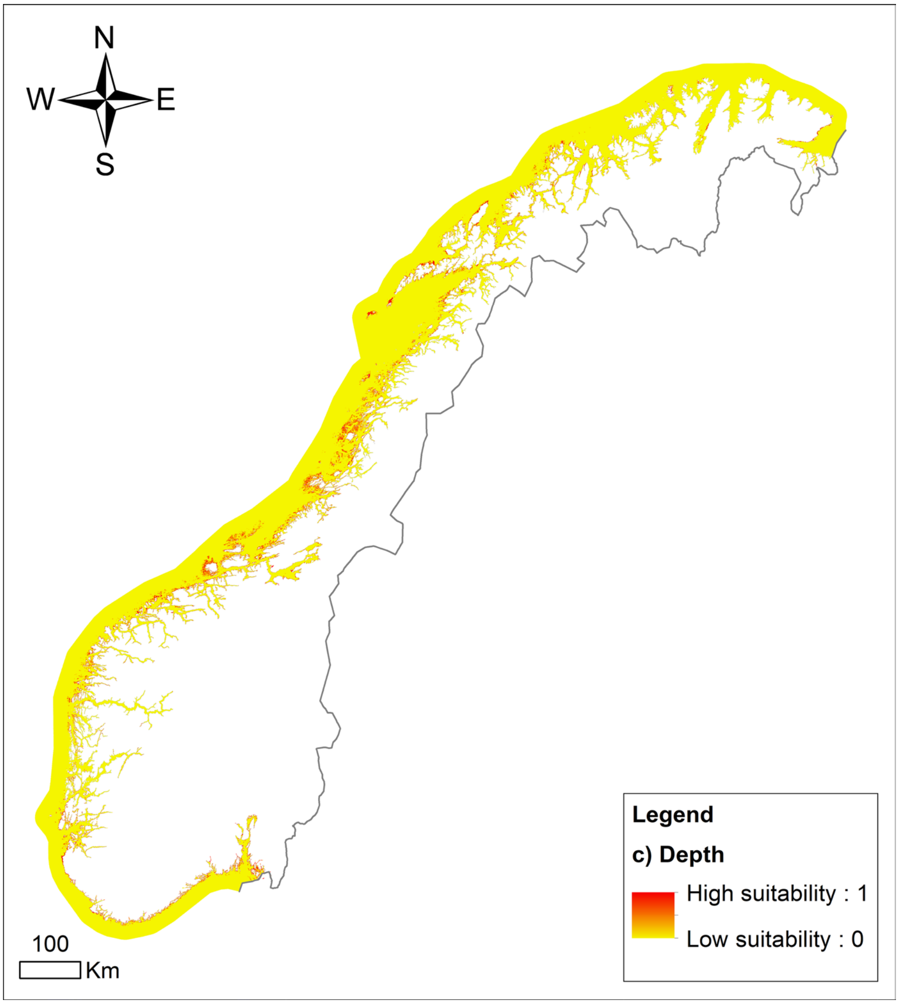
For colonisation and establishment to occur, a prerequisite is that the environmental conditions are

Fig. 3 (continued)



suitable with respect to the species' physiological tolerance and preferences. Other factors may, of course, also influence a species successful survival and reproduction, such as reproductive rate, presence of enemies and stochastic features of the introduction event (Blackburn et al., 2011). In our work we focused on abiotic conditions as a first screening of suitable locations. The round goby is a robust species with broad habitat and diet preferences (Kornis et al., 2012). Of the included environmental variables salinity is probably the most critical in terms of restricting the potential distribution of the species. The main part of the Norwegian coast is oceanic with euhaline salinities (up to 34.5 PSU) which, according to current knowledge, seem to be too high for survival and reproduction (Kornis et al., 2012). Despite this, there are many brackish areas where establishment should be possible. Even if physiological performance is hampered and survival reduced, the round goby can survive quite high salinities, even up to 30 PSU (Hempel & Thiel, 2015; Behrens et al., 2017). Moreover, there are several mechanisms that could help overcome physiological constraints, i.e. acclimation, epigenetically induced changes and selection. The upper limit regarding salinity for successful reproduction is not known, but it is likely lower than the limit for survival. Nevertheless, reproductive traits are expected to be under strong selection and rapid adaptive trait change to local salinity has been observed for reproductive traits in the species (Green et al., 2019). Some shallow fjord localities are both brackish and have low wave exposure, hence providing suitable conditions for establishment. In contrast, many outer coastal areas do not seem suitable for establishment

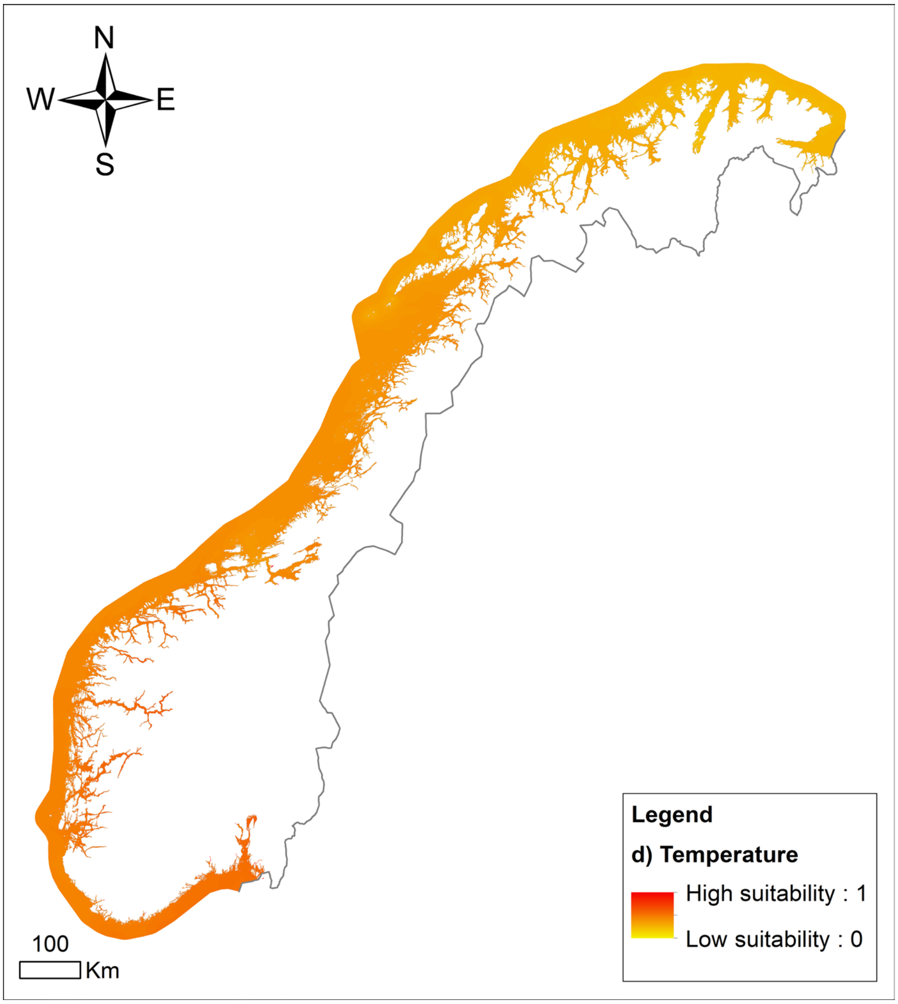
Fig. 3 (continued)



because of more wave exposure and high salinities. Differences in water temperature should also affect suitability (Kvarnemo, 1994; Lee & Johnson, 2005) making southern Norway more suitable than the northern regions.

Our results suggest that there are many locations along the Norwegian coast where potential introduction coincides spatially with suitable environmental conditions. The relative risk, however, varies depending on location. Our model suggests that especially shallow localities in sheltered areas and fjords of western and southern Norway are associated with a higher risk of first establishment, whilst the risk seems lower along exposed coast and in the north. This could be explained by several factors, including water temperature, the location of estuarine areas and narrow fjords, as well as the location of international harbours and distance to Sweden. There are several areas that come out as hotspots, i.e. where there are significant clusters of localities where introduction and establishment are especially likely. Particularly, the region around the Oslo Fjord stands out as a hotspot. This can be explained by a combination of factors as the region is close to Sweden, has many international harbours and many areas with suitable abiotic conditions. There are also many other regions with hotspots, suggesting that areas farther north are not exempted from potential invasion risk. However, whether the (cold) summer temperatures in the most northern part of Norway allows a time window long enough for successful breeding is unknown. Similarly, the model identified several coldspots where introduction is possible but the environmental conditions are not

Fig. 3 (continued)



suitable for establishment. These are typically found along exposed coastline.

Given the likely eventuality that the round goby invades Norway, it would be possible to validate models with absence–presence data and to further improve prediction of new areas of establishment. After introduction it could also be interesting to carry out spatial analyses on a more local scale (cf. Florin et al., 2018) and to include more factors, for example, substrate. We did not include bottom structure because our model focused on a larger regional scale and because the round goby inhabits a wide variety of substrates, from soft to rocky bottom, making predictions more difficult. Even less favourable habitats, like open flat sandy bottoms, have been found to be inhabited by the species (Sapota & Skora, 2005). In the Gulf of Gdansk, the point of first introduction in the Baltic Sea, the round goby first colonised shallow areas with stony and rocky habitat (Sapota, 2004). In another part of the Baltic Sea, Florin et al. (2018) found round gobies to be positively associated with both hard rock and mud substrate. In the Caspian Sea, round gobies were found to be most abundant on riprap shores (Zarini et al., 2019), that is, human-engineered defense structures along the coast consisting of stones, rocks or concrete.

After introduction and first establishment of the round goby, natural dispersal into the surrounding environment is expected after a lag phase of 3–5 years, as population density rises and condition drops (Sapota, 2004; Sapota & Skora, 2005; Thorlacius & Brodin, 2018). Natural dispersal from coastal areas to new areas could imply both

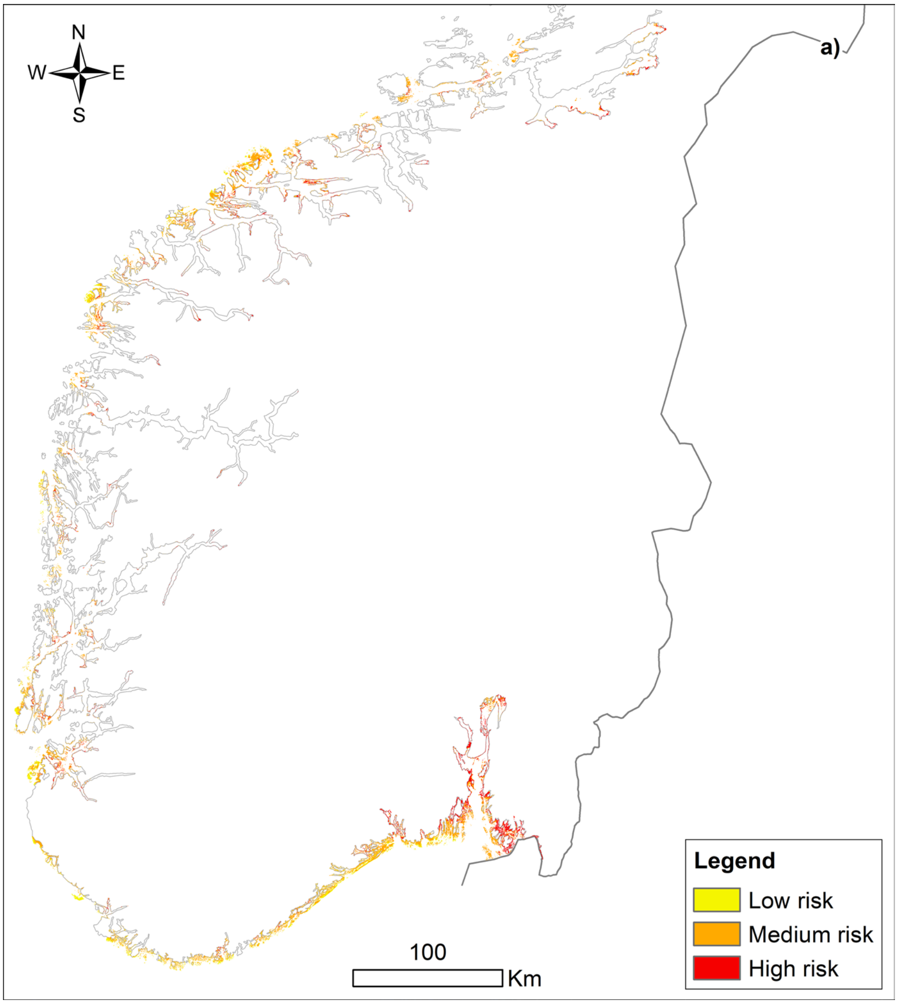


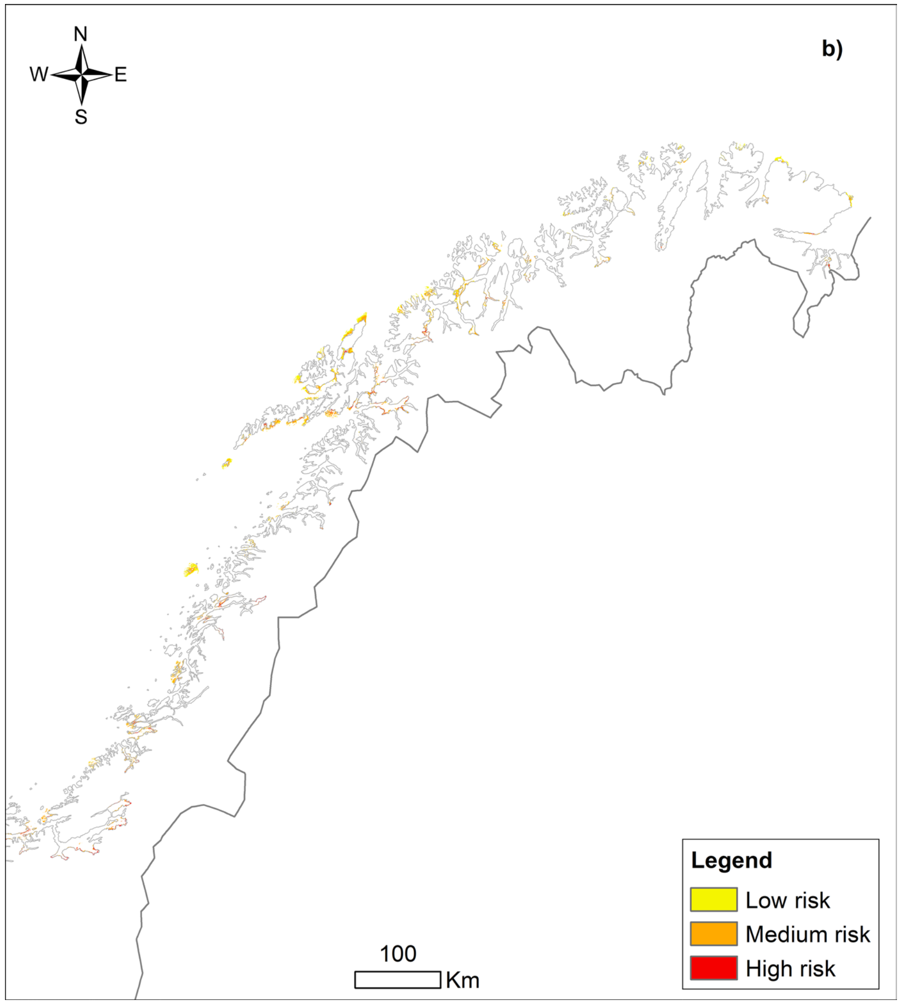
Fig. 4 Relative likelihood (risk) of first establishment of the round goby *Neogobius melanostomus* in Norway, south (**a**) and north (**b**). We classified the normally distributed risk values into three equal classes, and colours indicate relative risk from yellow (lower risk) to orange (medium risk) and red (higher risk). This is based on a combination of estimated relative propagule pressure and habitat suitability (four environmental variables) within the most relevant areas for introduction today. Areas with no colour are outside 10 km from international harbours, or not within reach by migrating fish from Sweden or deeper than 30 m. See methods for how the relative risk was calculated (HS*i*, habitat suitability index) and Table 1 for more information on the variables

migration within the coastal zone or migration into fresh water. Previous studies have shown up-stream riverine migration from estuarine populations in the Baltic (e.g. Sapota, 2004; Verliin et al., 2017; Christoffersen et al., 2019). Hence, a future introduction by the round goby to Norway would have the potential to negatively impact also freshwater ecosystems, like salmonid spawning grounds (Chotkowski & Marsden, 1999; Fitzsimons et al., 2006, 2009). If the round goby is introduced and established in estuarine areas in Norway, forecasting secondary dispersal and new areas of colonisation in fresh water would be very interesting. This has been done by spatial modelling in the Laurentian Great Lakes with tributaries (Kornis & Vander Zanden, 2010).

Conclusion

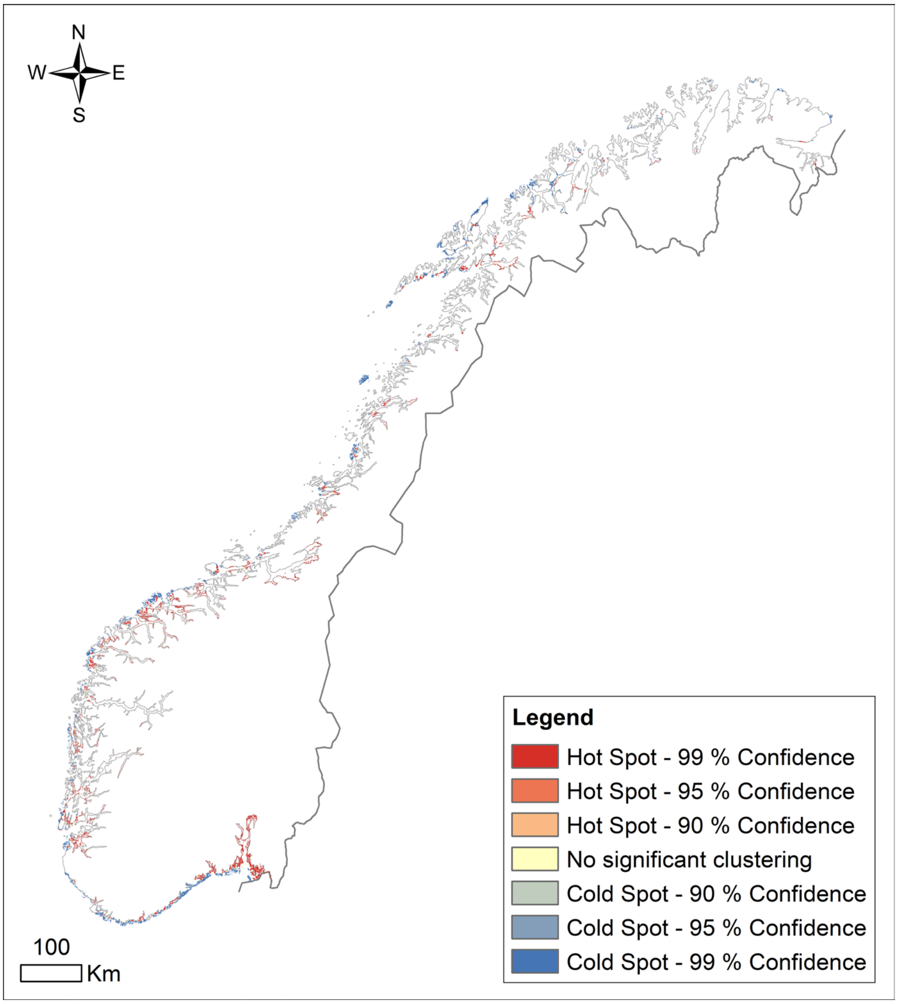
Our study could guide monitoring efforts to achieve early detection and potentially reduce the risk of

Fig. 4 (continued)



establishment and further spread once the round goby is introduced to Norway. After establishment it is often difficult to eradicate an invasive alien species, if at all possible, and associated costs are much higher (Leung et al., 2002; Keller et al., 2007). Hence, early detection is crucial for management action (Lehtiniemi et al., 2015). In the Baltic Sea, the round goby is so widespread and well established that eradication is now viewed as unrealistic (Ojaveer et al., 2015). Our work shows how a potential invasion by an aquatic door-knocker species can be addressed early by spatial modelling to identify high-risk areas, despite lacking presence–absence data. This should have wide relevance and be useful for management and could be applied to other door-knocker species in other regions around the globe.

Fig. 5 Map showing spatial distribution of relative risk for first establishment of the round goby *Neogobius melanostomus* in Norway based on hotspot analysis. Red indicates clusters of higher-risk areas, yellow indicates non-significant clustering and blue shows clusters of lower-risk areas. Areas without coloration are not likely areas of first introduction (not near international harbours, not close enough to round goby populations in neighbouring country) or is deeper than 30 m



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Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

Consent for publication Both authors agree to publish this work.

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