Modelling the risk of the introduction and spread of non-indigenous species in the UK and Ireland

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Disclaimer

Contents

Tables

Figures

Appendices

Glossary

ASSI: Areas of Special Scientific Interest (Northern Ireland equivalent to SSSI)

Bathymetry: the topology of the sea floor i.e. depth below sea level

Bed stress: the force exerted by waves and/or currents on the seabed, measured in Newtons/m^2

Biofouling: the undesirable accumulation of microorganisms, plants, algae and/or animals on wetted structures

SAC: Special Areas of Conservation

SPA: Special Protection Area

SSSI: Sites of Special Scientific Interest (England, Wales and Scotland, equivalent to Northern Ireland’s ASSI)

Substrate: the sediment type at the sea bed e.g. rock, gravel, mud, sand, mixed.

Executive summary

Non-indigenous species (NIS) pose a major threat to global biodiversity, and incur significant economic costs. As a result it is necessary to prevent their introduction and spread. This is reflected in the requirement to reduce the impact of marine NIS under the EU Marine Strategy Framework Directive (MSFD) (descriptor 2). The ability to predict where, and by which pathway, an NIS is most likely to arrive, establish and subsequently spread, is invaluable in reducing the impact of NIS on our marine environment. This study aimed firstly to identify potential hotspots of introduction and establishment of marine NIS across the UK and Ireland for nine broad taxonomic groups. The second main aim was to investigate the potential for internal spread within the study area, using *Didemnum vexillum* (DV) as a case study. DV is an invasive sea squirt that can have severe environmental and economic consequences, and in recent years has colonised several locations in the UK and Ireland.

The following steps were completed to achieve the above aims:

i) The highest risk pathways of introduction of marine NIS were identified as: commercial shipping (via ballast water or biofouling of hulls); recreational boating (biofouling); imports of live animals as stock for aquaculture; imports of live animals for the seafood trade; natural dispersal e.g. rafting.

ii) A grid was generated over the coastline of the UK and Ireland of cell size 70 km x 70 km.

iii) Data were collected on the intensity of activity for each pathway, to allow each grid cell to be scored from 0 (low activity) to 100 (very high activity) for each pathway.

iv) Weightings for each pathway were constructed, using published data, to account for their relative importance for each of nine taxonomic groups (plankton, algae, plants, worms, arthropods, crustacea, tunicates, jellyfish and molluscs), and DV.

v) Intensity scores and weightings were combined to create a score for each grid cell for 'likelihood of introduction' for each of the taxa, and for non-indigenous species generally.

vi) Environmental data was used to score each grid cell for likelihood of establishment, if introduced, for each taxonomic group.

vii) Data were collected on pathways of internal spread for DV (domestic commercial shipping, domestic recreational boating, internal aquaculture stock movements and natural spread) and plotted as network diagrams.

The following main results were obtained:

- Three areas have a high or very high likelihood of introduction for NIS in general, and for most of the taxonomic groups studied: the Thames Estuary, Kent coast and the Solent. These areas also score highly for likelihood of establishment. Medium risk areas for introduction and establishment include Devon, Cork and Dumfries.
- Four of the high or medium likelihood areas for introduction of DV correlate with known locations of the species: the north Kent coast, the Solent, Devon and Carlingford, Northern Ireland. All of the current known locations of DV are in areas with a medium or high likelihood of establishment. It can be hypothesised, based on the model, that populations found along the North Kent coast, the Solent and Plymouth were initial introductions, and the other populations were established through internal spread.
- The network analysis highlights several areas that may be at risk of being colonised by DV by spread from current locations by ferry movements (south west coast of Scotland, Isle of Man), movements of aquaculture stock (Thames Estuary, Essex coast), recreational boating and natural dispersal aided by currents (south Kent coast)
- The network analysis also demonstrates how well connected locations across the UK and Ireland are by the four pathways studied.

Our main recommendations from the results of this study are:

- Monitoring and biosecurity programmes should prioritise the areas with high likelihoods of both introduction and establishment. Such programmes may need to focus on specific taxonomic groups to optimise the probability of detection.
- Pathways that pose the greatest risk for a given area and/or taxonomic group should be targeted in terms of monitoring and biosecurity
- The current study should be combined with horizon scanning (such as that conducted by the GB Non-native Species Secretariat (NISS)) to determine the most likely points of introduction of these high risk species.
- Further work to develop the work presented here should be carried out, specifically:
    - collection of additional and finer resolution datasets (e.g. for ocean currents)
    - include a user interface to the risk model and GIS map display
    - conduct more case studies to further validate the model
    - include biosecurity measures as parameters in model
    - develop network analysis to allow quantitative outputs

In conclusion, this work has made a start in creating a model that enables a geographic analysis of risk. The process highlighted gaps in data availability, but also the benefits of collaboration between the constituent countries of the UK and Ireland. Methods have been developed that can be built on in the future to reach their full potential.

1 Introduction

1.1 Marine non-indigenous species (NIS) and the Marine Strategy Framework Directive (MSFD)

Non-indigenous species (NIS) pose a major threat to global biodiversity, and incur significant economic costs by direct impact on services, or indirectly through remediation requirements. Many aquatic ecosystems have been seriously affected by NIS because they may displace native organisms (through predation or by competing for resources), alter the genetic pool through hybridisation and introduce exotic pathogens and parasites (Eno *et al.* 1997). The impact of NIS is generally irreversible, particularly in the marine environment where NIS can be very difficult to eradicate once established. As a result there is an increasing necessity to prevent their introduction and spread. This is reflected in the requirement to reduce the impact of NIS under the EU MSFD (descriptor 2).

Prevention is increasingly recognised as the most effective means of avoiding or mitigating the impacts associated with unwanted NIS. Indeed, the guiding principles in the NIS management espoused by the Convention on Biological Diversity (CBD) are hierarchical in structure (Wittenberg & Cock 2001) and emphasize preventive measures over eradication, containment, control and mitigation. One of the main methods of preventing introductions is to manage the pathways by which NIS can be introduced. Pathway management of NIS is complex, especially in the marine environment. This is particularly true around the UK and Ireland due to the intensity of activity in the marine environment and the length of coastline. There are many pathways via which marine NIS can colonise new regions, as vessels, equipment and animals are frequently transported long distances. These pathways may involve either accidental or intentional movement of species as a consequence of human activities (Ruiz & Carlton 2003; Copp *et al.* 2005). Marine NIS have established in Great Britain (GB) and Ireland due to escapes from aquaculture (Pacific oyster, *Crassostrea gigas*), fouling of vessels' hulls (the invasive tubeworm, *Hydroides dianthus*), transport in ballast or bilge water (an invasive barnacle, *Elminius modestus*), accidentally with imports of aquaculture stock (slipper limpet, *Crepidula fornicata*) and by drifting or rafting, on either man-made or natural materials (e.g. wire weed, *Sargassum muticum*), from areas where the species is non-indigenous (Eno *et al.* 1997). Those pathways involving vessel movements (fouling of hulls and ballast water) are often cited as the highest risk routes for the introduction of marine NIS (Carlton, 1992) and this concurs with the finding that the hotspots for NIS in British waters are areas with a high volume of shipping traffic, such as the Solent (Eno *et al.* 1997). Loading and discharging of ballast water is an essential part of a ship's operation. Globally in excess of 10 billion tons of ballast water, containing thousands of species, is carried in ships every year, and almost 100 million metric tonnes of ballast water is discharged annually at ports in the UK (Enshaei & Mesbahi, 2009). The vast majority of organisms will not survive the journey, but those that do survive may establish themselves in a new environment if the biological and physical conditions are favourable. Most of the pathways listed are important to society, either for economic purposes (freight shipping), personal transport (passenger ferries) food sources (aquaculture) or leisure (recreational boating). Most of these pathways in addition to aiding in the introduction of NIS are also responsible for their internal spread.

A key component of preventing the introduction of NIS is the forecasting of (or horizon scanning for) the pathways by which potentially invasive NIS are likely to be introduced, as this is a means of reducing the potential success of introduction (Holeck *et al.* 2004). By identifying the areas around the coastline where there are high levels of activity related to these pathways it is possible to obtain an indication of the likelihood of a species being introduced at that location. This also applies to the internal spread of already introduced NIS. By including estimates of the probability of the introduction of species through different pathways, it is possible to estimate the probability of the species being introduced or spread to specific locations. The ability to predict where a NIS is most likely to arrive into GB waters, how it is most likely to arrive, where it is most likely to establish and then subsequently spread is crucial in reducing the impact of NIS on our marine environment. The basic precept of ‘closing the stable door’ applies.

When identifying areas most at risk from NIS, pathways of introduction and spread are important, but it is crucial that environmental conditions are also considered. Firstly, environmental conditions such as temperature, salinity and substrate must be considered in terms of suitability for the organism, as when a species is introduced into a location these conditions will dictate if it is able to survive. Secondly, an ecosystem’s resistance to invasion could be considered. One measure of this may be level of disturbance, as disturbance may lead to niches being not fully occupied and opportunities arising for non-indigenous species. Thirdly, It is important to consider the location of protected areas: the consequences of invasion by NIS may be more severe for designated regions, and management strategies for emerging NIS would need to take into account the species and habitats under protection.

1.2 *Didemnum vexillum* (DV)

DV, commonly known as the Carpet Sea squirt, is an ascidian tunicate that grows in colonies, often in a carpet-like form on the seabed and other substrates. It has spread worldwide and is particularly well documented in New Zealand, North America and continental Europe (Beveridge *et al.* 2011, Bullard *et al.* 2007). DV is able to spread rapidly, and become dominant in new environments, excluding other benthic organisms and creating a homogenous habitat (Lengyel *et al.* 2009). Fragments from a colony are able to break off and establish in a new location (Bell et al. 2011). The colonies may overgrow fish spawning grounds and hinder the ability of fish to feed on benthic species (Bullard *et al.* 2007). Commercially, DV is important as it poses a risk to aquaculture, for example preventing scallop recruitment due to its colonisation of substrates

(Morris Jr. *et al.* 2009), and smothering shellfish, e.g. mussels in New Zealand (Coutts & Forrest, 2007). Introductions of DV to new regions are likely to be have been by commercial ships, either due to movements of ballast water or biofouling of ships' hulls. Biofouling of recreational boats and movements of aquaculture stock and equipment could cause local spread of DV (Lambert, 2009). When animals are moved for aquaculture, they cannot be fully disinfected and DV could be attached to the animals themselves, on equipment, or in the water in which the animals are moved. Such movements can only spread DV if they are between seawater sites. This study will use DV as an example species to which the methods developed here can be applied.

1.3 Aims

The main objectives of this project were to:

1. use pathway risk analysis methods to recognise 'hotspot' coastal areas of the UK and Ireland that are at most risk of initial invasion (introduction) and establishment by each of the main taxonomic groups of potential NIS

    a. identify the highest risk vectors/pathways for the introduction and subsequent spread of NIS in the UK and Ireland.

    b. identify the hotspots of introduction for each taxonomic group by identifying the areas of most intense activity for the highest risk pathways.

    c. identify the areas that are most likely to be established by each taxonomic group using environmental data.

    d. the above analysis will also be carried out for DV as an example species (case study).

2. assess the potential for internal spread of NIS, using DV as a case study

a. identify connections between ‘nodes’ (locations such as ports and aquaculture sites) via the highest risk pathways identified for DV.

b. assess the areas that DV is most likely to spread to, given its current locations and other areas that the analysis in the second part of the study revealed to be at risk of introduction of DV.

2 Methods

The first main objective of this study was to identify the coastal areas where NIS are most likely to be introduced and establish. This required the following steps:

i) identification of the pathways most likely to introduce NIS to the UK and Ireland

ii) collection of data on the intensity of activity for each pathway

iii) division of the coastline of the UK and Ireland into a number of geographic areas.

iv) scoring the intensity of activity for each pathway for each of the geographic areas

v) weighting the pathways for each taxonomic group of potential NIS according to their importance as routes of introduction for each taxonomic group.

vi) combining intensity scores and weightings to create a score for each geographic area for likelihood of introduction by each taxon.

vii) using environmental data to score each geographic area on how likely an introduced NIS would be to establish, for each taxon.

2.1 Pathways of introduction and spread

Literature on the introduction and spread of NIS (for the UK and globally) was reviewed, and expert knowledge was used to compile a list of the pathways most likely to introduce NIS to the UK and Ireland or spread NIS within this region. The following pathways were identified as carrying the highest risk in terms of the introduction of NIS to the UK and Ireland, and subsequent spread:

i) Transport within the ballast water of ships (applies to commercial shipping only, i.e. cargo ships, tankers, ferries, larger fishing vessels) or biofouling of their hulls.

ii) Biofouling of recreational vessels

iii) Accidental transport with imports or internal movements of live marine animals as aquaculture stock.

iv) Accidental introduction with imports of live marine animals for the seafood trade.

v) Natural dispersal, such as rafting under the influence of ocean currents.

2.2 Data collection

To identify hotspots for invasion by NIS, data were required to provide scores for intensity of activity related to each of the pathways listed in the previous section. Data were therefore required for:

- Commercial shipping activity (including cargo, passenger ferries and fishing)
- Recreational boating activity
- Marine aquaculture activity: locations of sites and imports of stock for marine aquaculture
- Imports of live seafood
- Potential for drifting or rafting from other areas where the species is non-indigenous, i.e. distances to foreign landmasses and direction and speed of prevailing ocean currents.

To estimate how likely an introduced NIS would be to establish in an area, the following environmental data were required to assess each area's suitability for a given NIS:

- Salinity
- Temperature
- Bathymetry (depth)
- Substrate of the seabed
- Presence of ports and/or marinas (i.e. the presence of hard structures)
- Presence of marine aquaculture sites (i.e. the presence of hard structures)
- Bed stress

In the first instance, data were sought from within Cefas and each of the collaborators, and their contacts in government departments or other science organisations in each country. Internet searches were used to identify additional sources of data where required. The data were collected from the most recent time period possible. The datasets used in the analysis and their sources are described in the following sections and summarised in Table 1.

Table 1. *A summary of the datasets used in the analysis. There is some repetition where datasets were used for more than one part of the analysis*

Dataset	Region	Year[1]	Format	Source	URL (where publically available)
Outline map of the coastline of the UK and Ireland	UK and Ireland	NA	GIS layer	Department of Energy and Climate Change (DECC)	http://og.decc.gov.uk/en/olgs/cms/data_maps/offshore_maps/offshore_maps.aspx
Current known locations of *Didemnum vexillum*	UK and Ireland	2012	Spreadsheet	Cefas, Non Native Species Secretariat	NA
Pathways of introduction					
Number of international ferry passengers by port	UK	2010	Spreadsheet	DfT: spreadsheets SPAS0101 and SPAS0102	http://www.dft.gov.uk/statistics
	Ireland	2010	Table	Irish Maritime Development Office (IMDO)	http://www.imdo.ie/imdo/shipping
Number of shipping vessels arriving at each major port	UK	2010	Spreadsheet	DfT: spreadsheet: PORT0602	http://www.dft.gov.uk/statistics
	Ireland	2010	Published table	Central Statistics Office, Ireland	http://www.cso.ie/en/media/csoie/releasespublications/documents/transport/current/spt.pdf
Landings density (fishing) by port	UK	2005 - 2007	GIS shapefile	DECC / Anatec Ltd	http://www.maritimedata.co.uk/
Location of RYA (Royal Yachting Association) marinas	UK	2008	Map	DECC / Anatec Ltd / RYA	http://www.maritimedata.co.uk/
Location of ISA (Irish Sailing Association) marinas	Ireland and Northern Ireland	2010	Map	Sustainable Energy Authority of Ireland / ISA	http://www.seai.ie/Renewables/Ocean_Energy/Strategic_Environmental_Assessment_of_the_OREDP/Environmental_Report/SEA_ER_Volume_3_

					Figures_Chapter_9e.pdf)
Dataset	**Region**	**Year¹**	**Format**	**Source**	**URL (where publically available)**
Recreational boating routes and intensity	UK	2008	Map	DECC / Anatec Ltd	http://www.maritimedata.co.uk/
Location of marine aquaculture sites	England & Wales (farms)	2012	Geo-referenced spreadsheet	Fish Health Database (Cefas)	NA
	England & Wales (shellfish harvesting areas)	2011	GIS layers	MAGIC (Defra)	http://magic.defra.gov.uk/
	Scotland	2012	Geo-referenced spreadsheet	Marine Scotland	NA
	EIRE	2012	GIS shapefile; maps	BIM (Bord Iascaigh Mhara); Browne et al. 2008.	http://www.marine.ie/NR/rdonlyres/8AE234AC-820B-48F8-B6B9-53B4E69FF904/0/StatusofAQreport2007finaldraft.pdf (for maps only)
	Northern Ireland	2012	GIS shapefile	Department of Agriculture & Rural Development (DARDNI)	NA
Imports of stock for marine aquaculture	England & Wales	2009 - 2010	Geo-referenced Spreadsheet	Fish Health Database (Cefas)	NA
	Scotland	2001 - 2011	Geo-referenced Spreadsheet	Marine Scotland	NA
	Northern Ireland	2010 - 2011	Geo-referenced Spreadsheet	DARDNI	NA
	EIRE	2011	Spreadsheet	Marine Institute, Ireland	NA
Locations of live seafood holding facilities and	England & Wales	2012	Geo-referenced spreadsheet	Fish Health Inspectorate (Cefas)	NA

markets					
Dataset	**Region**	**Year[1]**	**Format**	**Source**	**URL (where publically available)**
Pathways of internal spread					
Domestic coastwise freight movements (by region)	UK	2010	Spreadsheet	Dft spreadsheet DWF0309	http://www.dft.gov.uk/statistics
Domestic ferry routes	UK and Ireland	2010 / 2012	Spreadsheets, lists	Dft spreadsheets SPAS0102 and SPAS0201, searches of ferry company websites to supplement	http://www.dft.gov.uk/statistics
Location of marine aquaculture sites	England & Wales (farms)	2012	Geo-referenced spreadsheet	Fish Health Database (Cefas)	NA
Internal movements of stock for marine aquaculture	England and Wales	2009-2010	Geo-referenced spreadsheet	Fish Health Database (Cefas)	NA
Recreational boating routes and intensity	UK	2008	Map	DECC / Anatec Ltd	http://www.maritimedata.co.uk/
Establishment					
Spring shelf surface salinity	UK and Ireland	2006	Map	UKSeaMap (JNCC, Proudman Oceanographic Laboratory (POL))	http://www.searchmesh.net/pdf/JNCC_UKSeaMap_FinalReport.pdf
Minimum bottom temperature	UK and Ireland	2006	Map	UKSeaMap Project (JNCC, ICES)	http://www.searchmesh.net/pdf/JNCC_UKSeaMap_FinalReport.pdf
Bathymetry	UK and Ireland	2008	Map	Atlas of UK Marine Renewable Resources (ABPmer, The Met Office, POL)	http://www.renewables-atlas.info/downloads/documents/Renewable_Atlas_Pages_A4_April08.pdf

Dataset	Region	Year[1]	Format	Source	URL (where publically available)
Substrate type	UK	2006	GIS layer / Map	UKSeaMap Project (JNCC / British Geological Society (BGS))	http://www.searchmesh.net/pdf/JNCC_UKSeaMap_FinalReport.pdf
	Ireland	2003 - 2011	Online map	INFOMAR	http://geos2.marine.ie/infomar/
Locations of ports	UK	2012	GIS layer	DECC, Anatec Ltd	http://www.maritimedata.co.uk/
	Ireland	2012	List	(IMDO)	http://www.imdo.ie/imdo/shipping
Locations of ISA marinas	Ireland and Northern Ireland	2010	Map	Sustainable Energy Authority of Ireland / ISA	http://www.seai.ie/Renewables/Ocean_Energy/Strategic_Environmental_Assessment_of_the_OREDP/Environmental_Report/SEA_ER_Volume_3_Figures_Chapter_9e.pdf)
Locations of RYA marinas	UK	2008	Map	DECC / Anatec Ltd / RYA	http://www.maritimedata.co.uk/
Bed stress	UK and Ireland	2006	Map	UKSeaMap (JNCC, POL)	http://www.searchmesh.net/pdf/JNCC_UKSeaMap_FinalReport.pdf
Locations of protected areas	UK	2012	GIS layers	JNCC	http://jncc.defra.gov.uk/protectedsites/SACselection/gis_data/terms_conditions.asp
Currents	UK	2000, 2010	Maps and text	OSPAR (2000) [after Turrell et al. (1992)] *and* Huthance et al. (2010)	http://www.ospar.org/content/content.asp?menu=00650830000000_000000_000000 http://chartingprogress.defra.gov.uk/

[1] Year of data collection where available from source, year of publication otherwise

2.3 Pathway risk analysis: identifying hotspots

A GIS layer of the coastline of the UK and Ireland was loaded into ArcGIS version 9.3. A grid was created using the Fishnet tool (Nicholas, 2003) of cell size 70 x 70 km (Fig. 1). This scale was chosen based on the spatial scales of the available data.

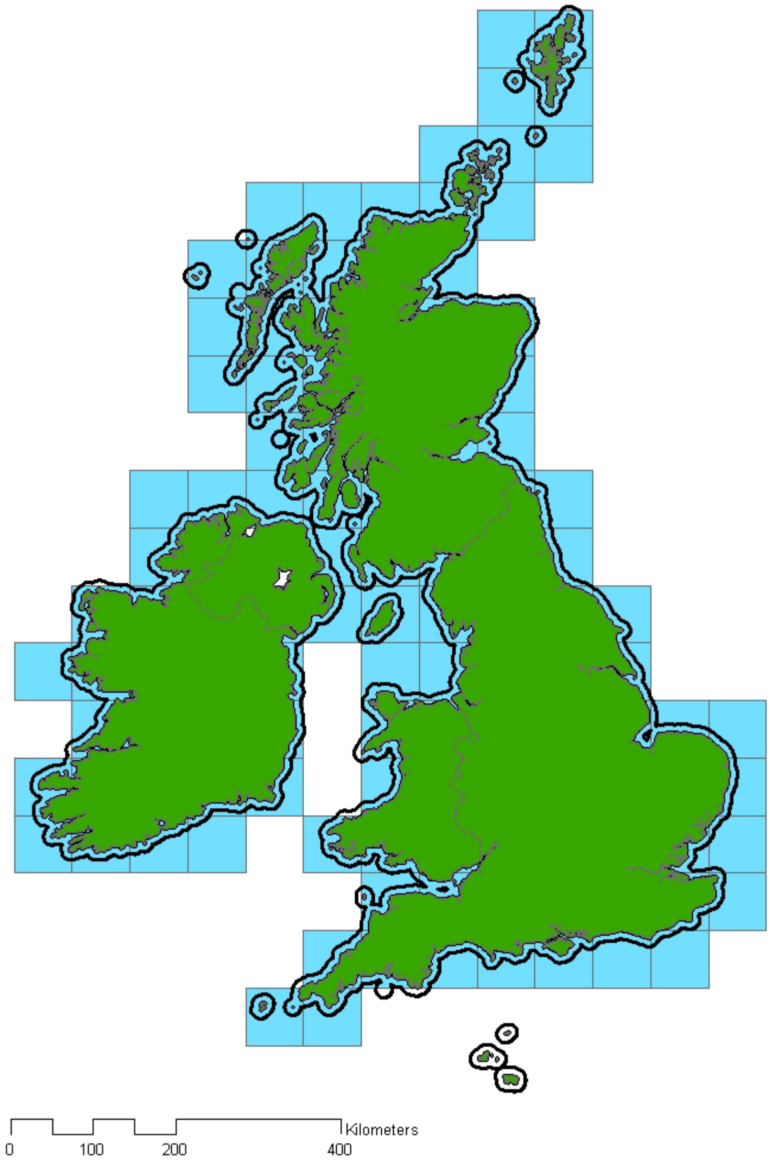


Figure 1. *The grid used as the spatial scale of analysis, superimposed over a map of the coastline of the UK and Ireland. Only grid squares that include a coastal area are included in the analysis, and shown here (in blue). The black line represents a distance of 6 miles from the coastline, the boundary of the coastal area.*

2.3.1 Pathways of introduction: scoring

For pathways of introduction, a score was given for each coastal grid cell (from 0 to 100) for each of the datasets based on the intensity of each activity (e.g. fishing activity, aquaculture imports) in that cell. For continuous variables, this required the scale for each dataset to be coerced to 0 to 100. The datasets (Table 1) were grouped under each of the 5 pathways (section 2.1). The scores for the datasets within each pathway were averaged to give an overall score (from 0 to 100) for each of the pathways for each grid cell. This score represents the likelihood of introduction of NIS via the pathway in that geographic area relative to that for the other areas of the UK and Ireland. The calculations were carried out in an Excel spreadsheet. In the following sections, the datasets and scoring systems are described. Heat maps of the scores for each of the five pathways are presented in Appendix A.

(i) Commercial shipping (ballast water and biofouling)

Three datasets were used as proxies for intensity of shipping activity for each grid cell: the sum of the number of ferry passengers (per annum) using the ports within each grid cell; the sum of the number of cargo vessels arriving at the ports (per annum) in each grid cell; and landings from fishing vessels (mean annual landings, tonnes). A GIS layer was available for landings, on a spatial scale of the ICES statistical rectangles, and the ICES rectangle that covered the greatest proportion of each grid cell was used to assign values to the grid cells.

Number of ferry passengers was expressed in 1000s of passengers, and values ranged from 0 to 13,548. To give each grid cell a score between 0 and 100, the number of passengers (in 1000s) was square rooted, and where the value was particularly high (one grid cell: the section of the Kent coast that includes Dover and Ramsgate had a value of 13.548), the score was capped at 100. The same scoring system was used to transform the values for number of arriving cargo vessels, which were between 0 and 22,171. The score for four grid cells with values of over 10,000 (number of vessels) were capped at 100. These areas were: the coastline around Dover; the Thames Estuary; the Humber estuary; and the grid cell that includes parts of the Dumfries coast and the area around Belfast). This transformation was used due to the skewed distributions of the two datasets, which both had a few very high values, and many lower values (<2000). Dividing the values by a fixed factor to give a scale of 0 to 100, and not capping scores for very high values would cause these few very high values to overwhelm the low and medium values and cause the scores for shipping to be very low on average compared to the other pathways. Landings density was less skewed in general than the other shipping datasets and values ranged from 0 to 1000 so scores were calculated by dividing the values by 10. However there was one outlier, with a value of 2440, and the score was capped at 100 for this value.

(ii) Recreational boating (biofouling)

Two datasets were used to represent recreational boating activity: numbers of RYA (Royal Yachting Association) or ISA (Irish Sailing Association) marinas in each grid cell, and a score based on recreational sailing routes to/from continental Europe. Numbers of marinas, which ranged from 0 to 33, were divided by 0.33 to coerce the scale from 0 to 100. The score for sailing routes was created using a map of commonly used recreational sailing routes. A grid cell was given one, two, or three points for each low-, medium- or high-use route from continental Europe respectively. The summed points were converted into a score of 0 to 100 by dividing by 0.18.

(iii) Aquaculture

Locations of marine aquaculture sites were provided by the relevant competent authority in each country. Due to differences in size and production between sites, it was most appropriate to score aquaculture sites as present (score of 100) or absent (score of 0) for each grid cell. Imports of aquaculture stock from overseas were available by receiving site for England, Wales and Scotland and by region for Northern Ireland. Data on the areas receiving imported stock in the Republic of Ireland were not available. Grid cells received a score based on the number of sources they imported stock from, either 0 (no imports), 50 (1 source), or 100 (2 sources).

(iv) Live seafood trade

The locations of holding facilities and seafood markets were available from Cefas records for England and Wales. Internet searches were used to identify any major importing markets in Scotland, Northern Ireland and Ireland. Each grid cell was scored based on the number of holding facilities or seafood markets present.

(v) Natural dispersal

The distance by sea from each grid cell to the nearest foreign land mass were calculated in ArcGIS, and scored in intervals of 10 (10, 20, 30... up to 100) with smaller distances gaining higher scores.

2.3.2 Weighting the pathways of introduction

To assign weightings for the pathways of introduction of NIS the main taxonomic groups of potential NIS were summarised as follows:

- Planktonic diatoms (including Bacillariophyta)

- Algae (including Rhodophyta, Chromophtya, Chlorophyta)
- Plants (including Anthophyta)
- Cnidaria (including Hydroza, Anthozoa)
- Worms (including Annelida)
- Arthropods (including Chelicerata)
- Crustacea (including Maxillipoda, Ostracoda, Eumalacostraca)
- Mollusca (including Gastropoda, Pelecypoda)
- Tunicata

These categories were selected as they were considered to represent all of the major NIS present within GB waters as described by Eno *et al.* (1997). Although other NIS have arrived in GB water since the publication of Eno *et al.* (1997), such as *D. vexillum*, this report was considered to be an accurate 'snap shot' in time from which information could be used to establish weightings for introduction, establishment and spread of species in each category. The only modification to the species listed in Eno *et al.* (1997) was the inclusion of the American lobster (*Homarus americanus*) as recently described by Stebbing *et al.* (2012) as an NIS which has been present in GB waters for a number of years. The nematode *Anguillicola crassus,* a parasite which effects the European eel (*Anguilla anguilla*), was excluded as it was not considered by the authors to be a problematic NIS, and was most likely introduced initially into freshwater. Further sources were used (such as the Non-Native Species Secretariat website) for additional information on the biology of species where insufficient information was available from Eno *et al.* (1997).

Each species recorded in the directory section of the Eno *et al.* (1997) report was categorised according to the taxonomic group that it fitted into and the pathway(s) by which it is considered to have been introduced into the country, for example the Pacific Oyster, *Crassostrea gigas*, is a mollusc and considered to have been introduced as a result of marine aquaculture activities. Each species was recorded against each pathway of introduction that it is considered to have entered by, therefore some species were recorded under multiple pathways. This allowed for a generic weighting to be calculated for each pathway (using the total number of species introduced by this means) or taxonomic specific weightings of the total number of species introduced per pathway for each taxonomic category. The final weighting was expressed as a proportion of 1, with the weightings for each pathway summing to 1. The weightings are set out in Table 2.

Table 2. *The weightings for the five pathways of introduction, for each taxonomic group and for all NIS*

	Pathway				
Taxonomic group	Commercial shipping	Recreational boating	Aquaculture stock movements	Live seafood trade for human consumption	Natural dispersal
Plankton	0.63	0	0.38	0	0
Algae	0.20	0.17	0.34	0	0.29
Plants	1.00	0	0	0	0
Jellyfish	0.38	0.38	0.25	0	0
Worms	0.57	0.07	0.29	0.07	0
Arthropoda	0.33	0.33	0.33	0	0
Crustacea	0.67	0.11	0	0.22	0
Mollusca	0.36	0	0.57	0	0.07
Tunicata	0.40	0.20	0.20	0	0.20
DV	0.42	0.21	0.29	0	0.08
Generic (all NIS)	0.39	0.13	0.32	0.03	0.12

The overall score for likelihood of introduction, for all NIS and for each taxonomic group, was calculated for each grid square by multiplying each pathway's score (out of 100) by its weighting and summing the weighted scores.

2.3.3 Establishment

To assess the likelihood of establishment, the biological preferences of each of the species assessed for introduction and spread were examined for the seven environmental variables listed in section 2.2. The presence of ports, marinas and aquaculture facilities were included due to the preference for hard, manmade substrates by some species. The values of the continuous variables salinity, temperature, bathymetry and bed stress were classed as low, medium or high, e.g. for temperature, 4-6°C was classed as low, 7-9°C as medium and ≥10°C as high. For each grid square, a value of low, medium or high was assigned for each variable based on collected data (Table 1), which was mostly in the form of maps.

Each taxonomic group was given a score between 0 and 10 for each value (low, medium and high) for each variable. The score was calculated by recording each known marine NIS in the UK (Eno *et al.* 1997) within each taxonomic group against its preferred category of the variable. For example, a species that has a preference for low temperatures would be recorded under 'low' for temperature. Species that had a range of preferences that encompassed several categories were recorded multiple times. The number of species within the taxonomic group per category were then totalled, and transformed to give a score between 0 and 10 for each of low, medium and high for each variable. For number of marinas and ports (a continuous variable) a scale from 0 to 10 was constructed for each taxon depending on whether it was more or less likely to colonise ports/marinas. For each grid cell, a score for likelihood of establishment of each taxonomic group, was calculated by averaging the scores obtained for the grid cell's seven variables. For full details of establishment scoring, see Appendix B. All calculations were carried out in an Excel spreadsheet. The spreadsheets for both introduction and establishment were imported into ArcGIS to allow the data to be displayed as heat maps.

2.4 Network Analysis

Four of the pathways were assessed as being able to spread DV within the UK and Ireland. These are (in order of importance based on the weightings generated; see Table 2): domestic shipping (freight and ferry movements), internal movements of aquaculture stock, recreational boating, and natural dispersal. A network analysis requires knowledge of the connections between 'nodes', i.e. ports, marinas and aquaculture sites. As much data as possible was collected on the locations of these nodes and the connections between them via these pathways (Table 1). The nodes and connections were then plotted as network diagrams.

3 Results

3.1 Likelihood of introduction

The likelihood of NIS being introduced via the five most important pathways (see section 2.1) was scored between 0 and 100 for each grid square in the UK and Ireland. The results of this analysis are presented in eleven heat maps: one for NIS in general (Fig. 2a), one for DV, and one for each of nine taxonomic groups of potential NIS (Figs. 2b-k). The likelihood of introduction score (0-100) was further categorised as 'low' (≤30-40), medium (41-60), high (61-80) or very high (81-100) for ease of description.

The results for all NIS (a generic analysis), show clear hotspots: likelihood of introduction is 'very high' in the Thames Estuary, and 'high' for the Kent coast and the Solent (Fig. 2a). Dorset and Devon, south east Ireland, Anglesey, Lancashire and parts of the west coast of Scotland are 'medium' risk areas. Tunicates, crustacea, plankton, plants, arthropods, worms, and jellyfish have similar patterns for the likelihood of introduction to the generic pattern (Figs. 2 c,d,e,g,h,i,j). The Thames Estuary has a very high or high likelihood of invasion for each of these taxonomic group, the Solent a high likelihood for all but two taxa (plankton and molluscs), and at least part of the Kent coast has a high or very high likelihood of introduction for all but two taxa (crustacea and jellyfish). Algae (Fig. 2f) has a similar pattern but a greater number of high and medium risk squares, which dominate southern Ireland, the south and east coasts of England, and the west coast of Scotland to a lesser extent. Molluscs have an even greater number of high and medium risk squares, particularly along the west coast of Scotland, southern Ireland, and south west England (Fig. 2k). The likelihood of introduction for *Didemnum vexillum* (DV) shows a similar pattern to the generic analysis (Fig. 2b); the Thames Estuary has a very high likelihood of introduction, and the Solent and Kent coast have high scores. These areas are where the majority of UK DV colonies are currently known to exist. The colonies in Northern Ireland and Devon are in areas estimated as having a medium risk of introduction. Dorset, the Cork and Waterford regions of Ireland, as well as Cornwall, Devon and the Belfast region also have medium likelihoods of introduction.

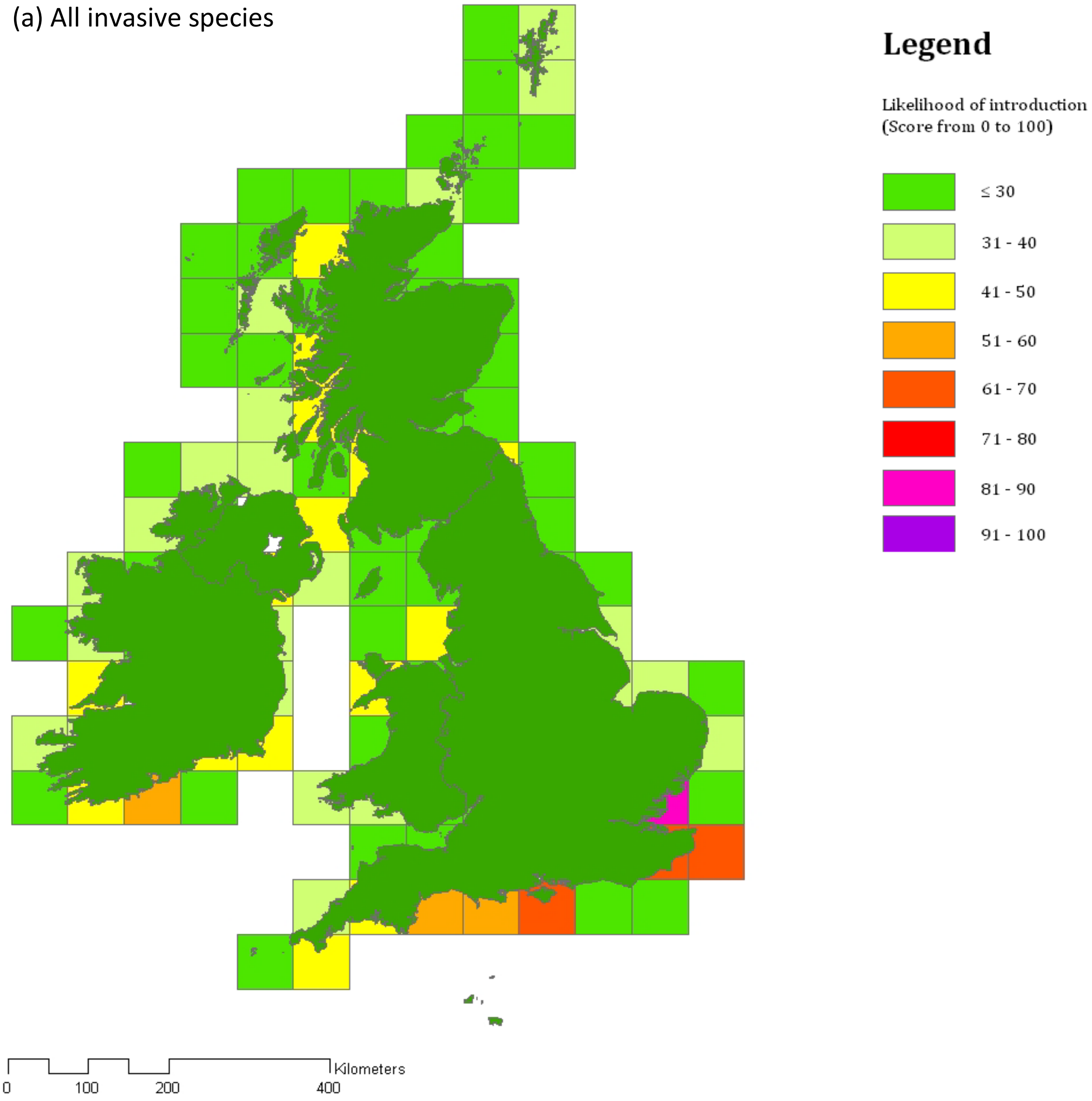
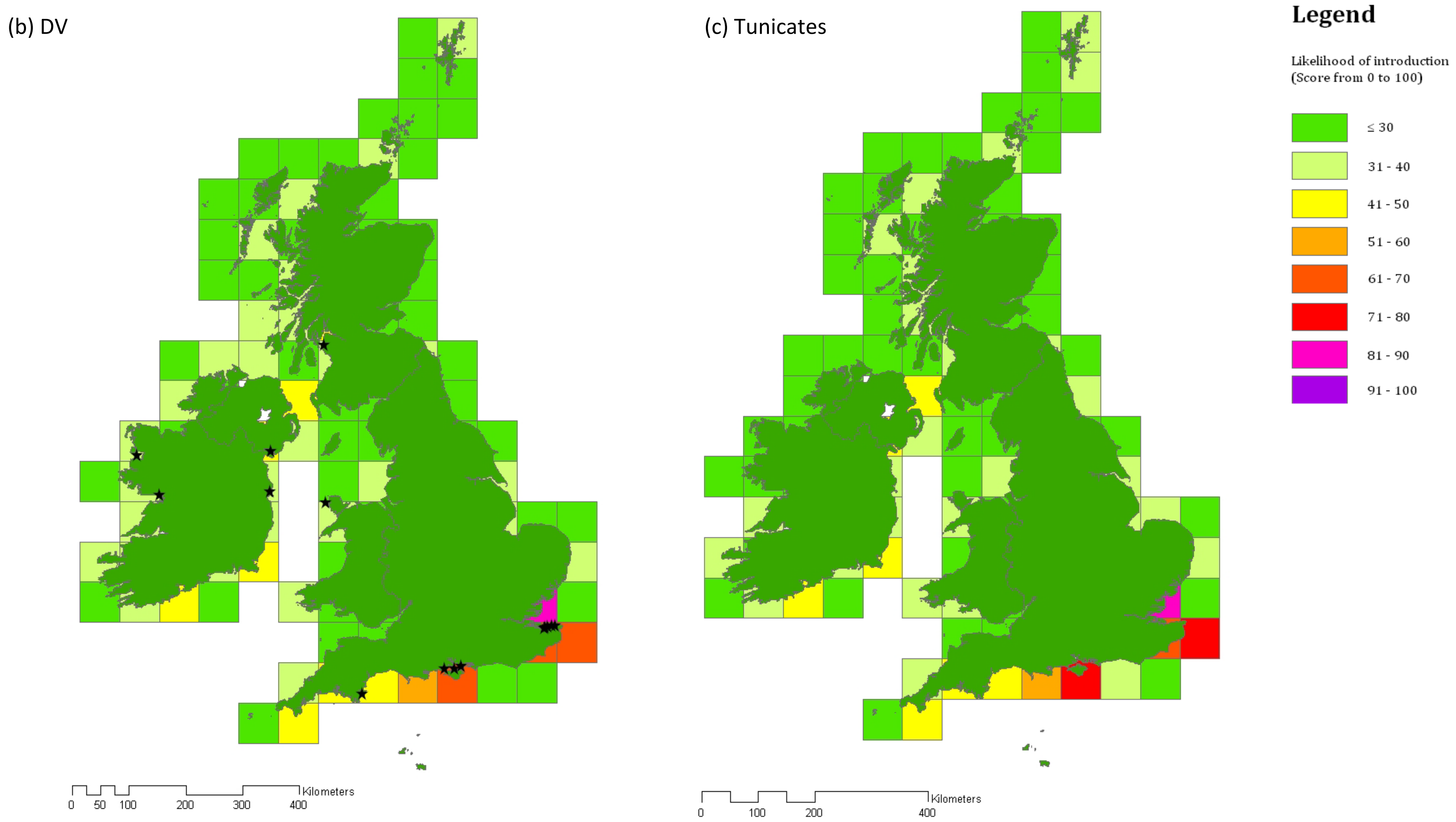
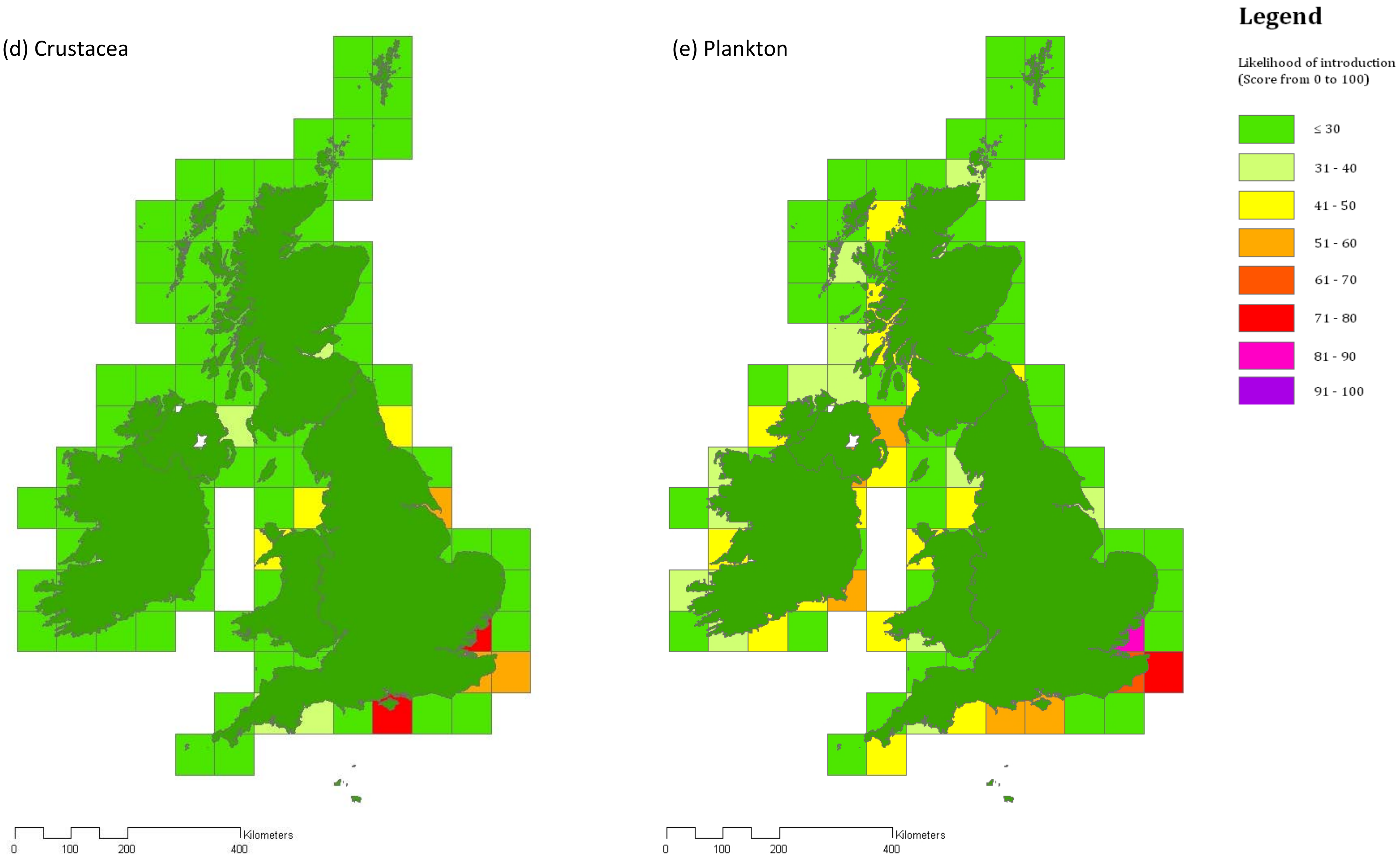

(a) All invasive species

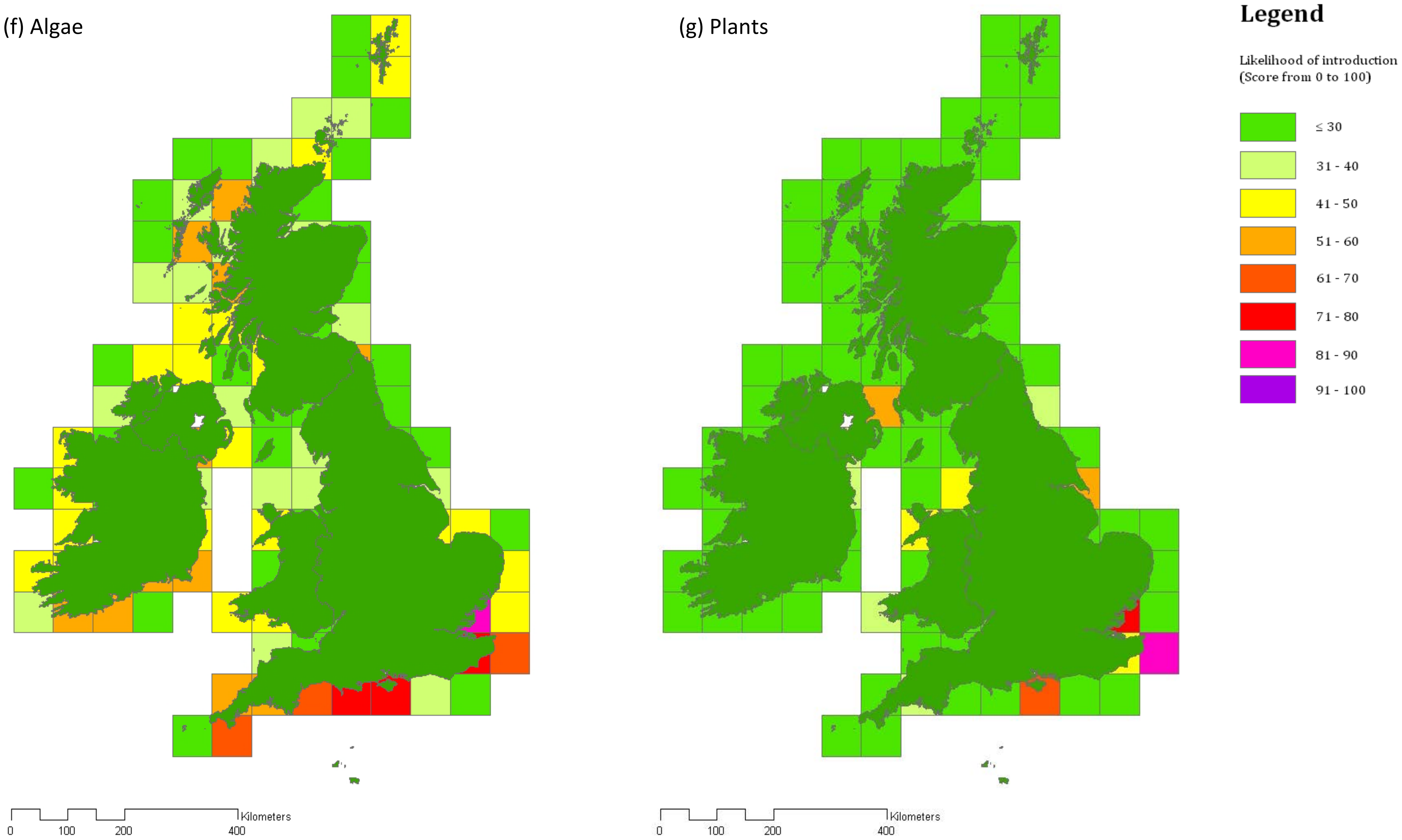
Figure 2. *Heat maps showing the relative likelihood of introduction (scored from 0 to 100) by the five main pathways for: (a) all species, (b) DV, (c) tunicates, (d) crustacea, (e) plankton, (f) algae, (g) plants, (h) arthropods, (i) worms, (j) jellyfish, and (k) molluscs. The black stars in part (b) represent current known locations of DV colonies*


(b) DV
(c) Tunicates
Legend
Likelihood of introduction (Score from 0 to 100)
≤ 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 90
91 - 100
0 50 100 200 300 400 Kilometers
0 100 200 400 Kilometers



(d) Crustacea

(e) Plankton



(f) Algae

(g) Plants

Legend

Likelihood of introduction
(Score from 0 to 100)

🟩 ≤ 30

31 - 40

🟨 41 - 50

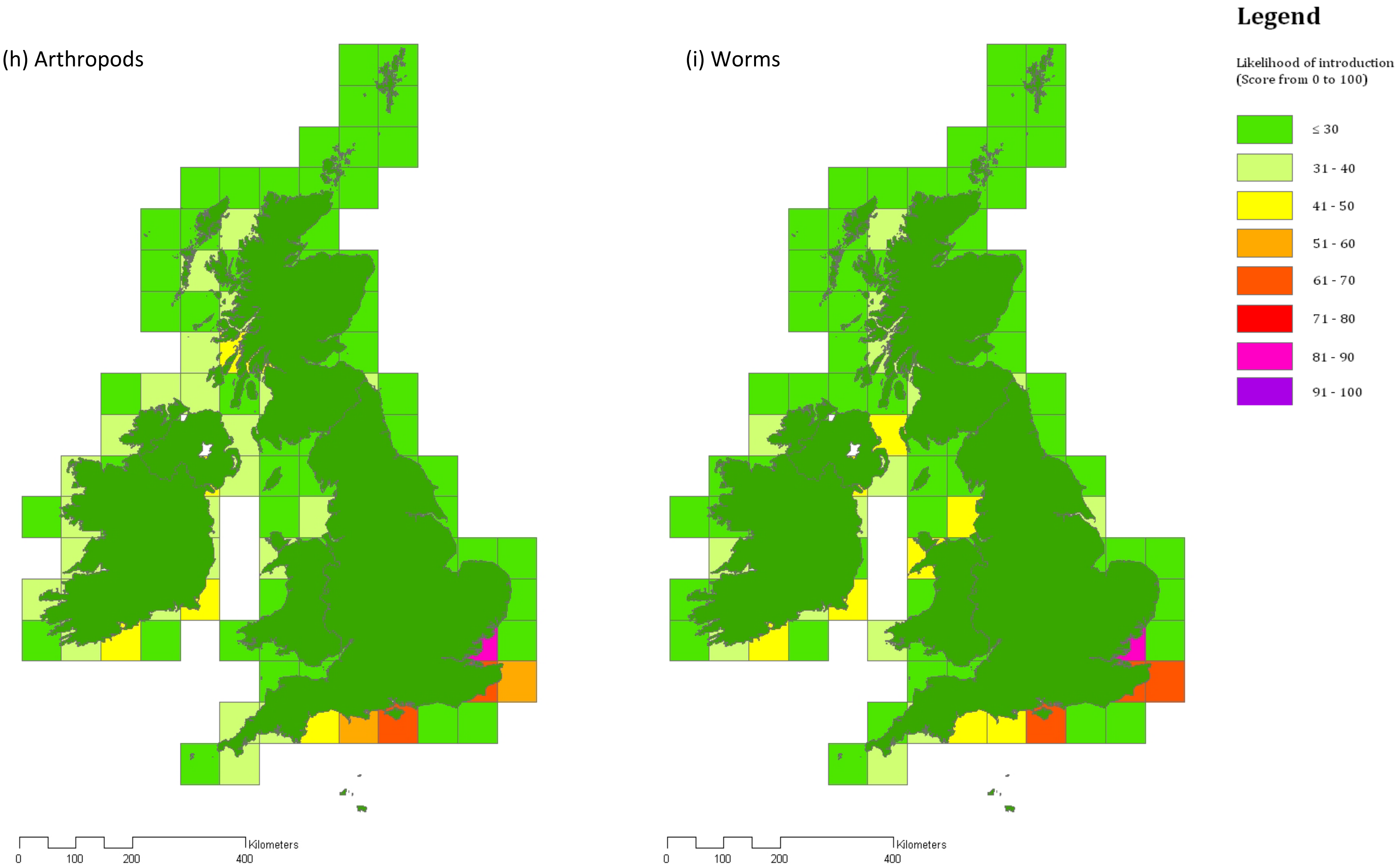
🟧 51 - 60

61 - 70

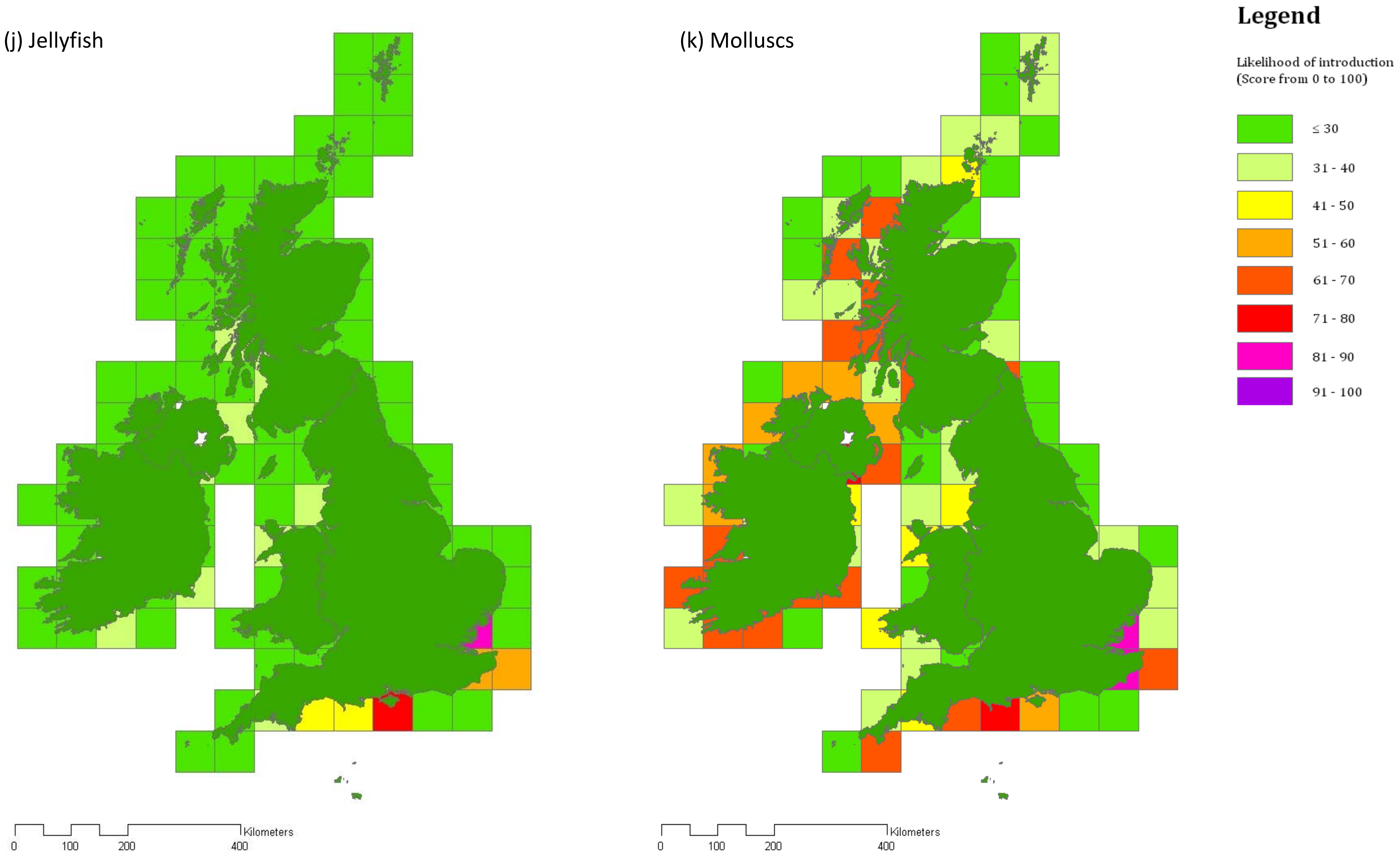
🟥 71 - 80

81 - 90

🟪 91 - 100


(h) Arthropods

(i) Worms



(j) Jellyfish

(k) Molluscs

3.2 Likelihood of establishment

The likelihood of a NIS establishing (if it were initially introduced) was scored between 0 and 10 for each grid square. The results of this analysis for DV and each of the other nine taxa are presented as heat maps (Fig. 3). There is much greater variation between the taxa in likelihood of establishment than likelihood of introduction. However, tunicates, algae, arthropods, worms, jellyfish and molluscs (Figs. 3 b,e,g,h,i,j) have similar spatial patterns of likelihood of establishment. The areas where these taxa would most easily establish are: the Thames Estuary and Kent coast; East Anglia; Humberside and north east England; the Isle of Man and south west Scotland; Devon and south Wales; the Western Isles of Scotland, and Waterford and County Donegal, Ireland. North west Wales is also a hotspot for some of these taxa. Crustacea (Fig. 3c) show a similar pattern of very high risk areas, but all grid squares around England, Wales and Northern Ireland and most squares in Scotland and Ireland have a medium or high risk of establishment for crustacea. The results for DV alone (Fig. 3a) are similar to those for tunicates in general, although fewer areas score very highly. The areas where DV would most easily establish (scores of 8 or above) are well distributed around the UK: the Kent coast, Humberside, the Thames Estuary, south Devon coast, Isle of Man, and south west Scotland.

Plankton (Fig. 3d) show an entirely different, and quite distinct, pattern of establishment: south west England, the south west tip of Wales, almost the entire coastline of Northern Ireland, Scotland, and north east England would have a very high risk of establishment if invasive planktonic species were introduced. Unlike the patterns seen for most of the other taxa, the whole stretch of coastline from Humberside to Hampshire and the Isle of Wight (including the Thames Estuary, Kent coast and the Solent) were found to have only a medium risk of establishment. The likelihood of plants establishing (Fig. 3f) is highest along the Lancashire coast (including Morecambe Bay), but also high in south Wales, north Norfolk, parts of west Scotland, and County Donegal. Many of the grid squares have a low risk of establishment for plants (scores of under 5).

3.3 Overall likelihood of introduction and establishment

Three of the four squares that score highly for likelihood of introduction of DV also score highly for risk of establishment: Thames Estuary, Kent coast, the Solent. Several areas score over 40 for both introduction and establishment: Devon, Cork and the area between Northern Ireland and Dumfries. Much of the Thames Estuary/Kent and Essex coasts and part of the Dumfries coast are designated protected areas (Fig. 4). The same three hotspots (Thames Estuary, Kent Coast and the Solent) score highly for introduction and establishment of most of the taxa: tunicates, algae, jellyfish, arthropods and worms. The same areas, but also the Humber, have a high likelihood of both introduction and establishment for crustacea. For crustacea, north east England and north west Wales have a high likelihood of introduction and medium likelihood of establishment. For plankton, only Dorset has a high risk of both introduction and establishment, while the Thames Estuary, Kent coast, and the Solent have a medium likelihood of establishment. Only the eastern tip of Kent and one square between Northern Ireland and Scotland have high values for both introduction and establishment for plants; there is little overlap between them. For molluscs, there is more overlap, and besides the previously mentioned three major hotspots (Thames Estuary, Kent coast, and the Solent), the west Devon coast, part of north east England, and several areas of west Scotland score highly for introduction and establishment.

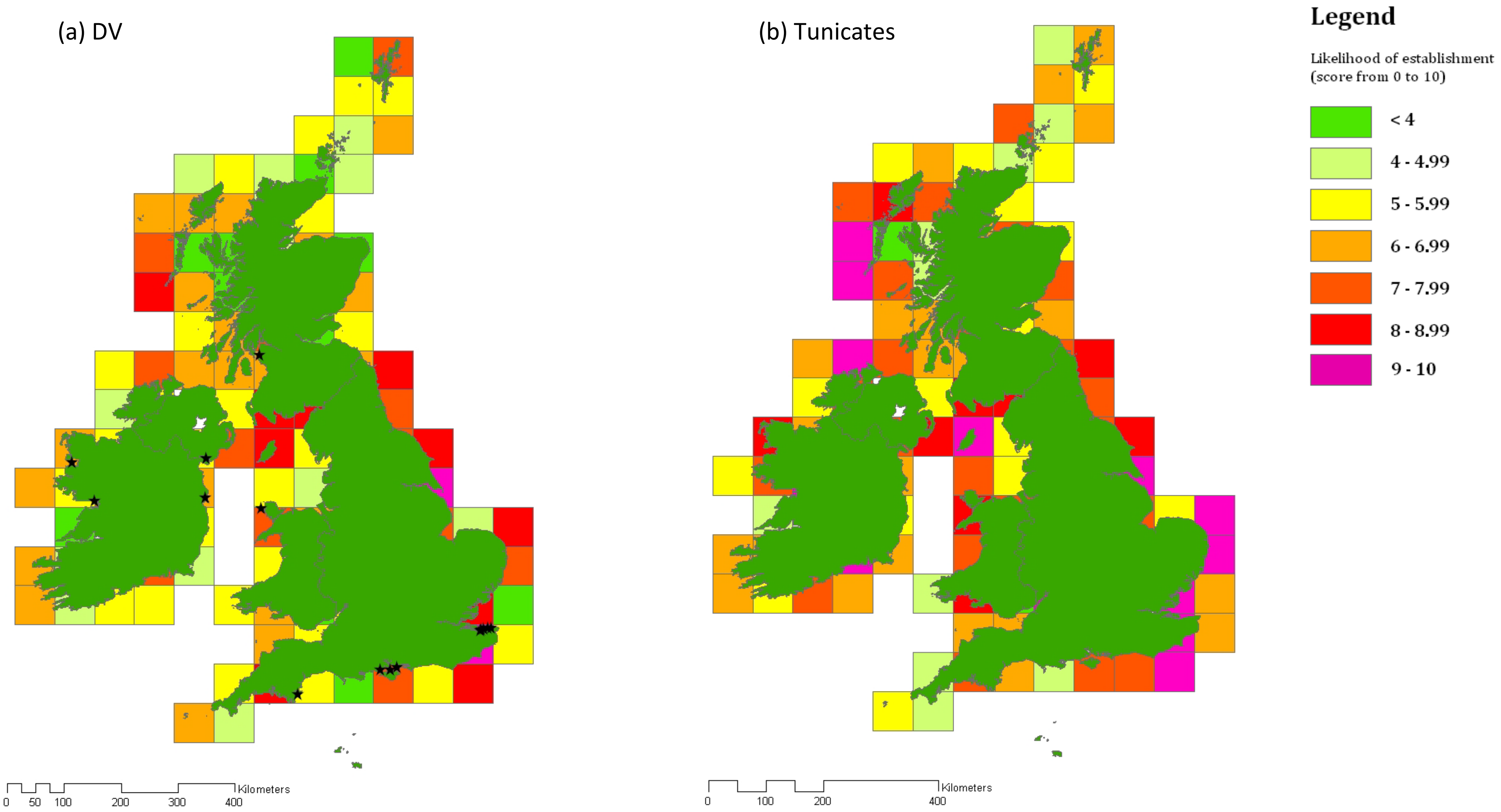
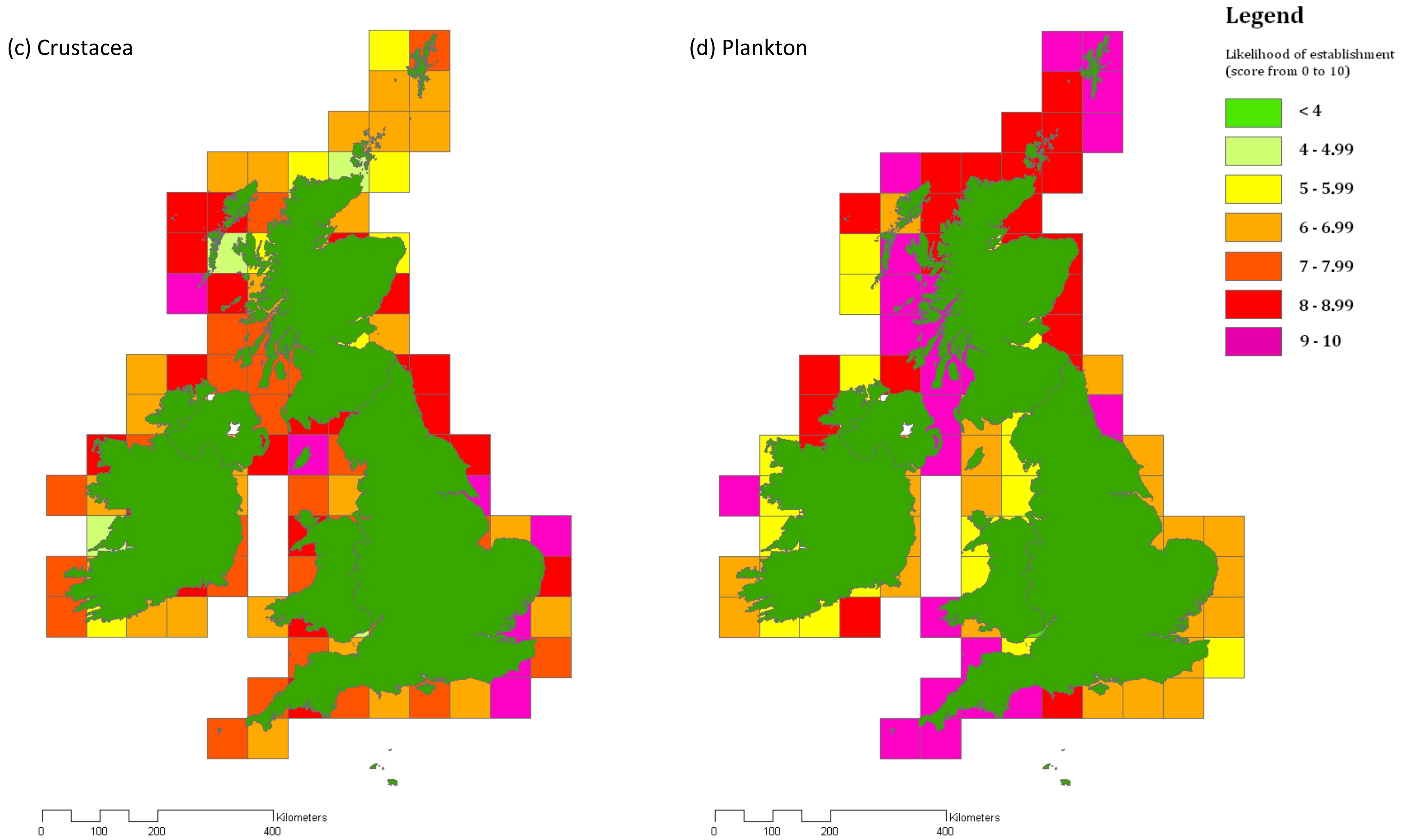
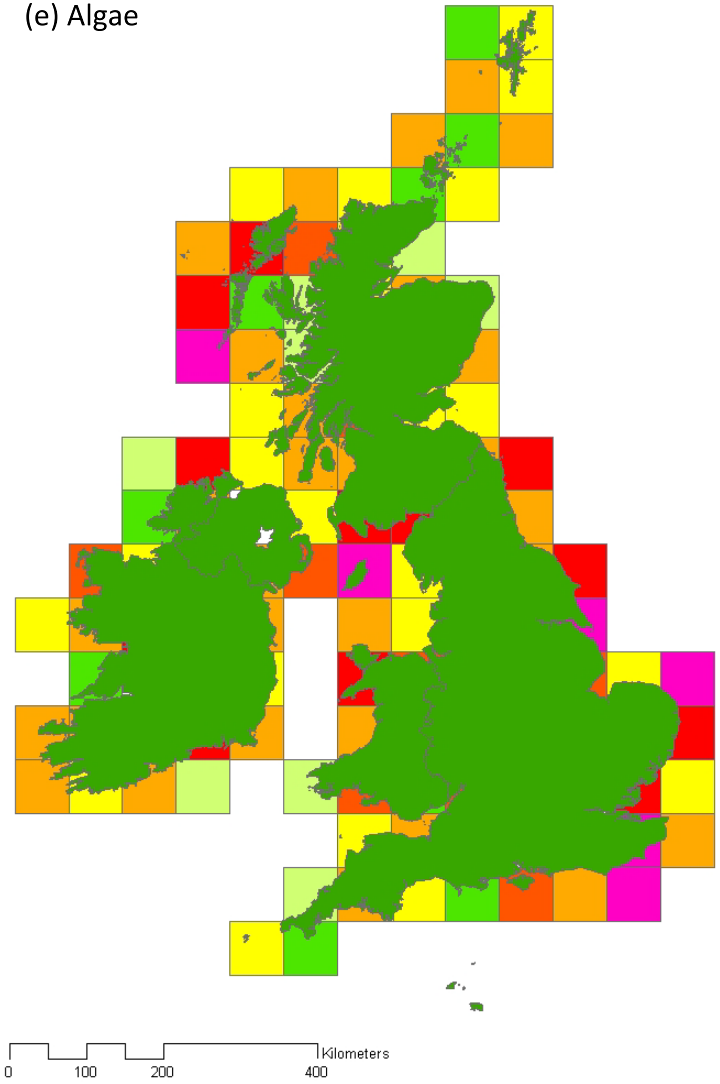


Figure 3. *Heat maps showing the relative likelihood of establishment (scored from 0 to 100) by the five main pathways for (a) DV, (b) tunicates, (c) crustacea, (d) plankton, (e) algae, (f) plants, (g) arthropods, (h) worms, (i) jellyfish, and (j) molluscs. The black stars in part (a) represent current known locations of DV colonies.*

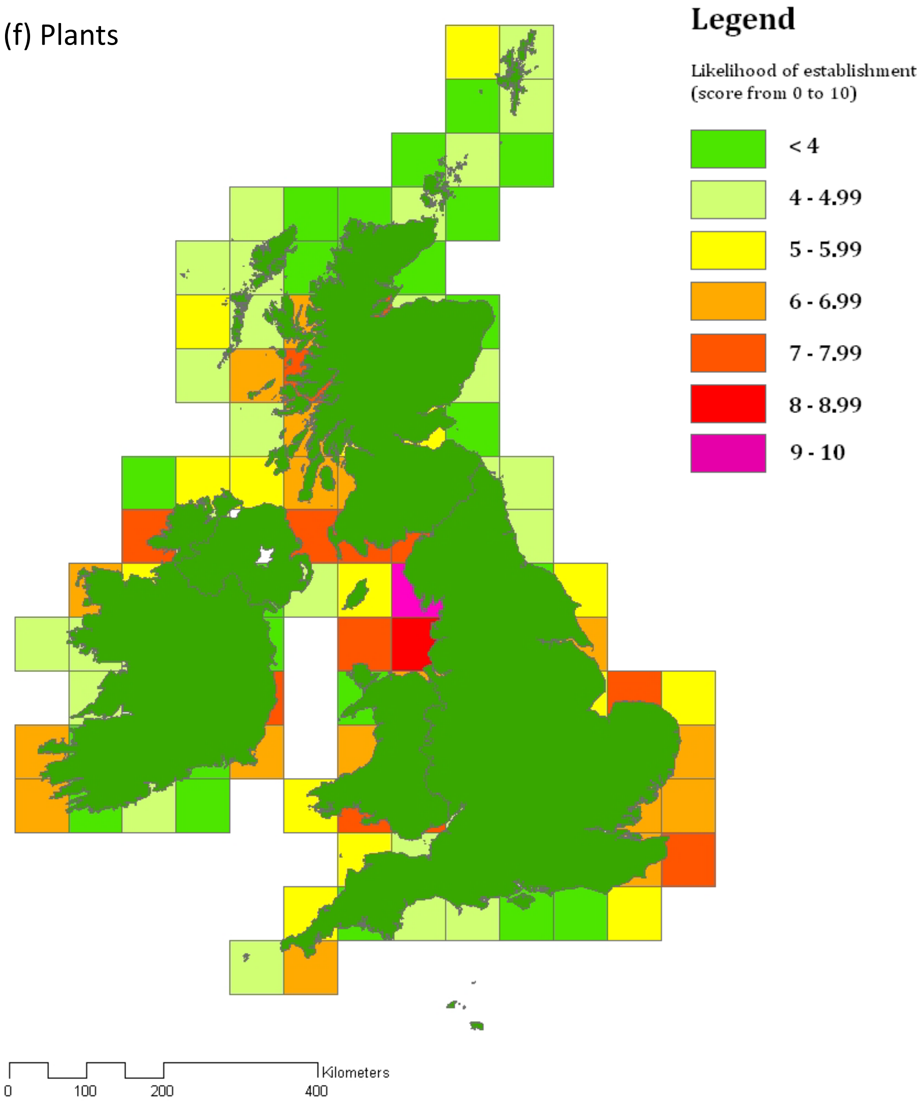

(c) Crustacea

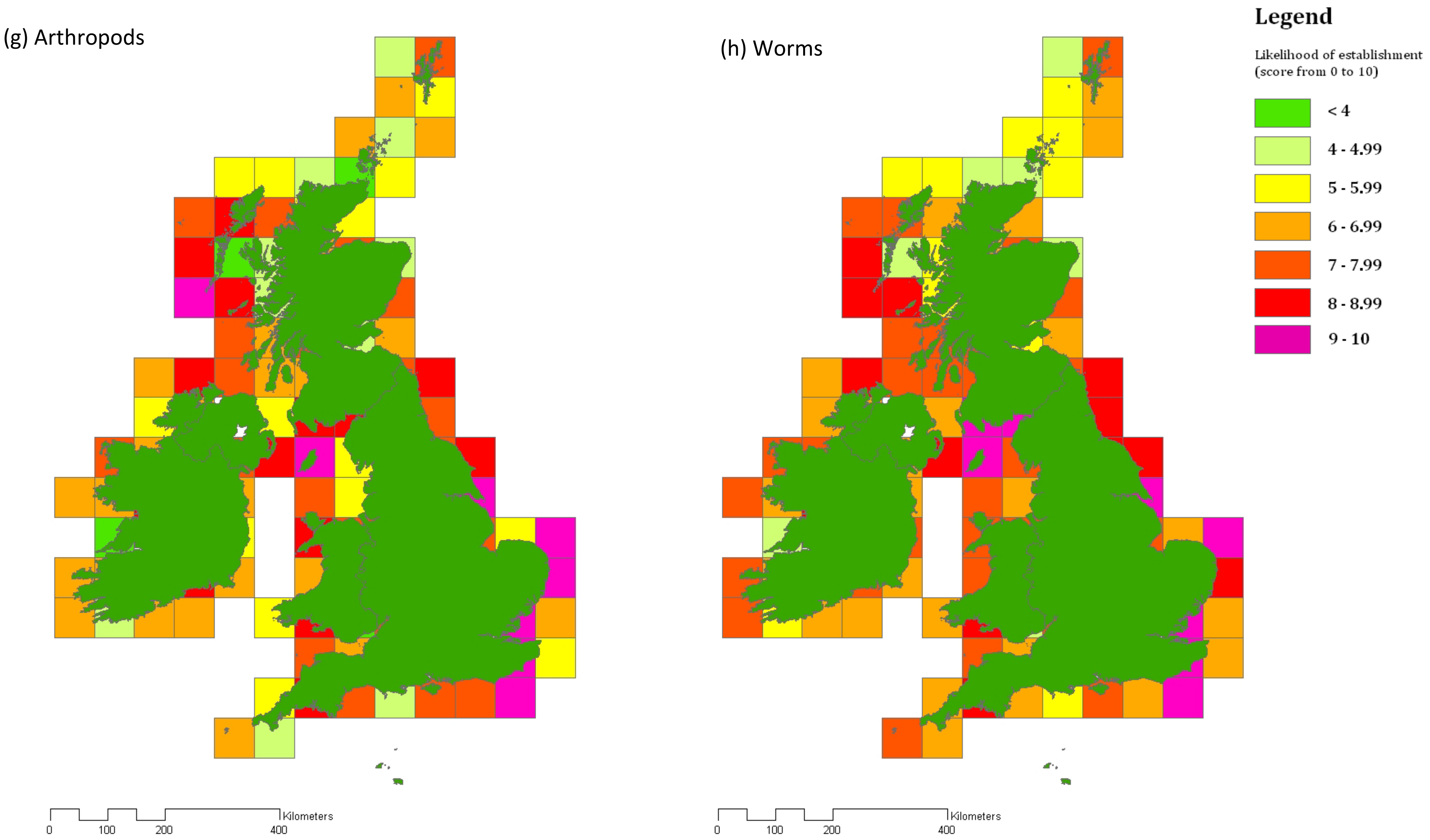
(d) Plankton

(e) Algae

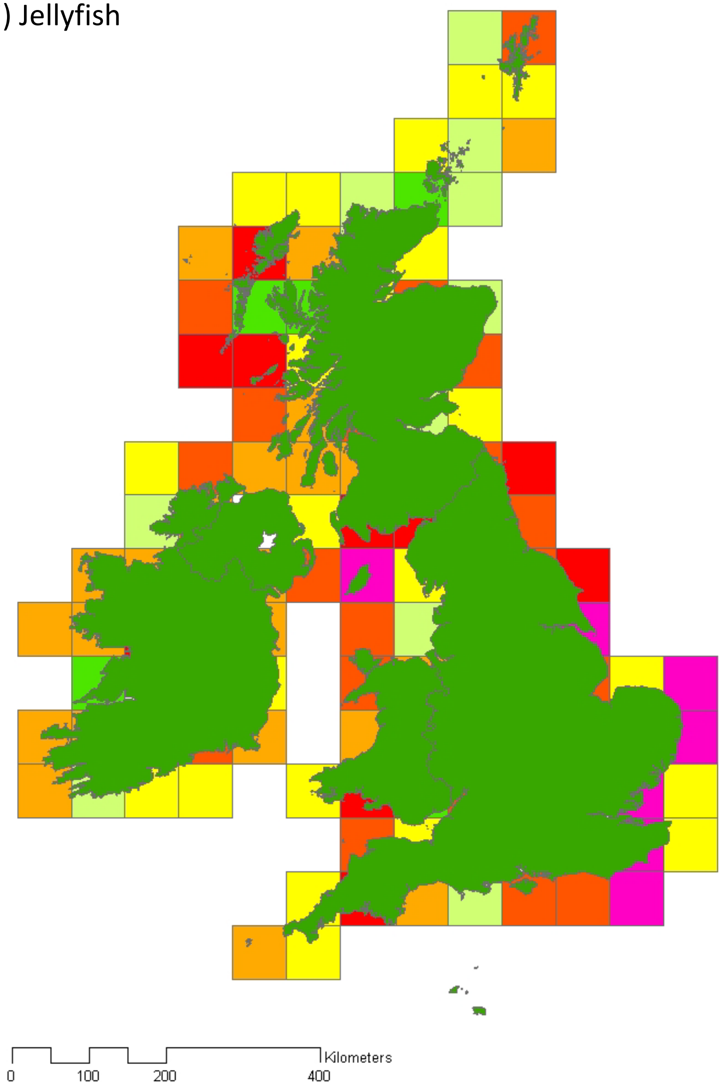


(f) Plants

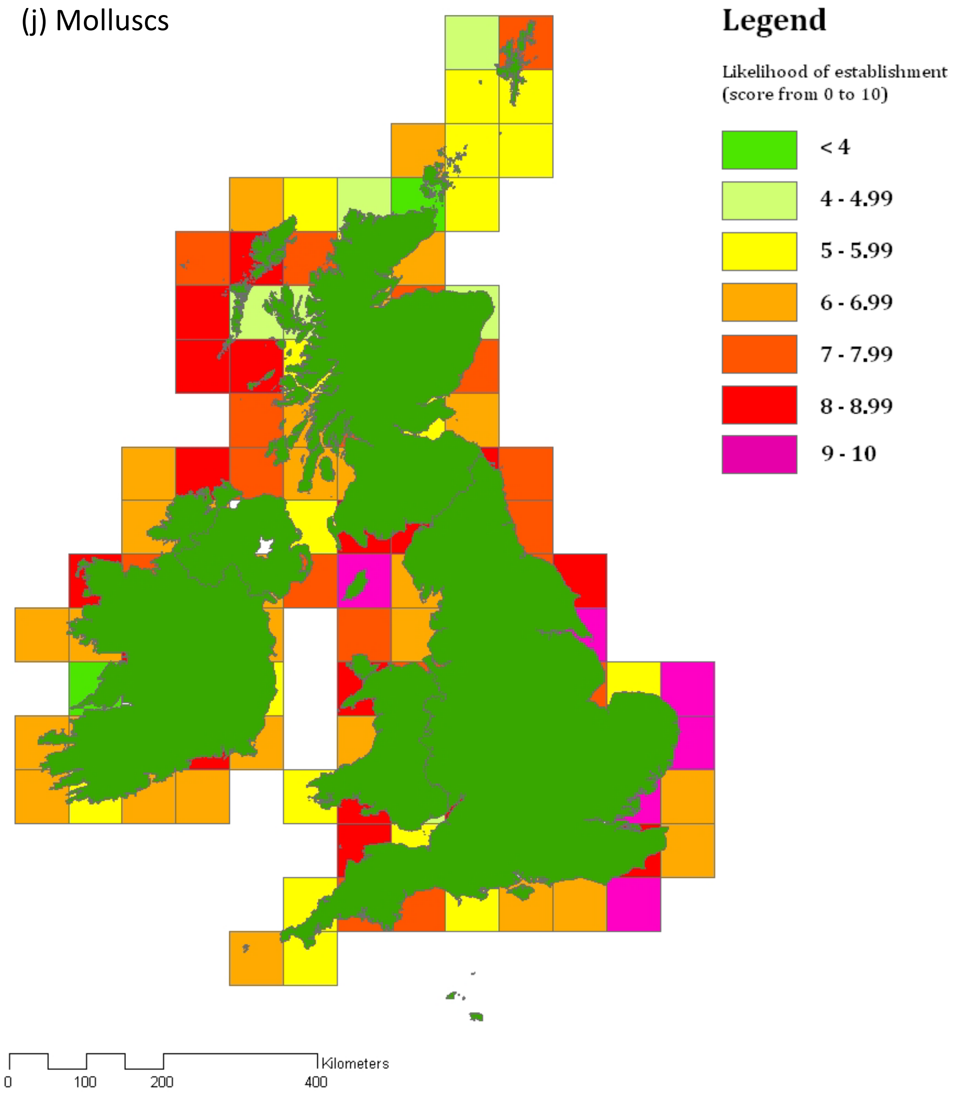



(g) Arthropods
(h) Worms
Legend
Likelihood of establishment (score from 0 to 10)
< 4
4 - 4.99
5 - 5.99
6 - 6.99
7 - 7.99
8 - 8.99
9 - 10
0
100
200
400
Kilometers

(i) Jellyfish



(j) Molluscs



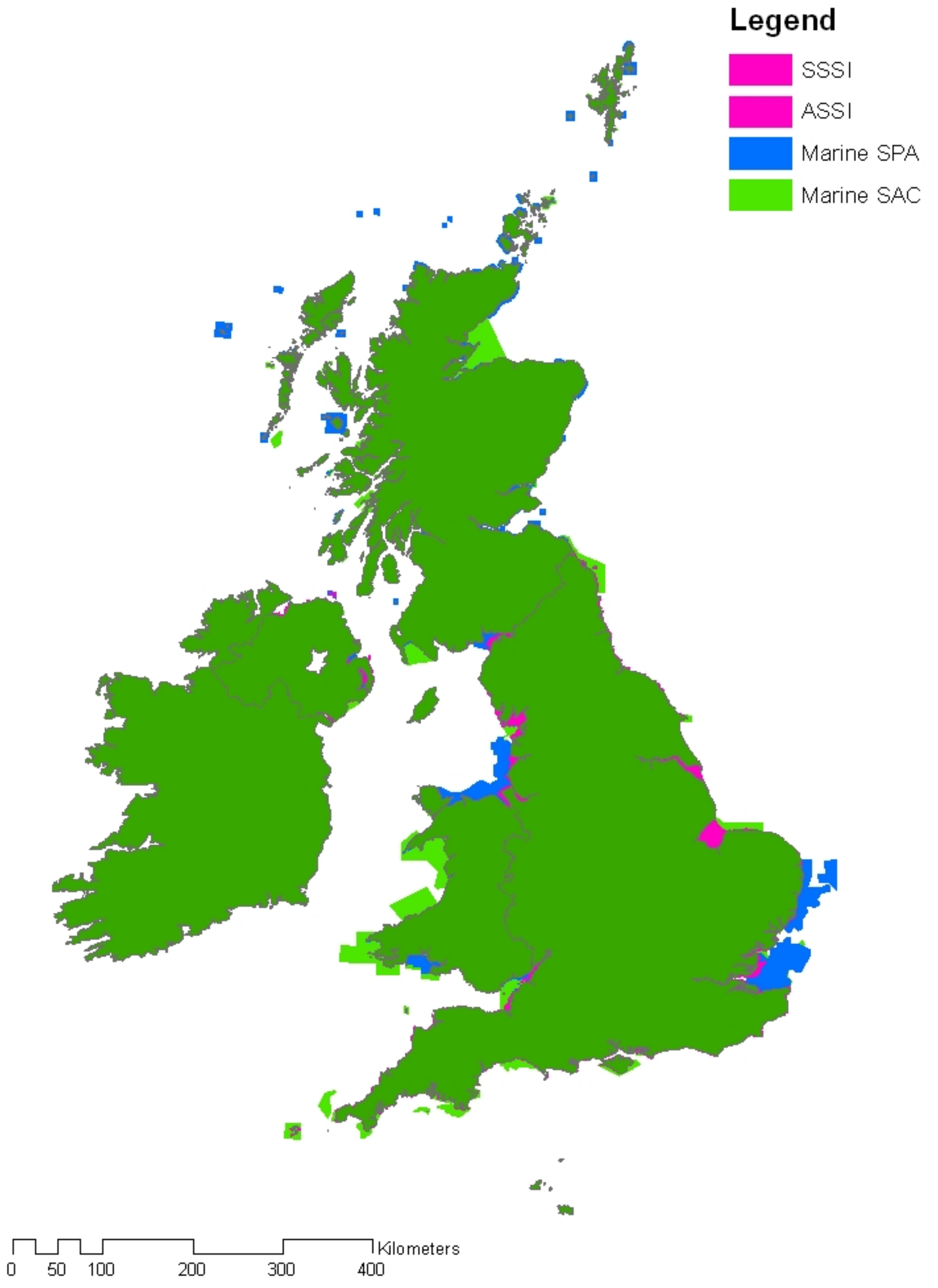


Figure 4. *A map of the protected areas (SSSI, ASSI, SPA and SAC) in the UK. See glossary for definitions.*

3.4 Network analysis of spread within the UK and Ireland: a DV case study

Networks were generated for internal movements of aquaculture stock, domestic ferry routes, commonly used recreational routes and the pattern of prevailing currents in British waters. Domestic shipping connects most of the regions of the UK (Fig. 5, Table 3). Of these regions, the following receive more than 5 million tonnes of domestic freight annually: Lancashire and Cumbria

(9.9 million tonnes), Northern Ireland (9.3), Humber (8.2) Sussex and Hampshire (6.0), and the east coast of Scotland (5.3). Three of these regions have been colonised by DV. Ferry movements, the other component of domestic shipping, do not connect all regions (Fig. 6). Most domestic contacts are between Scottish islands and the Scottish mainland, and between the east coast of Britain and Ireland/Northern Ireland. There are also movements within the Solent region. Most ferry routes from overseas connect continental Europe with the south and east coasts of England, and North Europe and Scandinavia with the east of England.

The network of aquaculture stock movements (Fig. 7) only includes movements within England and Wales (E&W), and from E&W to Ireland (the only available data), but even this restricted dataset demonstrates how well connected coastal locations are by movements of live animals for marine aquaculture. The dataset only includes shellfish movements; there is no marine finfish aquaculture in England and Wales and in Scotland, movements of fish between marine sites are relatively rare (Werkman et al. 2011) and generally occur in local areas or between adjacent management areas (Murray et al. 2010) so are unlikely to spread DV except locally. Shellfish movements occur over long distances, for example between Carlingford Lough and Poole, and from Cornwall to the Blackwater Estuary. Of particular interest is the Morecambe Bay area which is a ‘supersource’ i.e. supplies animals to many other sites in both E&W and Ireland. Areas including the Wash, the Thames and Blackwater Estuaries, and Poole are ‘super-receivers’ i.e. receive from a number of other locations. Animals have been moved from Holyhead, where a DV colony is located, to Carlingford Lough, another location where DV has colonised. Similarly, movements have occurred between the Solent and the north Kent coast, both of which are areas DV has colonised.

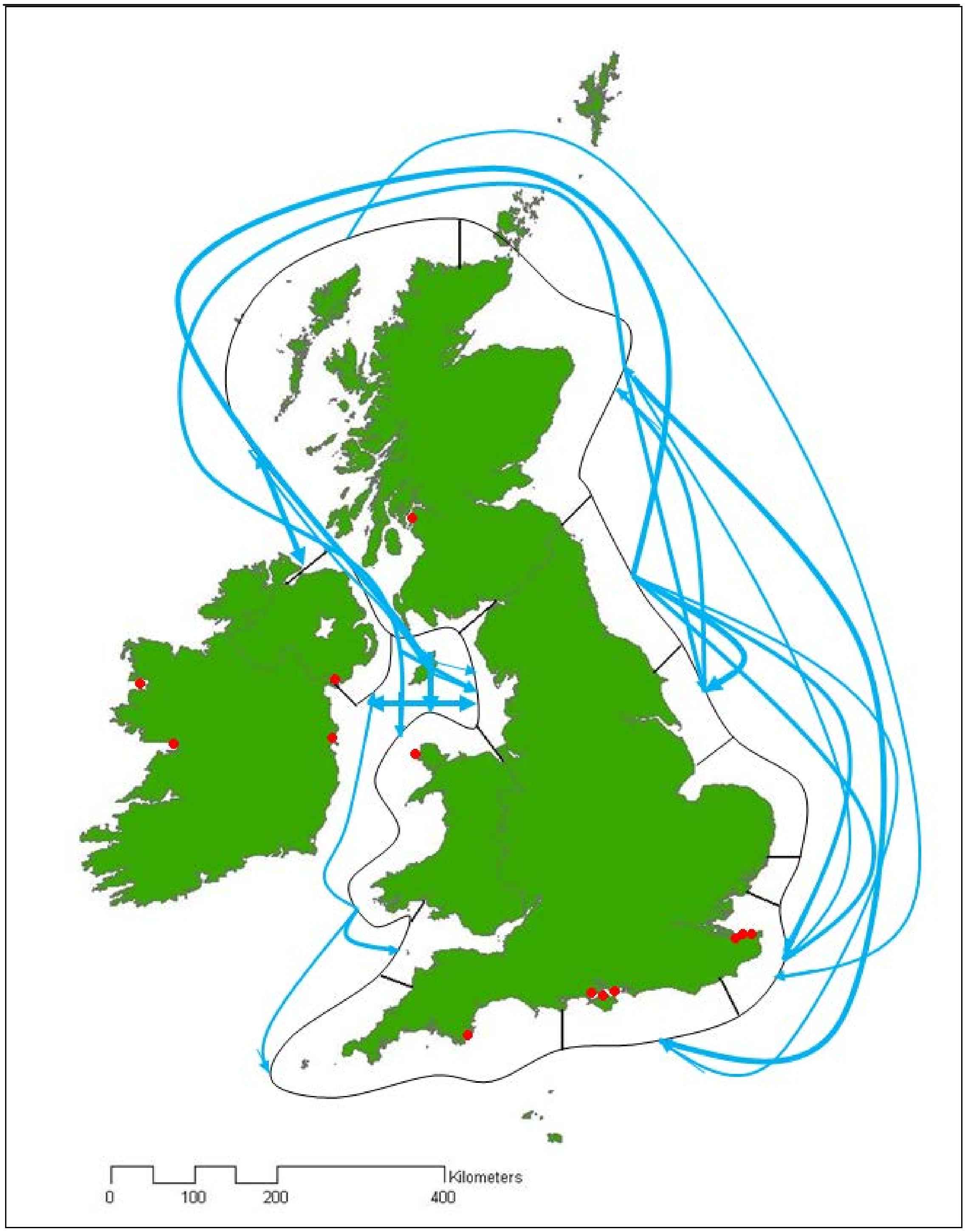


Figure 5. *A network diagram of domestic freight (by sea) between regions of the UK (from Dft data). Lines are not representative of exact routes, only sources and destinations. Only routes with an annual freight weight of over 0.5 million tonnes are shown, for clarity. Red dots represent current known locations of DV colonies in the UK and Ireland.*

Table 3. *A contact matrix showing the connections between regions of the UK by domestic coastwise freight movements (reproduced from Dft data)*

	Destination													
Origin	Thames and Kent	Sussex and Hampshire	West Country	Bristol Channel	West and North Wales	Lancashire and Cumbria	Scotland West Coast	Scotland East Coast	North East	Humber	Wash and North East Anglia	Haven	Isle of Man	Northern Ireland	*Total leaving*
Thames and Kent	0.00	0.14	0.01	0.04	0.02	0.12	0.05	0.04	0.15	0.12	0.00	0.00	0.00	0.08	*0.77*
Sussex and Hampshire	0.06	0.00	0.00	0.00	0.09	0.08	0.02	0.26	0.01	0.00	0.00	0.00	0.01	0.17	*0.70*
West Country	0.05	0.28	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	*0.49*
Bristol Channel	0.04	0.00	0.03	0.00	0.07	0.01	0.14	0.02	0.04	0.14	0.00	0.00	0.00	0.31	*0.80*
West and North Wales	0.26	0.33	0.72	1.51	0.00	0.27	0.00	0.01	0.04	0.33	0.00	0.01	0.07	0.98	*4.53*
Lancashire and Cumbria	0.10	0.28	0.00	0.06	0.08	0.00	0.10	0.03	0.03	0.02	0.00	0.00	0.30	3.42	*4.42*
Scotland West Coast	0.77	0.19	0.02	0.03	0.04	0.87	0.00	0.05	0.01	0.05	0.02	0.00	0.00	3.84	*5.88*
Scotland East Coast	0.99	2.54	0.11	0.03	1.03	4.07	0.15	0.00	0.27	1.33	0.03	0.23	0.00	0.13	*10.91*
North East	1.00	0.76	0.00	0.42	2.31	0.72	0.46	0.19	0.00	4.18	0.01	0.15	0.00	0.04	*10.26*
Humber	0.29	0.02	0.04	0.03	0.02	0.05	0.01	1.43	0.20	0.00	0.17	0.11	0.00	0.06	*2.43*
Wash and North East Anglia	0.04	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	*0.24*
Haven	0.09	0.00	0.01	0.00	0.00	0.01	0.00	0.30	0.30	0.01	0.01	0.00	0.00	0.19	*0.92*
Isle of Man	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	*0.16*
Northern Ireland	0.33	0.09	0.13	0.28	0.01	2.84	2.37	0.08	0.00	0.03	0.01	0.15	0.00	0.00	*6.32*
Rigs	0.23	1.29	0.00	0.00	0.61	0.69	0.23	2.92	0.00	2.01	0.23	0.00	0.00	0.00	*8.19*
Total arriving	*4.24*	*6.01*	*1.07*	*2.49*	*4.41*	*9.90*	*3.52*	*5.33*	*1.06*	*8.24*	*0.48*	*0.65*	*0.38*	*9.34*	*0.77*

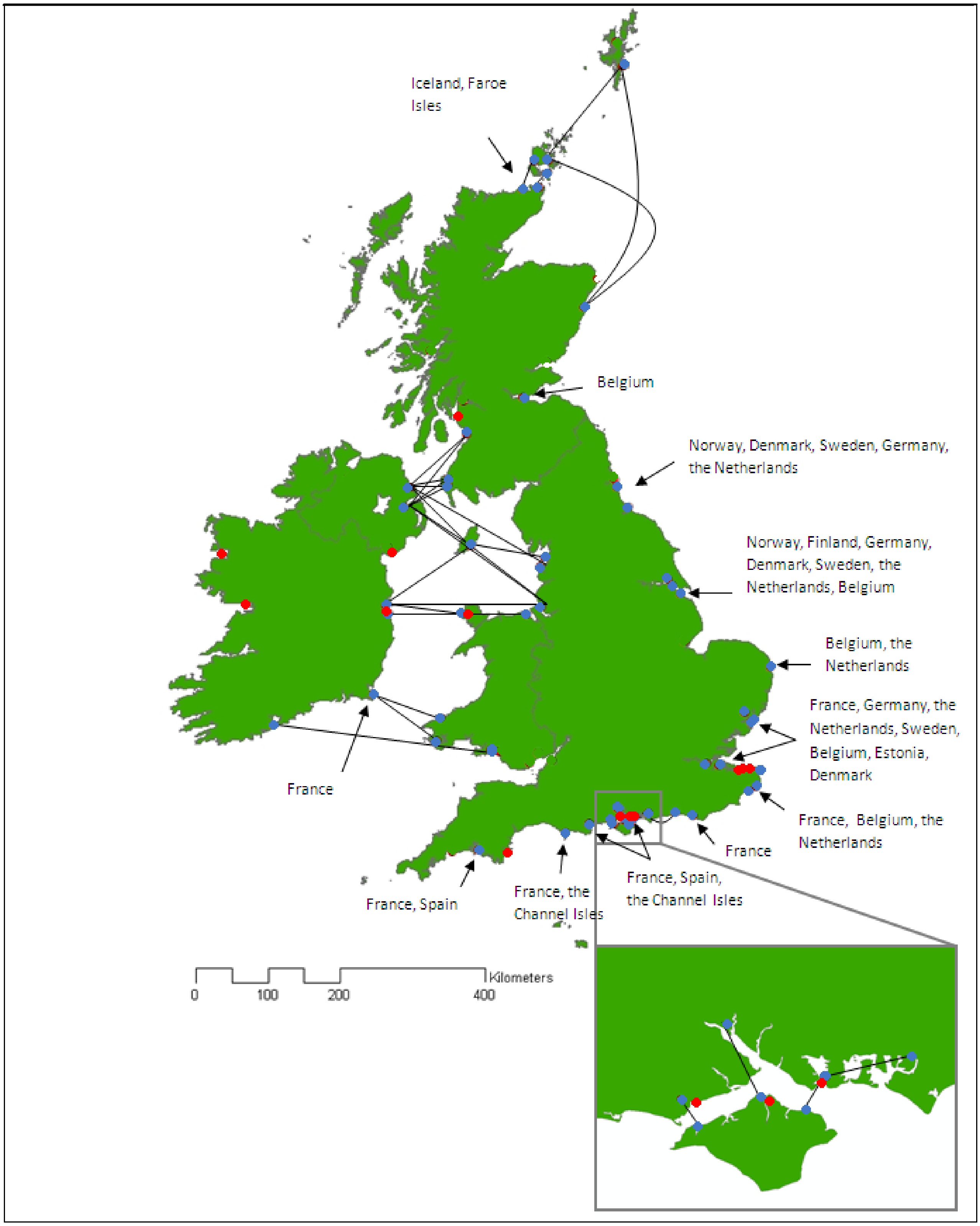


Figure 6. *A network diagram of ferry routes within the UK and Ireland. The Solent region is magnified for clarity. Arrows indicate which ports are connected to overseas ports by ferry routes, the overseas countries they connect to are named for each. Ferry ports are marked as blue dots. Red dots represent current known locations of DV colonies in the UK and Ireland.*

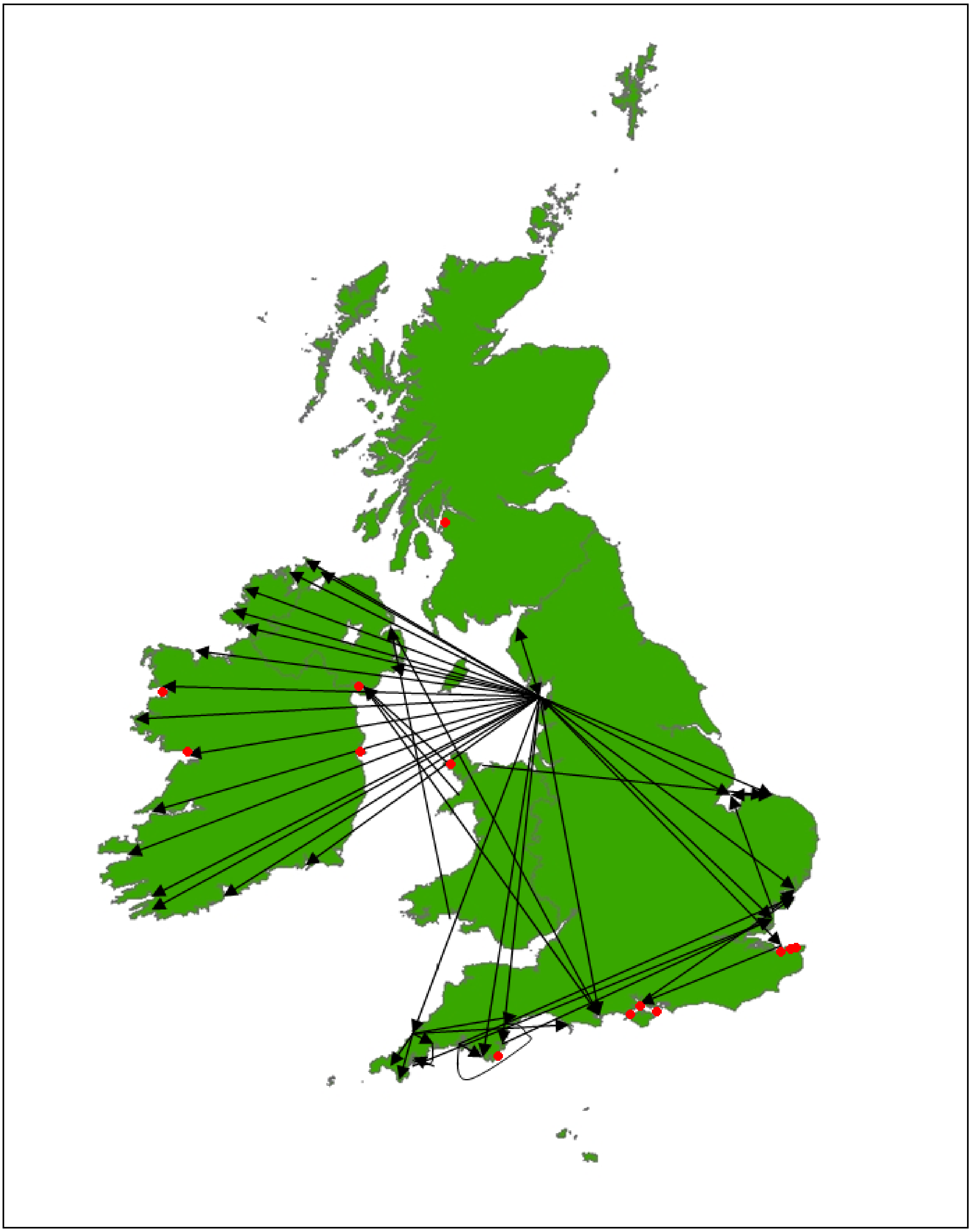


Figure 7. *A network diagram of internal movements of aquaculture stock in England and Wales (E&W), and movements from E&W to Northern Ireland and the Republic of Ireland. Red dots represent current known locations of DV colonies in the UK and Ireland. Black lines represent a movement between two locations.*

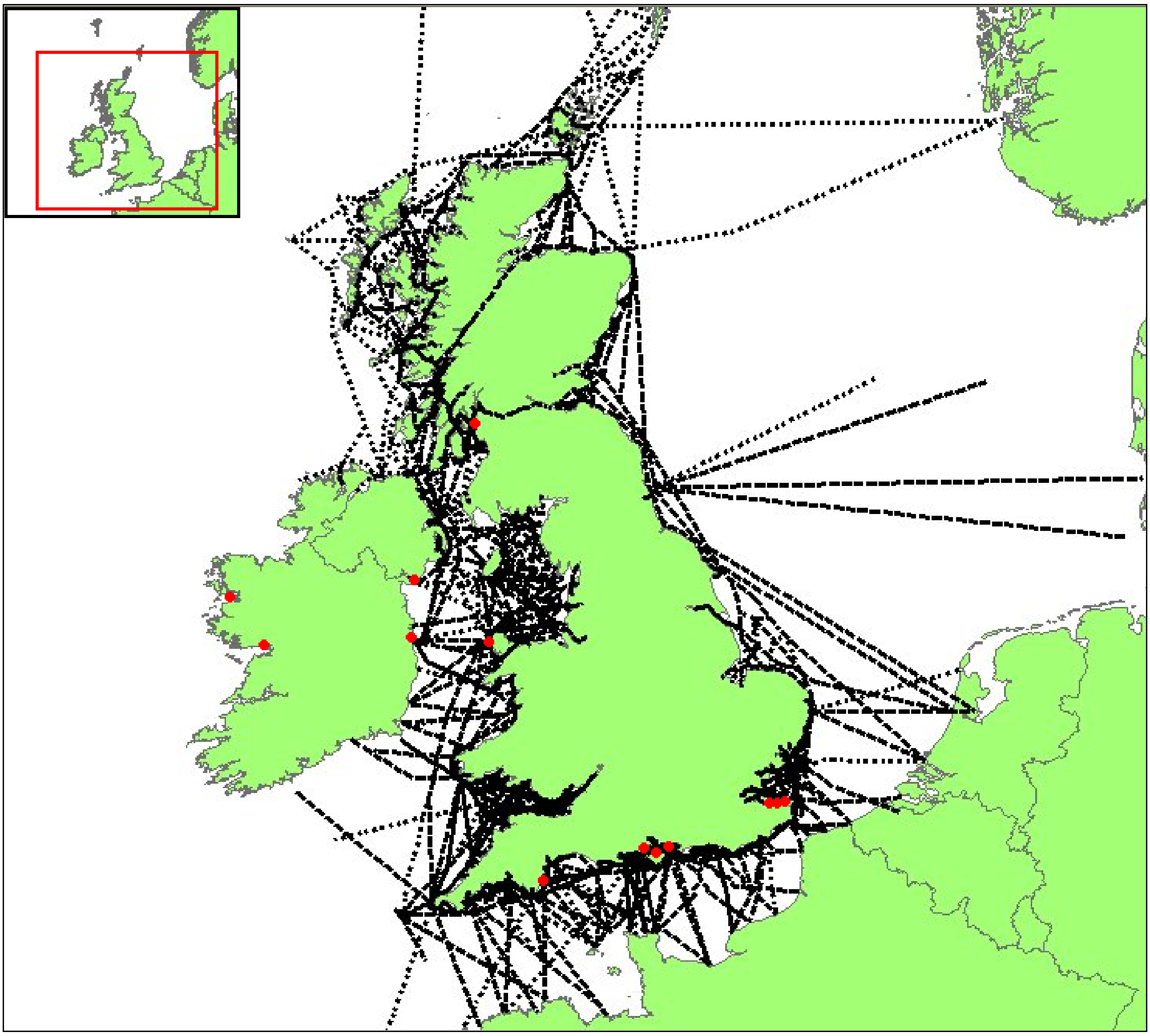


Figure 8. *A map of the most commonly used recreational routes in British waters, taken from the Maritime Data website (http://www.maritimedata.co.uk/) (DECC / Anatec). Source data from the RYA. Red dots represent current known locations of DV colonies in the UK and Ireland.*

All regions of the UK and Ireland are very well connected by commonly used recreational boating routes (Fig. 8). Maps of recreational routes in Ireland were also available to us for several regions: these are included in Appendix C. They show a similar pattern of high connectedness. The south and west coasts of England, and the Thames Estuary are areas of very high intensity of activity. Northern Ireland and the west coast of Scotland have fairly high levels of activity.

From Northern Ireland, the prevailing ocean current heads north up the west coast of Scotland to the Shetland Islands, where it heads in a southerly direction along the east coast of Britain, converging with the prevailing west to east current along the south coast of Britain (Fig. 9). The Bristol Channel sees currents both into and out of the channel, and from Cornwall, the current heads north- and west- wards, and along the south coast of Ireland.

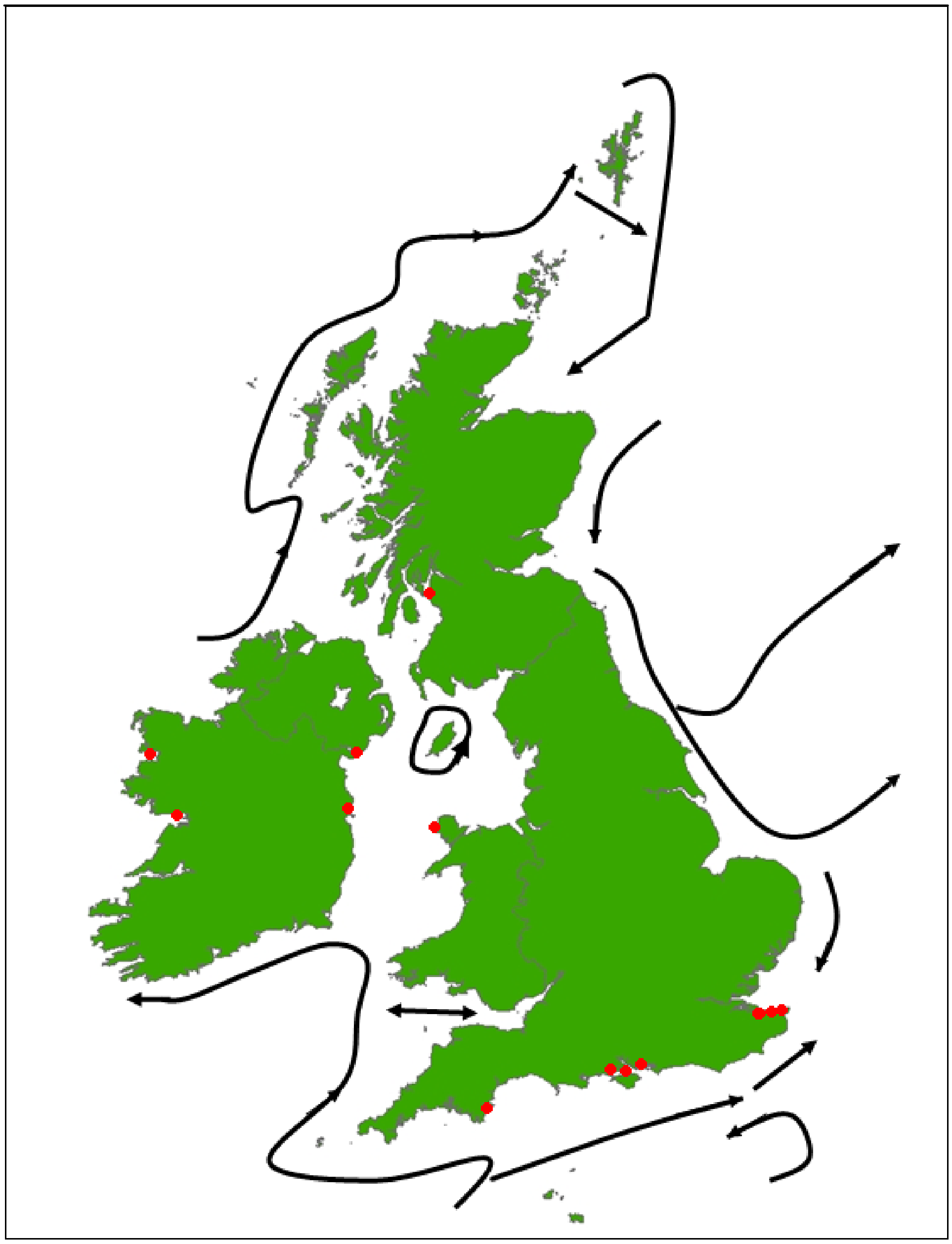


Figure 9. *A diagram of the prevailing sea currents in waters around most of the UK, based on Huthnance* et al. *(2010) and OSPAR (2000). Red dots represent current known locations of DV colonies in the UK and Ireland.*

4 Discussion

4.1 Introduction and Establishment of NIS

There are several conclusions that can be drawn from the analysis presented here. However, it should be noted that a threshold of likelihood that triggers a response needs to be established for introduction and establishment of NIS. For the purpose of this discussion a threshold of 51+ is used, but ideally thresholds should be decided upon individually for each taxon using available data.

From analysis of the likelihood of introduction data it is clear that there are key areas where NIS are more likely to enter UK or Irish waters, such as the Thames estuary, the Kent coast, the Solent, Dorset, Devon and the coastline around Cork, Ireland. These are areas that are well connected to continental Europe by commercial shipping (Thames, Solent and Kent), recreational boating (Thames, Solent, Kent and Dorset), live imports of animals for aquaculture or the seafood trade (all locations), and proximity (all English locations). However, likelihood of introduction cannot be looked at in isolation, and should be considered alongside the likelihood of establishment. Results of our analysis suggest numerous locations within the study area are suitable for the establishment of most of the broad taxonomic groups examined. If this is looked at in combination with the likelihood of introduction, in generic terms, the Thames estuary, Kent coast and the Solent are key locations that score highly for both. Devon, Cork and the area between Northern Ireland and Dumfries also score fairly highly overall. It can therefore be concluded that it is these locations that should be the priority for monitoring and biosecurity to facilitate early detection and reduction in risk of establishment respectively. However, many monitoring and surveillance programmes need to be specific for certain taxonomic groups to optimise the probability of detection. The individual models for each taxonomic group should be referred to in order to assist with deciding where specific monitoring should be focused. For example, additional monitoring for non-indigenous crustacean species may be required around the Humber. Combining this risk-based approach to surveillance with that of a horizon scanning programme, where new potential invaders are recognised, could form a robust surveillance programme for NIS.

4.2 Introduction and establishment of DV

The analysis of the introduction of DV highlights several locations where there is a high or very high likelihood of introduction: the Solent, Thames estuary/north Kent coast, and Dorset. The Devon coast, the east coast of Northern Ireland and two locations along the southern and eastern coast of the Republic of Ireland are medium likelihood areas. Four of these areas: the Thames, the Solent, Devon, and Carlingford, correlate with known current locations of DV. There are several known locations of DV that are not found in areas of high likelihood of introduction. but are located in areas of high likelihood of establishment. It can be hypothesised, based on the model, that at least one of the populations found along the North Kent coast, the Solent and Plymouth were initial introductions, and the other populations were established through internal spread. These predictions of the model could be tested by determining the origins of the DV populations found in the study area, which is possible using modern molecular techniques.

4.3 Network analysis: DV case study of internal spread

The network analysis assists in the assessment of potential pathways by which DV could have spread from the ‘original’ hypothesised locations. The interpretations presented here do not attempt to implicate any pathways as the only vector of DV or any NIS, rather show the high level of connectivity within the UK and Ireland, and highlight possible linkages between areas. The network analysis highlights interesting links between movements of shellfish and DV populations: aquaculture stock movements link the populations found on Anglesey and in Carlingford, Northern Ireland, and there are also links between the DV populations on the North Kent coast and the

Solent. Aquaculture stock movements could put additional locations in the Thames Estuary/Essex coast region at risk, particularly as this area has a high likelihood of establishment for DV. Ferry movements are a potential link between the Anglesey population and the population on the east coast of Ireland, and may also be a route of initial introduction for the southern English populations. The north west coast of England could be at risk of the spread of DV by ferries, although establishment likelihood is low to medium in this region. Ferry movements could also spread DV to the Dumfries and Galloway coast, where likelihood of establishment is medium to high, and the Isle of Man (high likelihood of establishment). Domestic freight movements link all regions of the UK and Ireland, and could be important vectors of NIS over both short and long distances. The regions that receive the most domestic freight (Lancashire and Cumbria, Northern Ireland, the Humber, Sussex and Hampshire) may be most at risk in terms of the spread of DV or other NIS. Commonly used routes by recreational boat users link almost all areas within the UK and Ireland, and recreational boating is probably most important over short distances i.e. linking neighbouring areas. Levels of activity are particularly high along the south coast of England, and therefore the south coast of Kent could be at risk due to a high likelihood of establishment. In addition, the prevailing direction of currents could aid spread from the Solent to the south coast of Kent.

In general, the data presented here demonstrates that there exist a number of very active networks (particularly shipping and recreational yacht movements) that result in a high level of connectivity between many parts of the coastline which are separated by considerable seaway distance. Currents provide a pathway for contiguous spread, and although the map presented is a simplification of the complex pattern of ocean currents, it does show in which direction spread by rafting could be facilitated by currents. For example, further spread from the Solent by rafting would likely be in an easterly direction. The combination of pathways for long distance and local spread means that the potential for spread of that an introduced NIS following initial establishment is high. The ultimate geographic distribution of NIS is likely to be primarily determined by environmental and other factors influencing establishments, and not pathways of spread.

Lack of knowledge of the initial introduction of an NIS severely hampers the ability of a network analysis to assist in predicting how it may spread. Being able to determine the point of origin (be it external or internal to the study area) of a population would greatly enhance the performance of such data.

4.4 Recommendations for surveillance and mitigation

Once an NIS becomes abundantly established in more than a few locations the prospects for elimination and even control (of further spread) are poor. Therefore, surveillance aimed at early detection of new NIS is a crucial element in an overall strategy to minimise the risk posed. Ideally, however, biosecurity measures should prevent any initial invasions, and a pathway analysis such as this can assist in deciding where to focus such measures. Specifically, it is recommended that the pathway and establishment risk analyses and network analysis (in its current form) could be used in the following manner:

- To determine where, and by which pathways, certain taxonomic groups are most likely to appear in GB waters.
- Identify which of the pathways used in the analysis are most prevalent in certain areas and contributing to the high risk of introduction and/or spread (a sensitivity analysis).
- To provide an indication of where certain species of NIS are likely to establish.

Therefore it is possible to:

- Design and assist in the implementation of an environmental monitoring programme aimed primarily at areas of high risk of introduction of NIS.

- Implement specific monitoring programmes developed for certain taxonomic groups targeting specific hotspot'.
- Identify pathways that pose the greatest risk of introducing NIS into certain areas so that the pathways can be targeted for surveillance programmes.
- Focus surveillance on areas that are at the highest risk of invasion by taxa judged to be of highest priority.
- Recognise pathways and specific routes of spread and introduction that pose the greatest risk and use this information in the development of targeted biosecurity measures either to a specific sector or regionally.
- Combine the current study with horizon scanning (such as that conducted by the NISS) and determine the most likely points of introduction of these high risk species.

4.5 Data

This study required the integration of a large number of datasets from diverse sources. As is to be expected, the datasets do not all have the same spatial resolution. The spatial resolution of the pathway risk analysis had to be set at the resolution of the lowest resolution dataset. In addition, there were problems with spatial scales of data being incompatible e.g. locations of GIS polygons for fishing landings did not match locations of the grid squares, and spatial interpolation was required to obtain a value for each grid square. The data was not all from the same year, as can be seen in Table 1, although all data was recent where this was important.

There are also some missing datasets, inclusion of which could improve the analysis. Ideally we would have liked data on the locations where ballast water is exchanged within British waters, and the country of origin of the ballast water, but this type of data is not available. Unfortunately, GIS data from the RYA for locations of marinas and commonly used recreational boating routes was not made available in time for this project. It is hoped that this may be able to be included in future projects. Internal movements of aquaculture stock within the UK and Ireland were not available for all regions, or were only available at a very coarse scale. While we constructed a map of the prevailing patterns of sea currents using two publications, we were not able to obtain data pertaining to currents, either direction or speed to integrate into our pathway risk model or network analysis.

4.6 Methods

This study aimed to carry out a risk assessment for NIS in general, and for broad taxonomic groups, rather than for a specific species. This complicates the methods of assessing likelihood of introduction, establishment and spread, but is helpful from a policy, surveillance and regulatory perspective. The approach taken has been to maintain a high level of transparency; thus analyses (and data) for the introduction and establishment were undertaken and presented separately. The risk model in Excel was created allowing data underlying the scores for each pathway to be examined. Nevertheless, methodological issues arise. Data sources were highly variable, from overdispersed continuous data (e.g. ferry passengers) to categorical data (e.g. number of sources for imported aquaculture animals). The need to transform and standardise values (to scores between 0 and 100) results in the loss of resolution.

Weightings were used to account for differences in importance of the routes of introduction. Generating these weightings is more complex for generic analyses, i.e. for all species or for broad taxonomic groups, than for a single species. Weightings are based on published data, but inevitably on historical data and therefore do not take account of current mitigation, for example the Alien Species in Aquaculture Regulations. The model provides a framework for the impact of statutory regulations and other mitigation to be assessed.

Ideally, the scale at which likelihood of establishment is estimated should be finer than we achieved in this study. Our scale was restricted by data quality, and a finer resolution would have resulted in the loss of accuracy. At this scale it is not sensible to disregard areas with low scores for likelihood of establishment, but the results of the analysis can indicate which areas may require prioritisation for surveillance for certain taxa.

The analysis has focused on likelihoods estimates for introduction and establishment: consequence assessment has not been attempted, over and above an assessment of spread following introduction. Information on the location of marine protected areas has been collated and could be used in future consequence assessments.

4.7 Other pathways of introduction

In this study, we focussed on the main pathways of introduction of NIS to the UK. Other potential pathways and vectors do exist, however, and may play an important role for specific species. NIS may be imported in the transport water or packaging of bait (Haska *et al.* 2012), research vessels may transport species between sites, animals may escape from research facilities, and migratory birds may act as vectors for some marine species. Any detailed analysis at the species level should attempt to consider all potential routes.

4.8 Marine NIS in the future

Changes in pathways of introduction and likelihood of establishment of NIS are highly likely to occur over time and therefore risk-based surveillance strategies must use models based on up to date data. Global climate change is likely to alter risk of establishment for many species, and expansion of range due to climate change is one route of entry for NIS. Other factors, such as changes in shipping routes and ports (e.g. the London Gateway development, which is constructing a new deep sea container port), and changes in the aquaculture movement network, are likely to affect individual locations.

4.9 Further Work

This study was a preliminary study looking at the risk of NIS to the UK and Ireland. While it has produced some interesting results, it is recommended that further work is carried out to build on this project. The following actions in particular should be conducted:

- Develop the network analysis further by gathering a more comprehensive set of data, and carrying out quantitative analysis of network properties using the 'igraph' package in the statistical programme R (http://www.r-project.org/). Additional datasets that would make this possible are:
    - Internal movements of aquaculture stock in Scotland, Northern Ireland and the Republic of Ireland.
    - Domestic shipping (freight) movements at a finer resolution (i.e. between ports rather than at a region level)
    - Data for speed and direction of ocean currents in a format that could be included quantitatively in a model of introduction and spread.
    - GIS data for locations of marinas and recreational routes, both for the UK and Ireland
    - Locations of offshore installations, such as windfarms, that may act as stepping stones to promote natural dispersal.
- Obtain finer resolution datasets (aquaculture stock movements for some regions, fishing landings) to allow analysis of introduction to be carried out at a finer scale. Higher quality environmental data, ideally in a GIS format, particularly for salinity, sea temperature and bathymetry, would allow analysis of establishment to be carried out at a finer scale. For example, it would be beneficial to be able to identify locations where a barrier to establishment (e.g. high salinity) would render it impossible for a given taxon to establish,

regardless of how favourable other conditions are. Thus better information would be generated on which to develop risk based surveillance for NIS.

- Develop the risk assessments as a computer package that can be used and incorporated into structured marine management programmes
- Include a front end to the Excel model to facilitate changing weightings and examining the impact on the risk scores. Dynamic programming that links the Excel spreadsheet to the GIS would create maps illustrating the risk scores, where the user could input values for a chosen species of interest and be presented with a heat map of risk of introduction and/or establishment.
- Conduct more case studies to assist in determining the effectiveness of the risk assessment as a predictor of introduction, establishment and spread i.e. validate the model
- Reassess the weightings of the different taxonomic groups by a more in depth literature review of species currently found in the UK.
- Assess if reductions in risk could be achieved by biosecurity measures by adding these as parameters in the model
- Establish which thresholds of likelihood would result in the introduction, establishment and spread for each of the taxonomic groups. This is effectively the threshold above which action should be taken.
- Carry out a consequence assessment i.e. assess the impact of invasion based on vulnerability of area e.g. presence of threatened species or habitats. This would allow surveillance and/or control prioritisation based on the potential consequences of establishment as well as the likelihood of this occurring.

5 Conclusions

The work detailed in this report has begun to collate data relevant to introduction, establishment and spread and create a model to enable a geographic analysis of risk. While the main aims of this study were to identify the hotspots for introduction, establishment and spread of NIS in the UK and Ireland (which it has achieved), the project has also fulfilled a number of other important purposes. The collaborative nature of the process, particularly in the data collection stages, gave an opportunity for organisations in the constituent countries of the UK and Ireland to work together. This approach is recommended for future work as co-operation brings efficiencies in terms of data collection and knowledge sharing, and is a sensible way to work particularly where borders do not represent geographical barriers to NIS. Secondly, much time was spent researching sources of data, and the catalogue of data gathered will be useful for future projects. This process also highlighted gaps in data availability, deficiencies in data, and the difficulties involved in integrating many datasets. Importantly, this study has developed methods for identifying spatial patterns of the likelihood of introduction, establishment and spread of NIS. The network analysis is a tool that could be used in the future to a greater extent now that data has begun to be gathered and formatted for such a use, while the pathway risk analysis has already produced results in terms of identifying hotspots for introduction and assessing likelihood of establishment. These are both tools that should be developed further in order to reach their full potential. The damage that can caused by NIS is well established, therefore investment in research to underpin surveillance and mitigation, thereby reducing the future threat, is amply justified.

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Appendices

Appendix A: Heat maps of the scores for the five pathways of introduction

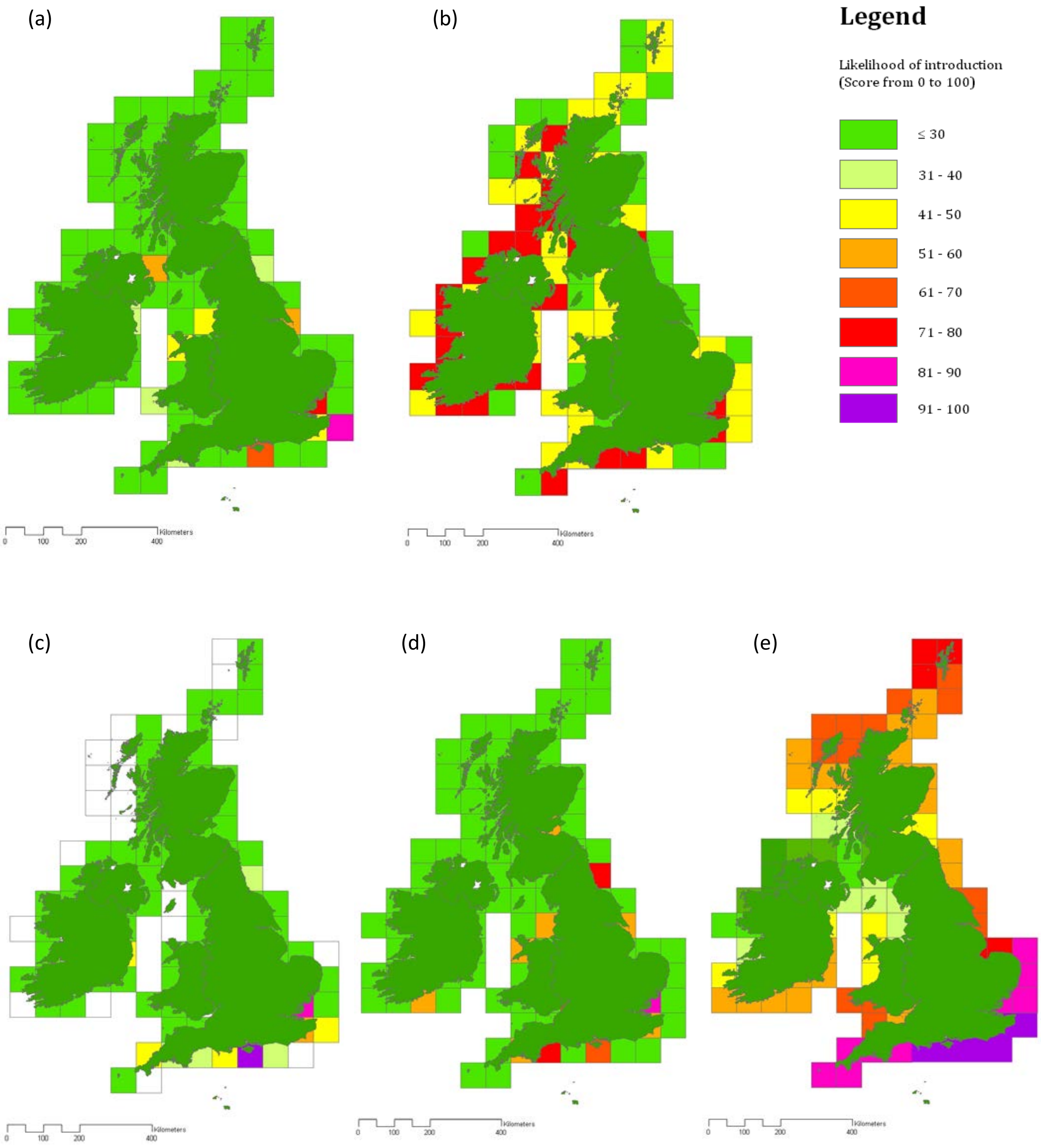


Figure A1: *Heat maps for the scores for the five pathways: (a) commercial shipping, (b) imports of live animals for aquaculture, (c) recreational boating, (d) imports of live animals for the seafood trade, and (e) natural dispersal.*

Appendix B: Establishment scoring

Table B1: *The scoring system used to generate a likelihood of establishment value for each grid cell, for each taxonomic group, and Didemnum vexillum. The first three columns describe the categories (range of values) created for each environmental variable, and the following ten columns give the scores assigned to each category for each taxonomic group, from 0 (low preference) to 10 (high preference).*

			Taxonomic Group									
Environmental variable (units)	**Values**	**Category**	**Plankton**	**Algae**	**Plantae**	**Jellyfish**	**Arthropoda**	**Worms**	**Crustacea**	**Mollusca**	**Tunicata**	***Didemnum vexillum***
Salinity (PSU)	10 – 30	Estuarine	0	4	10	6	0	6	5	9	5	0
	30.1 – 34.0	Coastal	10	10	10	10	10	10	10	10	10	10
	≥ 34.1	Oceanic	10	0	0	0	0	0	0	0	0	0
Minimum bottom temperature (°C)	4 – 6	Low	6	6	0	0	5	1	4	4	10	0
	7 – 9	Medium	10	8	10	10	10	5	7	10	10	0
	≥ 10	High	10	10	10	10	10	10	10	7	10	10
Bathymetry (metres below mean sea level)	< 10	Shallow	0	10	10	10	10	10	10	10	10	10
	10 – 40	Medium	10	0	0	10	10	10	10	10	5	10
	> 40	Deep	10	0	0	0	0	0	1	0	0	0
Substrate	Rock / reef / coarse sediment	Hard	NA (no effect)	10	0	10	10	10	10	8	10	10
	Mixed sediment	Mixed		4	0	3	10	5	4	10	10	0
	Sand / mud	Soft		0	10	3	0	5	3	4	0	0
Presence of aquaculture site(s)	Yes	NA	10	10	0	10	10	10	10	10	10	10
	No		0	0	10	0	0	4	5	0	0	0
Bed stress	< 2.7	Low	NA (no effect)	10	10	10	10	10	10	10	10	10
	2.7 – 11.5	Medium		1	0	0	0	1	0	0	0	0
	> 11.5	High		1	0	0	0	0	0	0	0	0

Environmental variable (units)	**Values**	**Category**	**Plankton**	**Algae**	**Plants**	**Jellyfish**	**Arthropods**	**Worms**	**Crustacea**	**Mollusc**	**Tunicate**	***Didemnum vexillum***
Numbers of ports and marinas	0	NA	NA (no effect)	0	10	0	0	4	5	4	0	0
	1			1	9	1	1	5	6	5	1	1
	2			2	8	2	2	6	6	6	2	2
	3			3	7	3	3	6	7	6	3	3
	4			4	6	4	4	7	7	7	4	4
	5			5	5	5	5	7	8	7	5	5
	6			6	4	6	6	8	8	8	6	6
	7			7	3	7	7	8	9	8	7	7
	8			8	2	8	8	9	9	9	8	8
	9			9	1	9	9	9	10	9	9	9
	10+			10	0	10	10	10	10	10	10	10

Appendix C: Recreational boating routes in Ireland

Figure C1: Maps of commonly used recreational routes along the west and south coasts of the Republic of Ireland. Six maps are presented, each of a different region, ordered from North to South.

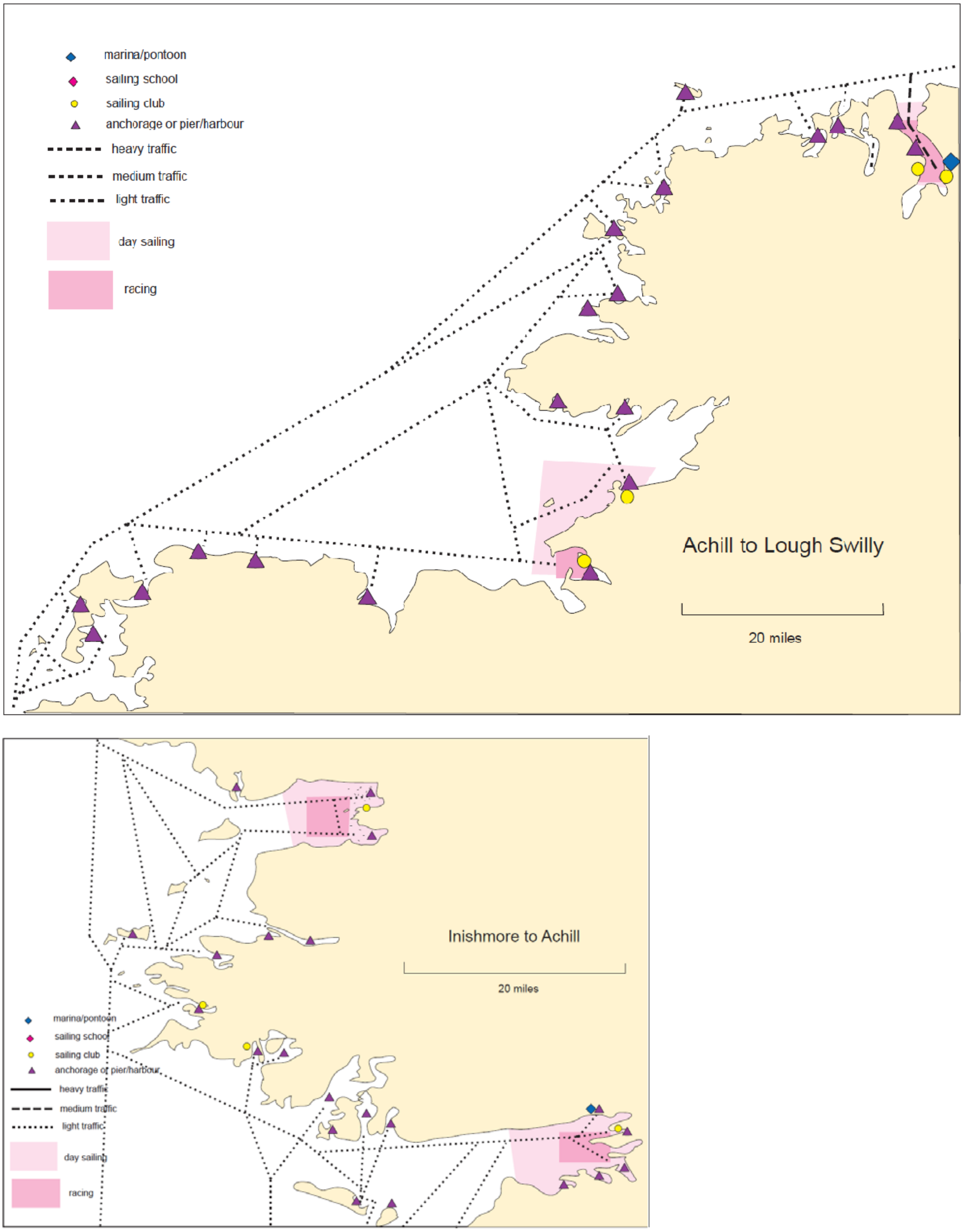
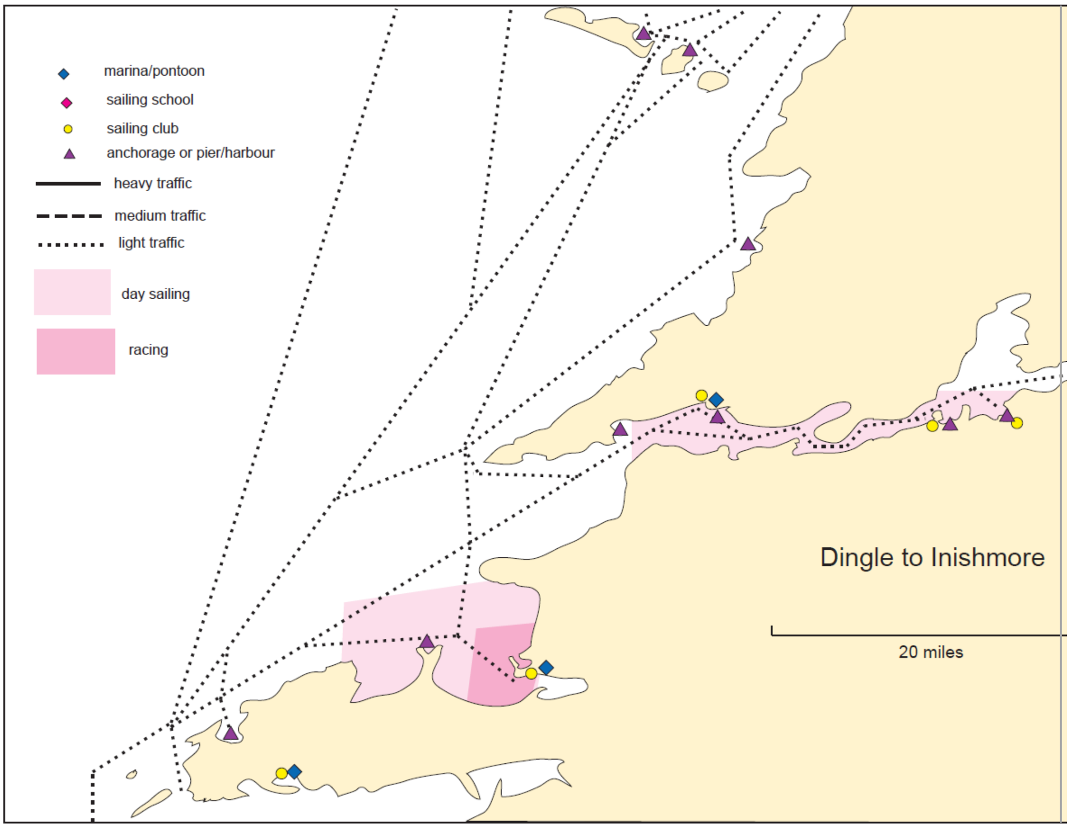


Figure C1 (continued): Maps of commonly used recreational routes along the west and south coasts of the Republic of Ireland. Six maps are presented, each of a different region, ordered from North to South.



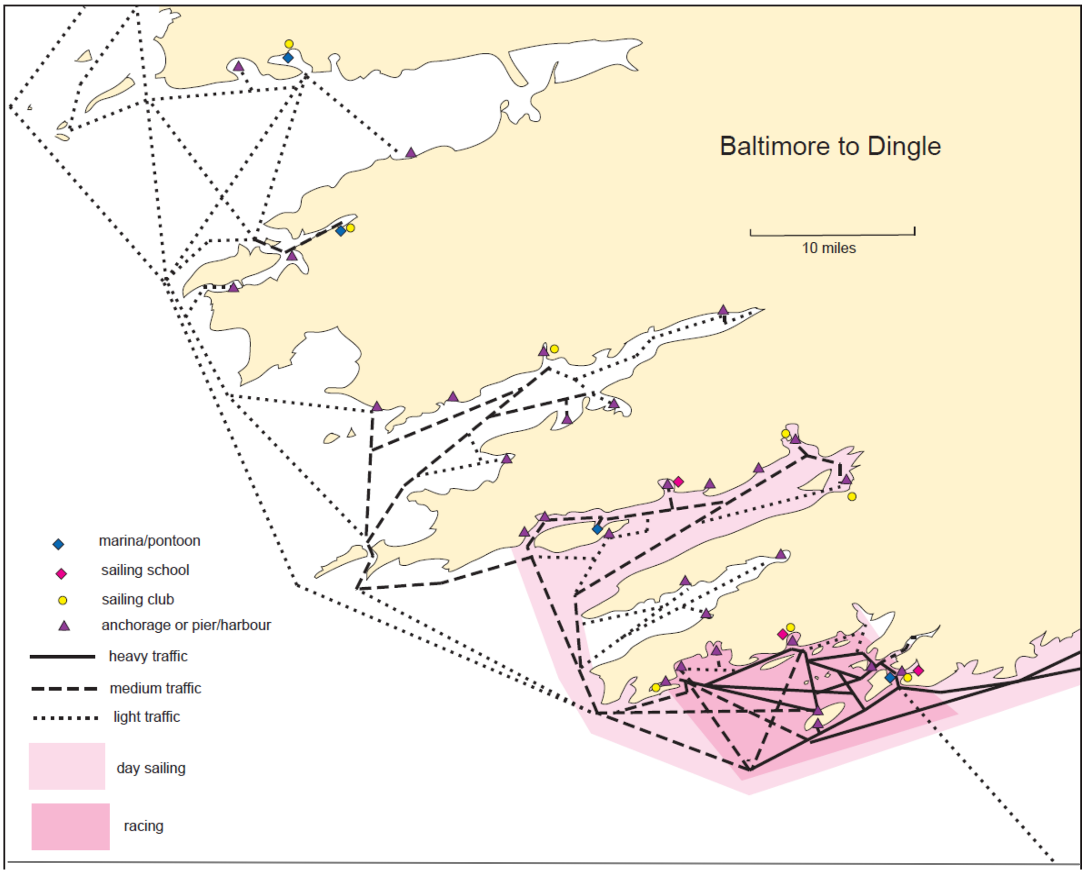


Figure C1 (continued): Maps of commonly used recreational routes along the west and south coasts of the Republic of Ireland. Six maps are presented, each of a different region, ordered from North to South.