Introduction of Marine Non-Indigenous Species into Great Britain and Ireland: Hotspots of Introduction and the Merit of Risk Based Monitoring.

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Non-indigenous species (NIS) can have negative environmental, economic and social impacts. The Marine Strategy Framework Directive (MSFD) aims to protect the marine environment across Europe and manage the sustainable use of marine waters for both economic and social benefit. Reflecting the potential threat posed by NIS, management of NIS is incorporated into the MSFD.

Management of NIS will be facilitated by the assessment of introduction pathways and identification of coastal areas where pathway activity is high and therefore where the likelihood of introduction of NIS is increased. In addition, development of a simple method to determine the likelihood of introduction of specific NIS and consideration of the relative merit of different monitoring strategies (namely risk based monitoring and random, non risk based monitoring) to detect NIS introductions will be valuable in focusing monitoring and management efforts and optimising their cost effectiveness.

This study aimed to:

1. Assess the intensity of introduction pathway activity in coastal regions around Great Britain (GB) and Ireland.
2. Develop a tool to be used to estimate the likelihood of introduction of a species by a specific pathway based on key characteristics.
3. Assess the merit of different monitoring strategies using a mathematical modelling framework.

These aims were achieved by:

- Identifying key introduction pathways (commercial shipping, recreational boating, aquaculture stock imports and natural dispersal) and acquiring high quality data to determine the intensity of activity associated with each introduction pathway in coastal areas (50x50km grids) of GB and Ireland. Pathway intensity scores were then plotted as heat maps to enable visualisation of relative intensity of activity of each introduction pathway in different coastal regions.

- Developing a simple species risk tool which can be used to indicate the relative likelihood of introduction of NIS based on specific characteristics, the introduction pathways associated with these characteristics and the intensity of the introduction pathway activity.
Developing a mathematical modelling framework, incorporating the intensity of introduction pathway activity scores, to assess the time taken to detect an introduced NIS based on risk based and non risk based monitoring strategies.

The main findings of this study highlight that:

- Introduction pathway activity is high in coastal waters around GB and Ireland and the location of pathway activity hotspots is dependent on the specific introduction pathway.
- Commercial shipping activity was greatest in coastal regions around London, Immingham, Dover, Tees, Dublin and Southampton. Recreational boating activity was greatest in coastal regions around the Isle of Man, Bognor Regis, Northern Ireland/South West Scotland, Dartmouth, Holyhead, Southport/Blackpool and Southampton. Aquaculture pathway activity was greatest in coastal regions of Ireland, namely around Milford, Cardonough, South of Waterford and Carlingford Loch. Coastal regions considered at greatest threat from the introduction of NIS by natural dispersal on ocean currents are the south coast region of England and Wales, the south coast of Ireland and the west coast of Scotland. Finally, regions where the introduction of NIS is more likely to be facilitated by offshore structures are located on the east coast of England and the coast around North Wales and the east of England.
- Using species characteristics to assess the likelihood of introduction by different introduction pathways avoids the need for taxonomic classification and means assessment of the likelihood of introduction of particular species is quicker and more accessible.
- Some correlation exists between initial sites of species introductions, their distributions and the areas indicated, from our analysis, as associated with increased likelihood of receiving introductions of this species.
- Risk based monitoring may reduce the time taken to detect an introduction of a NIS compared to random, non risk based monitoring. However, focusing too heavily on high risk sites may act to increase the time taken to detect an introduction compared to random, non risk based monitoring and may therefore reduce the likelihood of detecting a NIS within a given time period compared to random, non risk based monitoring.

In conclusion, this study provides information which can be used to develop and implement a monitoring programme for NIS thereby aiding achievement of Good Environmental Status under the MSFD. While this study has focused on the introduction of NIS, to gain a full understanding of the
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Glossary

**Non-Indigenous Species (NIS)**: species which occur outside their historic or natural range.

**Hotspot**: an area where pathway activity or likelihood of introduction is high. For this project, for a grid square to be considered a hotspot it has a pathway activity intensity score of great than 75 or a likelihood of introduction score of greater than 75.

**Adhering**: can attach to surface or substance.

**Contaminating**: makes impure by mixing.

**Fragmentation**: The act or process of breaking into smaller pieces or fragments.

**Great Britain (Great Britain)**: England, Wales and Scotland

**Ireland**: Northern Ireland and Republic of Ireland.

**Mean**: Average calculated by summing values and dividing my how many values there are.

**Oyster Spat**: young oysters/oyster larvae.
Introduction


Non-indigenous species (NIS) are species which occur outside their natural range. They can have negative environmental, economic and social impacts (Eno et al. 1997, Grosholz 2002, Bax et al. 2003). Environmental impacts include loss of biodiversity through displacement of indigenous species, loss of genetic diversity and introduction of pathogens into naïve indigenous populations. NIS are recognised globally as the second greatest threat to biodiversity (after habitat loss) by the Convention on Biological Diversity (CBD). Social and economic impacts may be the consequence of disruption to services and industries and the cost of intervention and remediation. Marine NIS are of particular concern given that they are particularly difficult to eradicate following their introduction. Therefore, the need to monitor, manage and control NIS, specifically marine NIS, is clearly apparent.

The marine strategy framework directive (MSFD) is an EU directive, formally adopted in July 2008, which aims to manage and protect the marine environment across Europe. The central goal of the directive is to achieve Good Environmental Status (GES) in marine waters of EU Member States by 2020. The framework promotes an ecosystem based approach to manage the sustainable use of marine waters for both economic and social benefit. The MSFD is compiled of a list of descriptors on which GES will be assessed. In accordance with the understanding that NIS may have negative impacts on the marine environment and the need for their management and control, one of the 11 MSFD descriptors refers to NIS, stating:

“Non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystems”.

Indicators have also been developed on which GES in relation to NIS will be assessed. These indicators are as follows:

1. Trends in abundance, temporal occurrence and spatial distribution in the wild of NIS, particularly invasive NIS, notably in risk areas, in relation to the main vectors and pathways of spreading of such species.

2. Ratio between invasive and NIS and native species in some well-studied taxonomic groups (e.g. fish, macroalgae, molluscs) that may provide a measure of change in species composition (e.g. further to the displacement of native species).

3. Impacts of NIS at the level of species habitats and ecosystem where feasible.
In the development of a risk based approach to monitoring (as described in indicator 1), a method by which areas at high risk of introduction, related to the main pathways and vectors, can be identified in a quantifiable manner, is required.

1.2 Introduction of Non-Indigenous Species

There are a number of pathways by which marine NIS can be transported to new locations. Although a number of introduction pathways exist, key pathways include commercial shipping, recreational boating, aquaculture stock movements and natural dispersal (Ricciardi and Rasmussen 1998, Molnar et al. 2008, Acosta and Forrest 2009, Katsanevakis et al. 2013). For example, it has been suggested that *Elminius modestus* (acorn barnacle) was introduced into marine waters around GB and Ireland following transport in ballast water, *Hydriodes dianthus* (tubeworm) was introduced by fouling of ship’s hulls, *Crepidula fornicata* (the slipper limpet) was introduced via contamination of imported aquaculture stock, *Crassostrea gigas* (pacific oyster) was introduced following deliberate introduction for aquaculture and finally, it is thought that *Sargassum muticum* (wireweed) was introduced by drifting or rafting facilitated by ocean currents (Eno et al. 1997, www.Marlin.ac.uk).

Prevention of introduction and early mitigation following introduction are recognised as the most effective approaches to reducing the potential impacts of NIS (Wittenberg and Cock 2001, Hulme 2009). This is especially true in a marine environment where control and eradication may not be possible. By assessing the intensity of introduction pathway activity it is possible to identify coastal areas where NIS may be more likely to be introduced. This will facilitate introduction pathway management, a promising tool for NIS management and will contribute to the achievement of GES under the MSFD.

1.3 Towards a Management and Monitoring Strategy

Monitoring and management of NIS on the coast of GB and Ireland pose significant challenges given the length of coastline and the high levels of introduction pathway activity. Identification of areas of coastline where introductions are more likely is crucial for more cost effective monitoring and management of NIS and achievement of GES under the MSFD.

There are a number of different monitoring approaches which may be used for the early detection of NIS. Of particular interest is a risk based approach. A risk based monitoring programme would involve focusing monitoring on areas which are at high risk of introduction of NIS, something which introduction pathway analysis is fundamental to informing. Though risk based monitoring is
often considered beneficial, there is little explicit quantitative assessment of its merit relative to random, non risk based monitoring. This is perhaps due to the complexity of exploring this without specific data and infrastructure. Mathematical modelling is a valuable tool often used for the investigation of hypotheses which would be very costly, problematic and time consuming to investigate empirically. The application of mathematical modelling to the investigation and assessment of the merit of risk based versus non risk based monitoring may be advantageous and outputs used to inform a monitoring programme for NIS.

1.4 Project Aims

The main aims of this project were to:

i. **Refine NIS introduction pathway risk assessment by:**
   a) Identifying important introduction pathways.
   b) Acquiring high resolution data to inform risk of introduction by different pathways.
   c) Determining the intensity of pathway activity in coastal regions around GB and Ireland

ii. **Develop a tool to be used to estimate the likelihood of introduction of a species by a specific pathway based on its characteristics.**

iii. **Assess the merit of different monitoring strategies by:**
   a) Developing a mathematical modelling framework to simulate risk based and non risk based monitoring.
   b) Incorporating pathway intensity scores into the modelling framework and assessing time taken to detect an introduction based on simulations representing a non risk based strategy and two different levels of risk based strategy.

iv. **Provide advice on the development of a monitoring programme.**
2 Methods

2.1 Introduction Pathway Assessment

2.1.1 Introduction Pathway Identification

Though other introduction pathways exist, the following pathways have been identified as key in the introduction of NIS into coastal waters of GB and Ireland:

i. Commercial shipping
ii. Recreational boating
iii. Aquaculture
iv. Natural dispersal

There are a number of mechanisms associated with these pathways which may facilitate the introduction of NIS (Table 1).

2.1.2 Introduction Pathway Assessment Area

The pathway assessment areas in this report are Great Britain (GB) and Ireland (Republic of Ireland and Northern Ireland) (Figure 1). We considered Ireland as a whole given that it is one land mass and that under the MSFD bordering countries sharing the same coastal waters, in this instance Republic of Ireland and Northern Ireland, should work together to achieve GES. In addition, this report focuses on the risk of introduction of NIS. Movement of animals from the Republic of Ireland to Northern Ireland (or vice versa) would be considered as spread in the context of this report. Activity into these assessment areas and between these assessment areas associated with each introduction pathway was considered in the analysis. Activity within GB and Ireland was not included in the analysis as this was considered to be important for the subsequent spread of NIS rather than their introduction. Despite being a self-governing crown dependency, for completeness, the Isle of Man was also included in the assessment (where data was available) due to its close proximity to the UK coastline and its potential importance in the introduction and spread of NIS into and within UK coastal waters. The Isle of Man was considered a separate area so that activity between the Isle of Man and GB and activity between the Isle of Man and Ireland was considered in the analysis where data was available.

2.1.3 Data Acquisition
In order to determine the intensity of introduction pathway activity detailed data were sought (Table 2).

Table 1. Mechanisms by which NIS may be introduced that are associated with each introduction pathway.

<table>
<thead>
<tr>
<th>Introduction pathway</th>
<th>Mechanism which may facilitate the introduction of NIS</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial Shipping</td>
<td>Ballast water</td>
<td>Organism, at some development stage, may be taken up in ballast water and introduced where ballast water is released.</td>
</tr>
<tr>
<td></td>
<td>Biofouling</td>
<td>Organisms, at some development stage, may adhere to boat surfaces and be introduced into new locations where they become detached from the surface or release propagules.</td>
</tr>
<tr>
<td>Recreational boating</td>
<td>Biofouling</td>
<td>Organisms, at some development stage, may adhere to boat surfaces and be introduced into new locations where they become detached from the surface or release propagules.</td>
</tr>
<tr>
<td>Aquaculture</td>
<td>Contamination of imported aquaculture stock.</td>
<td>Organisms, at some development stage, may attach to and due to their small size, go undetected in aquaculture stock.</td>
</tr>
<tr>
<td>Natural dispersal</td>
<td>Rafting/ drifting facilitated by ocean currents.</td>
<td>Organisms, at some development stage, may be transported to new locations by the action of ocean currents, often by rafting on debris. It is possible that offshore structures may aid introduction by natural dispersal by providing stepping stones between landmasses.</td>
</tr>
</tbody>
</table>

I. Commercial shipping
Commercial shipping data were acquired from Marine Traffic (Table 2). The data came from AIS (Automatic Identification System) vessel tracking records. AIS is required (since Dec 2004), by the International Maritime Organization’s International Convention for the Safety of Life at Sea (SOLAS), to be fitted to all ships weighing 300 Gross Tonnage (GT) and upwards and which undertake international voyages or call at a port of a Member state of the EU. In addition, AIS is required to be fitted to all passenger ships, including High Speed Craft, irrespective of size or to ships of 300 GT and upwards if engaged in domestic trade (International convention for the safety of Life at Sea (SOLAS)). Please note that the data used will also include traffic by fishing vessels weighing 300 Gross Tonnes and upwards. For this project we acquired AIS shipping traffic data for 6 months of 2012 (February, April, June, August, October and December). This selection of months was a consequence of balancing cost while being able to gain an understanding of seasonality in shipping movements into and between GB and Ireland coastal waters. In addition, we were advised that shipping traffic data for November 2012 was not complete. Specifically the data provided details of shipping traffic (connections, number of ships and number of voyages) for vessels categorized as large (≥50m length) or small (<50m length). N.B. Shipping traffic into the Isle of Man is not included in the dataset.

II. Recreational boating

Recreational boating data for the UK were acquired from The Royal Yachting Association (RYA) (Table 2). These data were in the form of GIS layers showing probable recreational boating routes. Maps indicating likely cruising routes for coastal waters around ROI were also acquired from the Irish Sailing Association (ISA) and the Irish Sailing Club. Routes highlighted by both the RYA and ISA were defined as light use, medium use and heavy use. Extra information regarding recreational boating in the pathway assessment area was acquired from personal correspondence with contacts within the RYA, ISA and Irish Sailing Club and the books: South and West coasts of Ireland Sailing Directions (Kean, N. (Editor), (2013)) and East and North Coast of Ireland Sailing Directions (Kean, N. (Editor), (2008)). Cruising routes into ROI from non UK and ROI origins were not featured on maps acquired from ISA/Irish Sailing Club. Although rare, it is possible that recreational boats travel from North-West France non-stop to the south-east coast of ROI (personal correspondence). These potential routes were therefore added to the recreational boating dataset.

The recreational cruising route data used for the recreational boating pathway assessment is not based on actual movements of recreational boating vessels. Routes taken by recreational vessels are not restricted and precise routes are not often predetermined and will likely vary and be influenced by a number of factors including weather, tide, boat type, and crew capability. Therefore the data acts as an indication of likely routes taken by recreational boating vessels and allows
estimation only of activity by recreational boating vessels into coastal grid squares (personal correspondence with RYA, ISA).
Figure 1. The geographical area for which the intensity of introduction pathway activity was considered. Specifically, scores estimating pathway activity intensity were based on pathway activity into GB and Ireland from outside GB and Ireland and activity between GB and Ireland. (N.B the Isle of Man was considered a separate area so that activity between the Isle of Man and GB and activity between the Isle of Man and Ireland was considered in the analysis where data was available).
Table 2. Details of data used in the introduction pathway assessment.

<table>
<thead>
<tr>
<th>Pathway</th>
<th>Data</th>
<th>Region</th>
<th>Format</th>
<th>Year</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recreational boating</td>
<td>Recreational boating cruising routes</td>
<td>Republic of Ireland</td>
<td>Map</td>
<td></td>
<td>Irish Sailing Association and Irish Sailing club – personal correspondence. <a href="http://www.sailing.ie/">http://www.sailing.ie/</a></td>
</tr>
<tr>
<td>Aquaculture</td>
<td>Shellfish imports</td>
<td>England and Wales</td>
<td>Spreadsheet</td>
<td>2012</td>
<td>Live Fish Movement Database (Cefas).</td>
</tr>
<tr>
<td></td>
<td>Shellfish imports</td>
<td>Northern Ireland</td>
<td>Summary notes on pacific oyster imports</td>
<td>2012</td>
<td>Department of agriculture and rural development – personal correspondence. <a href="http://www.dardni.gov.uk/">www.dardni.gov.uk/</a></td>
</tr>
<tr>
<td>Natural dispersal</td>
<td>Ocean currents</td>
<td>UK</td>
<td>Map</td>
<td>As referenced</td>
<td>(Turrell 1992, OSPAR 2000)</td>
</tr>
<tr>
<td></td>
<td>Offshore structures associated with oil and gas industry.</td>
<td>UK</td>
<td>Map layer</td>
<td>Current</td>
<td>UK Oil and Gas data - UKOilandGasData.com (website provided by CDA).</td>
</tr>
<tr>
<td></td>
<td>Oil wells</td>
<td>ROI</td>
<td>map</td>
<td>Current</td>
<td>Data from the Department of Communication, Energy and Natural Resources accessed through the Marine Atlas Viewer at <a href="http://atlas.marine.ie/">http://atlas.marine.ie/</a>, (2014).</td>
</tr>
<tr>
<td></td>
<td>Offshore windfarms</td>
<td>UK</td>
<td>Map layer</td>
<td>Current</td>
<td>Cefas</td>
</tr>
</tbody>
</table>
III. **Aquaculture**

Data detailing shellfish imports into the pathway assessment areas were acquired from different sources (Table 2). Information regarding imports of live shellfish into England and Wales in 2012 was obtained via the Cefas Live Fish Movement Database. Data detailing the imports of shellfish into the Republic of Ireland in 2012 were obtained from The Marine Institute, Ireland. Data regarding imports of shellfish into Scotland were obtained from Marine Scotland. Data were in the form of excel spreadsheets including details of aquaculture imports such as date, source of import, destination of import and species being imported. Information regarding live imports of Oysters into Northern Ireland from France was provided by the Department of Agriculture and Rural Development (DARDNI) in a written summary format. This information was then translated into a more usable format to comply with the rest of the aquaculture data.

IV. **Natural dispersal**

Information on ocean currents was acquired from various sources (Table 2) and used to map important prevailing currents into and between the risk assessment areas. A map detailing the location of offshore structures associated with the oil and gas industry in the UK was obtained from Oil and Gas UK and the location of windfarms was obtained from Cefas in the form of a GIS layer. A map detailing the location of offshore oil wells around the Republic of Ireland was acquired via the Marine Atlas Viewer.

2.1.4 **Heat Mapping and Identification of Pathway Activity Hotspots**

A 50x50km grid was created in ArcMap (version 10.1) using the fishnet tool. This grid was superimposed over a map of GB and Ireland. Grids within which coastal areas were present were selected to form a coastal grid map.

For each pathway, coastal grid cells were given a score to indicate the intensity of pathway activity. The specific method used to score coastal grid cells for the intensity of the pathway activity is detailed below (also see Table 3). The pathway intensity scores were then presented in heat map form for each pathway separately and combined to generate a heat map for all pathways. Coastal grid squares were colour graded based on their pathway intensity score with darker shades representing areas associated with high pathway intensity relative to other areas and paler shades representing areas associated with low pathway intensity relative to other areas. These maps therefore enable instant visualisation of relative pathway intensity for coastal regions within the pathway assessment areas.
i. Commercial shipping

Data on shipping movements into and between the pathway assessment areas were compiled using R studio. From the data, the number of unique connections and number of voyages into ports in GB and Ireland from ports outside GB and Ireland were determined. In addition, the number of unique connections and number of voyages between ports in GB and Ireland were determined. Shipping connections across the risk assessment area were visualised in ArcMap (version 10.1). The number of unique connections into each port within the pathway assessment areas and the number of voyages into each port in the pathway assessment areas were also visualised in ArcMap and analysed using R studio.

The pathway intensity heat map for the commercial shipping pathway was produced in ArcMap by calculating the total number of unique connections and the total number of voyages received into each 50x50km coastal grid cell using the spatial join function. The commercial shipping pathway intensity scores therefore reflect both the level of connection and the intensity of shipping traffic for each grid square. The scores thereby incorporate the number of potential sources from which a NIS can be introduced (assuming that the greater the number of sources the increase in likelihood of introduction) and the potential frequency with which NIS may be introduced (assuming that the greater the number of voyages the greater the likelihood of an introduction). Specifically, pathway intensity scores were determined by multiplying the number of unique connections into each grid cell by the number of voyages into each grid cell (Table 3). The highest score was 1,034,670 for the Thames region grid square. The second highest score was 487,306 for the Immingham area coastal grid square. This pathway intensity scores were coerced to scale 0 – 100 for the heat map. Though scores for different pathways are not directly comparable as they are based on different data, scaling the scores for all pathways means that all heatmaps will have the same gradient bands and therefore are more easily interpreted and compared. The scaled score for the Thames area grid square was capped at 100. To prevent the scores being over influenced by the large value for the Thames area grid square the scaled scores for other coastal grid squares were calculated using the score for Immingham grid square as a maximum. (See appendix 1 for scaling method).
Table 3. Methodology used to estimate the intensity of introduction pathway activity into coastal grid squares in the pathway assessment areas.

<table>
<thead>
<tr>
<th>Introduction Pathway</th>
<th>Data used to determine the intensity of introduction pathway activity for each coastal grid.</th>
<th>Introduction pathway intensity score formula.</th>
<th>Scale (see Appendix 1 for scaling method)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial Shipping</td>
<td>The total number of unique connections into ports within grid square. (6 months of 2012)</td>
<td>Number of unique connections * number of voyages into ports within grid square. (N.B. heavy intensity = 3, medium intensity = 2, low intensity = 1). E.g. if grid receives traffic from 100 different ports and receives, in total, 300 voyages, the pathway intensity score for that grid = 30,000.</td>
<td>0-100</td>
</tr>
<tr>
<td>Recreational Boating</td>
<td>The total number of potential recreational cruising routes into each grid square (current information).</td>
<td>The sum of the number of recreational cruising routes * intensity. E.g. if there is 1 heavy intensity route, 4 medium intensity routes, and 5 light intensity routes into a grid square, the pathway intensity score for that square = (3<em>1)+(2</em>4)+(1*5) = 16.</td>
<td>0-100</td>
</tr>
<tr>
<td>Aquaculture</td>
<td>The number of live imports into that grid in 2012. The number of individual animals imported was not incorporated into the score.</td>
<td>Total number of imports.</td>
<td>0-100</td>
</tr>
<tr>
<td>Natural Dispersal – ocean current</td>
<td>Proximity by sea from landmass where ocean current is flowing from.</td>
<td>Proximity to landmass</td>
<td>0-100</td>
</tr>
<tr>
<td>Natural Dispersal – offshore structures</td>
<td>Offshore structures (oil, gas and wind) in close proximity.</td>
<td>The total number of offshore structures in the coastal grid and the 8 adjoining coastal grid (see Appendix 2 for method details).</td>
<td>0-100</td>
</tr>
<tr>
<td>All Pathways</td>
<td>Scaled pathway intensity scores for each individual pathway.</td>
<td>Mean of scores for each individual pathway.</td>
<td>0-100</td>
</tr>
</tbody>
</table>
Additional analysis for the commercial shipping pathway assessment included determining the busiest shipping connections (i.e. port pairs between which there were the greatest number of voyages), assessing the ports from which the greatest number of voyages and connections originate and examining the temporal variation in the number of voyages for both large (≥50m in length) and small vessels (< 50m in length) in R.

ii. Recreational boating
All recreational boating cruising routes into GB and Ireland (from Europe and Scandinavia) and between GB and Ireland were plotted in ArcMap. In addition, cruising routes from the Isle of Man into GB and Ireland and from GB and Ireland into the Isle of Man were plotted. The number of cruising routes of each intensity (light, medium and heavy) into each coastal grid square was counted. A count of five cruising routes was given to coastal grid squares in South-East Ireland. This was an estimate assuming that each coastal grid square in the south-east of Ireland is the destination of a third of the potential cruising route origins in the north-west of France (personal correspondence with ISA/Irish Sailing Club). Detailed information regarding the intensity with which recreational boats travel from North-West France to South-East Ireland was not available. However, given that non stop cruising routes from North-West France to South-West Ireland is uncommon, these cruising routes were labelled as low intensity.

The recreational boating pathway intensity heat map was produced in ArcMap. The pathway intensity scores were calculated for each grid square from the number of cruising routes into the grid square and the intensity with which the cruising routes are likely to be used. Specifically, for each grid cell, the number of light intensity routes were counted, the number of medium intensity routes were counted and multiplied by 2 and the number of heavy intensity routes were counted and multiplied by 3. These values were summed to give the pathway intensity score for the grid square (Table 3). The pathway intensity scores for the recreational boating pathway therefore reflect both the number of cruising routes into the grid square but also how busy these cruising routes are estimated to be. The pathway intensity scores were coerced to a scale of 0 – 100. The highest pathway intensity score was 31 for the grid square on the coast of the Isle of Man. The next highest score was 14 for the grid square which covers the south-west coast of Scotland and the north-east coast of Northern Ireland and the grid square along the south of England near Bognor Regis. The scaled score for the coastal grid on the coast of the Isle of Man was capped at 100 and the scores for other coastal grids were coerced to scale 0 – 100 using the second highest scores as a maximum to avoid over influence by the highest scoring square (see appendix 1 for scaling method).
iii. Aquaculture

Data detailing shellfish imports into GB and Ireland were combined and visualised in ArcMap. Specifically, imports from Europe and Scandinavia into GB and Ireland were analysed. In addition, imports into Ireland from GB and imports into GB from Ireland were analysed. Pathway intensity scores for coastal grids were determined by calculating the total number of imports into coastal grid squares throughout 2012 using the spatial join function in ArcMap. The number of individual animals imported was not incorporated into the score. Scores based on the aquaculture imports were then scaled between 0 -100. The maximum score (of 90) for region on the North coast of Ireland, around Milford, was capped at 100 and the remaining scores scaled using the second highest score (of 55) for the region on the south east coast, south of Waterford as a maximum. (See appendix 1 for scaling method).

Temporal variation (imports per calendar month) in aquaculture imports was investigated in R. Results for Scotland, England and Wales, Northern Ireland and the Republic of Ireland are discussed separately as the data for these regions are from different sources.

iv. Natural dispersal

Prevailing Ocean currents around GB and Ireland were investigated and considered for their importance in the potential transport of NIS into GB and Ireland and between GB and Ireland. Ocean currents thought to have the potential to transport NIS into the pathway assessment area were selected (Figure 2). Coastal grid squares with increased probability of receiving an introduction of a NIS via transport by ocean currents from adjacent landmasses were then highlighted (Figure 2). To determine the relative likelihood of an introduction of a NIS into each coastal grid square (previously selected) being facilitated by ocean currents, the proximity of the grid square to the landmass from which the ocean current may transport the NIS was measured (in km) in ArcMap. These distances were scaled between 0 – 100 as for other pathways (see appendix 1) and a heat map drawn in ArcMap to indicate the relative likelihood of introduction of a NIS into coastal grid square being facilitated by ocean current.

Given that offshore structures may act as stepping stones and facilitate the introduction of NIS into coastal waters, the proximity of coastal grids to offshore structures was also examined as part of the natural dispersal pathway assessment. In addition to transport via ocean currents, it is possible that non natives could colonise offshore structures following release in ballast water or detachment from ship hulls. Introduction into coastal waters from offshore structures could also be aided by localised current and tidal movements in addition to ocean currents operating on a much larger scale. For these reasons, the proximity to offshore structures was determined for all coastal grids (not just those selected as likely to receive NIS via ocean currents). The number of windfarms
which are currently operating and windfarms which are under construction in close proximity to each coastal grid squares was determined. In addition, the number of offshore surface platforms associated with the oil and gas industry in close proximity to coastal grid squares was determined. (N.B. oil and gas wells in the coastal waters off the Republic of Ireland were used as a proxy for oil and gas platforms as this information was not available). Specifically, each coastal grid was given a score based on the total number of offshore structures in that coastal grid and the 8 coastal grids adjoining it (see appendix 2 for more details). The scores were scaled between 0-100 using the method detailed in Appendix 1. Note that the second highest score (43) was used as the maximum for scaling and the highest score (91) was capped at 100. The likelihood of introduction being facilitated by offshore structures is greatest for grids with higher scores. This is based on the assumption that the greater the number of offshore structures in close proximity of the coastal grid squares the greater the likelihood of them facilitating introduction of NIS into that coastal grid.

v. All pathways
A heat map was constructed to illustrate the relative intensity of activity of all pathways in each grid cell. Scores for coastal grid squares were calculated by taking the mean of scores for all pathways. At this point, all pathways were considered to be as important as each other in the introduction of NIS. The most likely method by which pathways could be ranked would be to determine how many NIS introductions the pathway has been associated with. It is, however, difficult to determine the exact pathway by which NIS have been introduced. Although there is much speculation within the scientific literature on how certain species have been introduced this is rarely based on more than circumstantial evidence. An alternative would be to rank pathways for each species, but would require considerable specific information on the species in question such as relative proximity, abundance at source point and chance of survival (such as reduced oxygen level tolerance in the case of ballast water). Much of this information is not currently available for NIS, making ranking of pathways through this process difficult to achieve. therefore, the scores for each pathway contributed equally to the final score for all pathways. The score were scaled between 0 and 100 as for individual pathways (see appendix 1 for more details).
Figure 2. Prevailing currents around and between GB and Ireland (Turrell 1992, OSPAR 2000). Bold current illustrations are those which may act to transport NIS into GB and Ireland from nearby landmasses (France) and between GB and Ireland. Hatched coastal grid squares are those predicted to be more likely to receive NIS following transport by ocean currents from neighbouring landmasses.
2.2 Non-Indigenous Species Introduction Risk Tool: Species’ Characteristics and Introduction Pathways

A range of NIS of potential threat to GB and Ireland were selected. Key characteristics of these species and the likely mechanism(s) by which these species may be introduced were then identified. In order to determine the relative importance of different species characteristics (waterborne, adhering, contaminating and food value) to the likelihood of their introduction by different mechanisms, a risk matrix was developed. Characteristics which increase the likelihood of introduction by specific mechanisms were given a score of 1, whereas characteristics which do not influence the likelihood of introduction by specific mechanisms were given a score of 0. The risk associated with specific characteristics was determined by calculating the number of introduction pathway mechanisms the species’ characteristic was considered important for. The overall risk of introduction (by any of the introduction pathways considered) for species exhibiting multiple important characteristics can be estimated by summing the relative risk score for each characteristic. Therefore NIS with high likelihood of introduction based on their characteristics will have an overall risk score of close to 1, whereas species with a lower likelihood of introduction will have a risk score of closer to 0.

2.3 Case Studies: Species’ Characteristics and Introduction Pathways

Using the NIS introduction risk tool, heat maps to indicate likelihood of introduction of species with each important characteristic into each coastal grid square in the pathway assessment areas were constructed. The heat maps were constructed using pathway intensity scores previously determined. For example, in order to construct a heat map to indicate the likelihood of introduction of a waterborne species into coastal grid squares, commercial shipping and natural dispersal pathway intensity scores were used. The mean score for these two pathways for each coastal grid was determined and the score scaled between 0 – 100 as for the pathway intensity heat maps (see appendix 1). This process was repeated for adhering species (using the commercial shipping, recreational boating, aquaculture and natural dispersal pathway intensity scores), contaminating species (using aquaculture pathway intensity scores) and species which have food value (also using the aquaculture pathway intensity scores).

In addition, four species were used as case studies to further demonstrate how the NIS introduction risk tool and the pathway intensity scores can be used together to determine the location of potential species introduction hotspots and the relative likelihood of introduction of
particular species into coastal grid squares. The four species were:

**The Chinese Mitten Crab - Eriocheir sinensis**

*Eriocheir sinensis* is a large crab with carapace length of up to 56mm. It is distinguished from other species by dense hair which is found at the base of the claws. This NIS is now established in and around the River Thames and the Humber. It has also been cited in other locations throughout England and Wales. This species of crab can have serious impact on marine and freshwater ecosystems where it predate and outcompetes native invertebrate and fish populations. During its breeding season it may also burrow into river banks, increasing erosion, river turbidity and causing the collapse of river beds. This species has a pelagic larval stage and is thought to have been introduced via transport in ballast water and natural dispersal on ocean current. It is also possible that *E. sinensis* has been introduced via the aquaculture pathway either through intentional release or by contaminating and going undetected in imported aquaculture products.

**The Slipper Limpet – Crepidula fornicata**

*Crepidula fornicata* is a gastropod mollusc. It is thought that this NIS was first introduced into Liverpool Bay and then into Essex over 100 years ago. Populations of *C. fornicata* are currently located along the south and south-east coast of GB in addition to South Wales, Northern Ireland and Scotland. This species outcompetes native filter feeding invertebrates and is considered a pest by oyster farmers as it disrupts settlement of oyster spat. It is thought that *C. fornicata* may have been introduced following its contamination of imported oysters. In addition, due to its ability to adhere, it may have been transported on ship’s hulls and due to its pelagic larval stage may also have introduced in ballast water.

**Wireweed – Sargassum muticum**

*Sargassum muticum* is a large brown seaweed. *S. muticum* is currently distributed along much of the coast of GB and Ireland including along the south coast of England, the Welsh Coast, the south-east coast of Scotland, the Isle of Man and the North coast of Ireland. It displaces native species by overgrowing and shading them. It also interferes with recreational water use when it forms large floating masses. It is thought that it was introduced into the marine waters of GB and Ireland following release of aquaculture stock which was contaminated with this species. In addition, this species has waterborne spores making introduction in ballast water possible. This species can also attach to surfaces and can float either as entire plant or following fragmentation making introduction via attachment to ships hulls or natural dispersal possible.
The carpet Sea Squirt – *Didemnum vexillum*

*Didemnum vexillum* is a tunicate which may form extensive thin sheets with pores and outgrowths present. It has been detected in a number of marinas around GB and Ireland. Including in North Wales, Devon, the Southampton area, North Kent, the Clyde and the east and west coast of Ireland. *D. vexillum* impacts native fauna by over growing them. Its occurrence in marinas and its ability to adhere to surfaces suggests that a major pathway of introduction is via recreational boating. It is also possible that this species was introduced with aquaculture stock which it may contaminate and go undetected in. Spores may also be taken up in ballast water, highlighting that this species may be introduced by this mechanism. In addition, colonies may raft and therefore introduction by natural dispersal via ocean current is a possible pathway of introduction of this NIS into GB and Ireland coastal waters.

These four species were selected as they are all considered high risk/high impact species (The Water Framework Directive Technical Advisory Group and Alien Species Group). In addition they represent 4 major NIS groups – crustacean, molluscs, seaweed and tunicates (respectively). They also have different characteristics and therefore different mechanisms of introduction associated with them, allowing for thorough application of the risk tool and the pathway intensity heat maps created in this report.

Risk scores were calculated for each of these species by combining individual scores from the risk matrix for each of the species characteristics. Potential pathways of introduction for each species, previously determined by consideration of their characteristics, were also highlighted. Heat maps were drawn for each species by combining intensity scores for pathways (previously determined) which the species may be introduced by. These heat maps enabled visualisation of introduction hotspots and the relative likelihood of introduction of these different species into coastal grid squares.

Species distribution maps for GB and Ireland were acquired from the NBN, via MarLIN (http://www.marlin.ac.uk/) for *E. Sinensis, C. fornicata, and S. muticum*. In addition, the current known locations of *D. vexillum* were plotted in ArcMap. Current known species distributions were examined and compared to species introduction heatmaps in order to further apply and validate the risk tool proposed in combination with the pathway intensity analysis.

### 2.4 Assessment of the Merit of a Risk Based Monitoring Strategy

In order to assess the relative merit of different monitoring strategies a mathematical simulation tool was developed. The simulation incorporated pathway intensity scores (presented previously in
heat map form) for each pathway separately and finally intensity scores for all pathways combined. All coastal grid scores were included in the simulation (153 grids in total). Those grid squares which had a pathway intensity score of 0 or did not receive any pathway activity were given a score of 100th the lowest (non zero) pathway intensity score to ensure that even grid squares considered very low risk were incorporated into the simulation.

A single introduction of a NIS into a coastal grid was simulated at random but weighted by intensity scores for the pathway. Therefore, the probability of a simulated introduction occurring in a coastal grid square with a relatively high pathway intensity score was greater than the probability of a simulated introduction occurring in a coastal grid square with a relatively low pathway intensity score. We assumed that on average, each coastal grid was visited once every two years. The simulation assumes no subsequent spread. The simulation was repeated 1000 times. Visits to coastal grids, reflecting different monitoring strategy approaches, were then simulated and the time elapsed before the site in which the introduction occurred is visited (time to detection) recorded.

Specifically, three different monitoring approaches were investigated:

1. **Non risk based (random) monitoring**: Coastal grids were visited at random. The probability of the grid being visited was independent of the pathway intensity score for that grid.

2. **Light risk based monitoring**: Coastal grid visits were weighted towards grids with relatively high pathway intensity scores. The number of visits per year will remain the same but as a result of the weighting of grid visits, grid squares with relatively high pathway intensity will be visited on average more than once every two years and grid squares with relatively low pathway intensity will be visited on average less than once every 2 years.

3. **Heavy risk-based monitoring**: Coastal grid visits are heavily weighted towards grids with a high pathway intensity score. Therefore, grid squares with high pathway intensity score will be visited on average much greater than once every two years and sites with low pathway intensity scores will be visited on average much less than once every two years.
3 Results

3.1 Introduction Pathway Assessment

3.1.1 Commercial Shipping

Ports within GB and Ireland have high connectivity with ports outside GB and Ireland by shipping traffic (Figure 3) with a total of 29,347 shipping voyages across 2,799 unique connections during February, April, June, August, October and December of 2012. GB and Ireland are well connected (Figure 4) with 6,483 voyages across 267 unique connections from GB into Ireland and 5,635 voyages across 272 unique connections from Ireland into GB. In addition there is shipping traffic into GB and Ireland from the Isle of Man. (While there is also shipping traffic into the Isle of Man, this data was not available from the dataset and therefore not included in this report). In total, 42,200 voyages across 3,386 connections were received into the pathway assessment areas.

The number of different ports outside the assessment areas which each GB and Ireland port receives shipping traffic from (the number of unique connections) throughout February, April, June, August, October and December of 2012 is highly variable and ranges between 1 and 142 (Figure 5, Figure 6). There are 7 ports which receive shipping traffic from over 100 different ports. These are Thames (receiving from 142 ports), Immingham (receiving from 133 ports), Liverpool (receiving from 130 ports), Belfast (receiving from 119 ports), Tees (receiving from 108 ports), Southampton (receiving from 103 ports) and Felixstowe (receiving from 102 ports). (N.B. a number of ports within the London Thames region occur in our shipping dataset. For example, ports in this area include; Thames, Thamesport, Sheerness, Ridham Dock, Gravesend, Cliffe and Tilbury).

The total number of voyages received by ports within GB and Ireland is also highly variable, ranging between 1 and 6,625 (Figure 7, Figure 8). There are 12 ports which receive greater than 1,000 shipping voyages in February, April, June, August, October and December of 2012. These are Dover (receiving 6,625 voyages), Dublin (receiving 2,977 voyages), Thames (receiving 2,759 voyages), Immingham (receiving 2,523 voyages), Liverpool (receiving 2,421 voyages), Felixstowe (receiving 1,550 voyages), Portsmouth (receiving 1,412 voyages), Larne (receiving 1,412 voyages), Belfast (receiving 1,382 voyages), Tees (receiving 1,281 voyages), Cairnryan (receiving 1,222 voyages), and Heysham (receiving 1,003 voyages).
Figure 3. Shipping connections into pathway assessment areas. (N.B the specific shipping route is not shown).
Figure 4. Shipping connections between ports in GB and Ireland. (N.B. the specific shipping route is not shown).
Figure 5. Shipping ports in GB and Ireland colour graded according to the number of unique connections they receive. Ports receiving traffic from >100 different ports are labelled.
Figure 6. The number of unique connections received by ports in GB and Ireland. (Only ports connected to >50 ports are presented).

The commercial shipping pathway heat map shows the relative intensity of pathway activity for each coastal grid square (Figure 9). Six coastal grid squares are highlighted as activity hotspots, i.e. where commercial shipping activity is very high. Activity hotspots are not found in Scotland or Wales. The London region grid square is an activity hotspot and has the highest score. The London region grid square contains 7 ports which receive traffic from 273 ports outside GB and receive 3,790 voyages. Other activity hotspots are coastal grid areas around Immingham, Dover, Tees, Dublin and Southampton. The Immingham area coastal grid square contains 2 ports which receive traffic from 167 ports and receive 2,918 voyages. The area around Dover contains 2 ports which receive traffic from 64 other ports and receive a total of 7,552 voyages. The Tees region coastal grid contains 5 ports which receive traffic from 237 ports and receive 2,034 voyages. The Dublin area coastal grid has the highest shipping activity score within Ireland, containing 3 ports which receive traffic from 124 ports and receive 3,140 voyages. The grid square in the Southampton region is also considered an activity hotspot relative to other coastal grid squares, and contains 5 ports which receive traffic from 224 other ports and receive 1,679 voyages.
Figure 7. Shipping ports in GB and Ireland colour graded according to the number of shipping voyages they receive. Ports receiving >1000 voyages are labelled.
There are a number of coastal grid squares which receive no shipping traffic in the 6 months of 2012 for which we have data. However, movements by smaller shipping vessels may not be included in the AIS dataset. It is therefore incorrect to assume that those grids highlighted as receiving no shipping traffic from the data used in this project will not receive a NIS by the shipping pathway, though clearly the likelihood of introduction by this pathway is much reduced compared to coastal squares receiving high volume of shipping traffic.

The port which is the origin of the greatest number of connections into ports in GB and Ireland is Rotterdam-Maasvlakte (connected to 82 ports) in The Netherlands (Figure 10). Also connected to over 50 ports in the pathway assessment areas are Helsinborg (connected to 56 ports) in Sweden, Vlissingen Stad (connected to 57 ports) in the Netherlands, Zeebrugge (connected to 58 ports) in Belgium, Ijmuiden (connected to 69 ports) in the Netherlands and Brunsbuettel (connected to 71 ports) in Denmark.

Twenty one ports source more than 1000 voyages into GB and Ireland ports (Figure 11). The top 5 ports from which the greatest number of voyages into GB and Ireland ports are received are; Calais in France (which 5,200 voyages come from), Rotterdam-Maasvlakte in The Netherlands (which 4,218 voyages come from), Dublin in ROI (which 1,991 voyages into GB come from), Zeebrugge in
Belgium (which 1,930 voyages come from) and Dunkerque in France (which 1,642 voyages come from).

By far the busiest shipping connection is between Calais and Dover (Figure 12, Table 4) with a total of 5,069 voyages in February, April, June, August, October and December of 2012. In addition, connections from Dunkerque (Dunkirk) to Dover, Holyhead to Dublin, Cairynryan to Larne, Larne to Cairynryan and Rotterdam-Maasvlakte to Felixstowe all have greater than 1000 voyages within the period we have data for.

The majority of shipping traffic into the pathways assessment area is by vessels ≥ 50m in length (Figure 13), with 38,962 voyages by vessels ≥ 50m compared to 3,238 voyages by vessels <50m. The number of voyages by both large and small vessels is greatest in August.
Figure 9. The commercial shipping pathway heat map showing the relative intensity of shipping activity for each coastal grid square.
Figure 10. Ports from which greatest number of connections with ports in GB and Ireland originate. (Only ports from which >30 connections into UK and Ireland ports originate are shown).

Figure 11. Ports from which the greatest number of voyages into ports in GB and Ireland originate. (Only ports from which >500 voyages into UK and Ireland ports originate are shown).
Figure 12. Shipping connections received by ports in GB and Ireland along which are the greatest number of voyages. (See Table 4 for connections details).

Table 4. Shipping connections received by ports in GB and Ireland along which are the greatest number of voyages. (See Figure 12 for the graphical representation of these data).

<table>
<thead>
<tr>
<th>Connection</th>
<th>From</th>
<th>To</th>
<th>Number of Voyages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CALAIS</td>
<td>DOVER</td>
<td>5069</td>
</tr>
<tr>
<td>2</td>
<td>DUNKERQUE</td>
<td>DOVER</td>
<td>1417</td>
</tr>
<tr>
<td>3</td>
<td>HOLYHEAD</td>
<td>DUBLIN</td>
<td>1307</td>
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<td>CAIRNRYAN</td>
<td>LARNE</td>
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</tr>
<tr>
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<td>LARNE</td>
<td>CAIRNRYAN</td>
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</tr>
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<td>FELIXSTOWE</td>
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<td>7</td>
<td>ROTTERDAM-MAASVLAKTE</td>
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<td>8</td>
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<td>THAMES</td>
<td>751</td>
</tr>
<tr>
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<td>OOSTENDE</td>
<td>RAMSGATE</td>
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<td>PORTSMOUTH</td>
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<td>ROSSLARE</td>
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<td>DOUGLAS</td>
<td>HEYSHAM</td>
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</tr>
<tr>
<td>20</td>
<td>ZEEBRUGGE</td>
<td>IMMINGHAM</td>
<td>328</td>
</tr>
<tr>
<td>21</td>
<td>ROTTERDAM-MAASVLAKTE</td>
<td>TEES</td>
<td>302</td>
</tr>
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</table>
3.1.2 **Recreational Boating**

The data received from the RYA highlights a total of 65 recreational cruising routes into GB from Europe and Scandinavia (Figure 14). Seven of these were considered to be used at high intensity, thirty nine at medium intensity and nineteen at low intensity. The majority of cruising routes into GB from outside GB and Ireland come from France. However, there are also cruising routes into GB from Portugal, Belgium, The Netherlands, Germany, Denmark, Sweden and Norway. Though it is clear from the RYA data that there are a number of cruising routes into Ireland from GB and the Isle of Man, detailed information regarding the cruising routes into Ireland from outside the pathway assessment areas was not available. However, discussion with experts in ISA highlighted that while it is rare to take direct routes into Ireland, avoiding stopping in South-East England, there may be a number of potential direct cruising routes from North-West France into South East ROI (Figure 14). As specific route information was not available the region which may receive recreational vessels following direct travel from North-West France is highlighted by the ellipse. Fifteen potential origins in France were highlighted, however this may be a conservative estimate and there may be more cruising routes into Ireland than considered in this study.
Figure 14. Recreational boating cruising routes into and between the introduction pathway assessment areas.

In total, 150 recreational cruising routes were present within the introduction pathway assessment area. 42 of these routes were estimated to be lightly used 99 were estimated to be used at medium intensity and 9 were considered to be heavily used. Heavily used cruising routes are from Northern France into the South of England and between Wales and Ireland. Medium and lightly used
routes are widespread around the coast of England and Wales and the East coast of Ireland, though as with heavily used routes, medium and lightly used routes are more concentrated around the south and west coast of England and the East coast of Ireland.

A heat map was created to illustrate the relative intensity of recreational boating activity (Figure 15). Based on the pathway intensity scores calculated, 7 coastal grid squares were considered activity hotspots and therefore may be more likely to receive an introduction of NIS as a result of the recreational boating activity relative to other grid squares. The hotspot grid squares within the UK are in the Bognor Regis region (with 7 medium intensity routes), Northern Ireland / South West Scotland region (with 6 medium intensity route and 2 light intensity routes), Dartmouth region (with 6 medium routes and 1 light intensity route), Holyhead region (with 5 medium intensity routes and 3 light intensity routes) the Southport/Blackpool region (with 6 medium intensity routes and 1 light intensity route) and the Southampton region (with 2 heavy intensity routes, 2 medium intensity routes and 1 light intensity routes). The highest scoring region is outside the UK on the coast of the Isle of Man with 14 medium intensity cruising routes and 3 light intensity cruising routes.

Recreational boating activity is greatest in the summer months. It is therefore likely that the risk of introduction of NIS via the recreational boating pathway will be greatest in the summer months and much reduced in the winter months.
Figure 15. The relative intensity of recreational boating pathway activity into coastal grids around GB and Ireland.
3.1.3 Aquaculture

The data indicates that in the year 2012, a total of 581 imports of shellfish were made into GB and Ireland. Of these, 455 imports were into aquaculture sites in the Republic of Ireland, 55 were into Scotland, 54 were into England and Wales and 17 were into Northern Ireland (pacific oyster only). Imports into Ireland were from France, Guernsey and England. Imports into GB were from Guernsey, Norway and Ireland.

Aquaculture activity hotspots, where the number of imports is relatively high compared to other regions, are located in Ireland (Figure 16). In total there are four coastal regions identified as activity hotspots. On the north coast, the region around Milford receives 90 imports and the neighbouring region around Cardonagh (covering both Northern Ireland and the Republic of Ireland) receives 47 imports. The region in the south east, south of Waterford receives 55 imports and the north-east region around Carlingford Loch (covering both Northern Ireland and Republic of Ireland) receives 48 imports.

The number of shellfish imports varies throughout 2012. The variation between months differs for each country/ region within the introduction pathway assessment areas for which data has been provided (Figure 17). Generally, the number of imports are less in winter months than in spring/summer months. The number of imports into England and Wales was greatest in July (15) and imports are received in all calendar months apart from December and January. The number of imports into Scotland was greatest in May (22). There were no imports into Scotland in January, February, March, November or December. The number of imports into Republic of Ireland was also greatest in May (132) and imports were received into the Republic of Ireland in every month of 2012. Imports into Northern Ireland are received in only 7 months of 2012 with the greatest number (4) received in May.

The majority of imports into England and Wales were Pacific Oyster (91%), with Abalone and Scallops also imported. While pacific oysters and scallops were imported into Scotland, the majority of imports were mussels (75%). Ninety eight percent of imports into the Republic of Ireland were Pacific Oysters with the remaining imports detailed being mussels. The data provided for Northern Ireland correspond to Pacific Oysters only.
Figure 16. The relative intensity of the aquaculture pathway in coastal grid cells in GB and Ireland.
3.1.4 Natural dispersal

There are a number of ocean currents which may act to transport NIS from France into GB and NIS between GB and Ireland. Two currents may facilitate the transport of NIS into GB. Current flow through the English Channel is in an easterly direction and may therefore transport NIS from the north coast of France into the south coast of England. In addition, current flowing northwards from Europe into the Celtic Sea has the potential to transport NIS from France into the south-west tip of England and South Wales. Currents flowing in an easterly direction between South Wales and the south coast of Ireland may also transport NIS from South Wales into Southern Ireland. The circular current located in the Irish Sea may also act to transport NIS in both directions between Ireland and GB.

Finally, the current flowing northwards from the north coast of Ireland into the west coast region of Scotland may facilitate the transport of NIS from Ireland into Scotland.
Coastal regions considered at greatest threat from the introduction of NIS by natural dispersal on ocean currents are therefore the south coast region of England and Wales, the south of Ireland and the west coast of Scotland. Hotspots of ocean current activity are located throughout all regions of concern with a high number of hotspots located on the south coast of England as a result of the close proximity to the French coast (Figure 18).

Figure 18. Relative likelihood of coastal grid (previously selected as likely to be influenced by ocean currents – see figure 2) receiving introduction of NIS facilitated by ocean currents. Scores are based on proximity to landmass from which ocean current is most likely to transport NIS.

The location of offshore platforms, namely windfarms and structures associated with the oil and gas industry was assessed as these may facilitate the introduction of NIS by natural dispersal.
Though there are currently large offshore wind farm areas in the pre planning stage the offshore wind farms areas currently operating or under construction are smaller in size (Figure 19). Those operating and under construction are located around the east coast of England, primarily in the south east, the north coast of Wales and the north-west coast of England and the north-east coast of Scotland.

Offshore platforms associated with the oil and gas industry are found around much of GB coast with clusters located around the coast of north Wales and North-West England, the east coast of England and to the north-east of Scotland (Figure 20). Oil and gas platforms are found further offshore than wind platforms, some being closer to the Scandinavian coastline than the coastline of GB. Oil and gas wells (a proxy for oil and gas platforms around the coast of the Republic of Ireland) are located around the majority of the coast of the Republic of Ireland and concentrated on the south-east coast (Figure 21).

Hotspot areas where the introduction of NIS is more likely to be facilitated by offshore structures than other areas are located on the east coast of England the coast around North Wales and North-East England (Figure 22). A total of 8 hotspot areas were identified with between 90 and 33 offshore structures located in close proximity. The scores for the coastal squares in the republic of Ireland are relatively high. However, as the data used for this was oil well location rather than platforms specifically these scores may be an overestimate.

The area around the north of Wales and the west of England has a high concentration of offshore structures which may aid the introduction of NIS on the prevailing current from Ireland. The likelihood of introduction of non natives via natural dispersal may therefore be considered high in this region.
Figure 19. Location of windfarms at different stages of operation and planning. Those which are currently operating and under construction are circled.
Figure 20. The location of offshore structures associated with the oil and gas industry. Structures marked include platforms, buoys, floating production storage and offloading units and terminals (UKOilandGasData.com).

Figure 21. The location of offshore oil and gas wells around the coast of the Republic of Ireland (Data from the Department of Communication, Energy and Natural Resources accessed through the Marine Atlas Viewer at http://atlas.marine.ie/, (2014)). These wells were used as a proxy for oil and gas offshore structures.
Figure 22. The relative likelihood that introduction of NIS into coastal grid squares around GB and Ireland will be facilitated by offshore structures.
3.1.5 All pathways

When activity by all introduction pathways was combined (by taking the mean of all individual introduction pathway scores for each grid), three general introduction pathway activity hotspots are highlighted (Figure 23). The coastal grid which has the highest score overall is in the south-east of England in the Dover area. The two other hotspots are outside the UK. The grid square which has the second highest score is on the east coast of Ireland, south of Waterford. Finally, the other activity hotspot is located around the Isle of Man. In addition to the three activity hotspots there are a number of regions which have intermediate to high pathway activity scores. For example, the south, east and north-west coast of England have many squares with intermediate or high pathway activity scores. In addition, coastal grids in the north-east, north-west and south-east of Ireland have intermediate and high pathway activity scores. However, the heat map for all pathways combined indicates that there is lower introduction pathway activity on the east coast of Scotland and the west coast of Ireland.
Figure 23. The relative intensity of all introduction pathway activity in coastal grids around GB and Ireland. Pathway intensity scores are means of all individual pathway intensity scores.
3.2 Non-Indigenous Species Introduction Risk Tool: Species Characteristics and Introduction Pathways.

A selection of NIS which are considered high risk and pose a threat to GB and Ireland were identified. These species are from a broad range of taxons. Key characteristics of these species which may be important for their introduction into GB and Ireland are indentified. In addition potential mechanisms of introduction, highlighted by several sources, are documented (Table 5). There are four main characteristics highlighted as associated with introduction. These are waterborne, adhering, contaminating and of food value. All but one of the species listed have more than one of these characteristics with some having all 4 of these characteristics. In addition, all but one species may be introduced by multiple introduction mechanisms, with many species having the potential to be introduced by commercial shipping, recreational boating, aquaculture and natural dispersal, all four pathways considered in this study. Although species are often defined as high risk based on their establishment and impact potential, it is clear from the table that many of the species considered here may also have a high likelihood of introduction given their characteristics.

A risk matrix was created in which introduction mechanisms were combined with species characteristics (Table 6). Scores were incorporated into the risk matrix to indicate which characteristics increase the likelihood of introduction of a species by each pathway mechanism (score is 1) and which characteristics do not influence the likelihood of introduction by each pathway mechanism (score is 0). For example, species which are waterborne in some form or have waterborne life history stages have an increased likelihood of introduction by commercial shipping, in ballast water and natural dispersal by ocean currents. The ability of a species to adhere to a surface is a characteristic which is important for mechanisms associated with all introduction pathways. Therefore, the risk of introduction of species which are adhering is greater than the risk of introduction of species which are waterborne. Specifically, assuming that all pathways are as important as each other for the introduction of NIS, a species which is adhering is twice as likely to be introduced than a species which is waterborne. Species which are contaminating and have food value are more likely to be introduced by the aquaculture pathway either accidently or intentionally respectively. Given that these characteristics are associated with only one introduction pathway, the risk score for species with these traits is less than for species which are waterborne or adhering.
Table 5. Identification of key characteristics and introduction pathways associated with NIS of threat to marine waters around GB and Ireland. (In addition to key references cited, other sources of useful information include: GB NIS secretariat (http://www.nonnativespecies.org/home/index.cfm), The marine life information network (http://www.marlin.ac.uk/) and references therein).
<table>
<thead>
<tr>
<th>Species</th>
<th>Common name</th>
<th>Taxon</th>
<th>Key species' characteristics</th>
<th>Potential mechanisms by which species is introduced</th>
<th>Key References</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Extended spawning period</td>
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<td></td>
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<td></td>
<td>• Benthic</td>
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<td></td>
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<td></td>
<td>• Waterborne/fragments</td>
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<td></td>
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<td></td>
<td>• Contaminating</td>
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<tr>
<td><em>Ruditapes philippinarum</em></td>
<td>Manilla clam</td>
<td>Mollusc</td>
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<td>• Intentional introduction for aquaculture</td>
<td>(Molnar et al. 2008)</td>
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<td></td>
<td></td>
<td></td>
<td>• Waterborne</td>
<td>• Natural dispersal</td>
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<td></td>
<td></td>
<td></td>
<td>• Contaminating</td>
<td>• Unintentional introduction via contamination of imported aquaculture products</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Economic/food value</td>
<td>• Ballast water</td>
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<td><em>Crassostrea gigas</em></td>
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<td>Mollusc</td>
<td>• Economic/food value</td>
<td>• Intentional introduction for aquaculture</td>
<td>(Eno et al. 1997, Minchin 2007, Molnar et al. 2008)</td>
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<tr>
<td></td>
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<td></td>
<td>• Waterborne</td>
<td>• Natural dispersal</td>
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<td></td>
<td>• Contaminating</td>
<td>• Unintentional introduction via contamination of imported aquaculture products</td>
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<td>• Adhering</td>
<td>• Ballast water</td>
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<td>• Benthic</td>
<td>• Biofouling</td>
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<td></td>
<td>• Economic/food value</td>
<td>• Unintentional introduction via contamination of imported aquaculture stock</td>
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<td></td>
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<td>• Contaminating</td>
<td>• Natural dispersal/migration</td>
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<tr>
<td><em>Didemnum vexillum</em></td>
<td>Carpet Sea squirt</td>
<td>Tunicate</td>
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<td>• Unintentional introduction via contamination of imported aquaculture stock</td>
<td>(Minchin 2007, Molnar et al. 2008)</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>• Waterborne/fragments</td>
<td>• Biofouling</td>
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<td></td>
<td>• Contaminating</td>
<td>• Natural dispersal</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>• Ballast water</td>
<td></td>
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<tr>
<td>Species</td>
<td>Type</td>
<td>Characteristic</td>
<td>Introduction Mechanisms</td>
<td>Source(s)</td>
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<tr>
<td><em>Rapana venosa</em></td>
<td>Mollusc</td>
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<td>• Ballast water • Unintentional introduction via contamination of aquaculture stock</td>
<td>(Kerckhof et al. 2006, Molnar et al. 2008)</td>
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<td>• Biofouling • Ballast water • Natural dispersal</td>
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<td>• Adhering</td>
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<tr>
<td><em>Crepidula fornicata</em></td>
<td>Mollusc</td>
<td>• Contaminating</td>
<td>• Unintentional introduction via contamination of aquaculture stock</td>
<td>(Eno et al. 1997, Minchin 2007, Molnar et al. 2008)</td>
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<tr>
<td></td>
<td></td>
<td>• Waterborne</td>
<td>• Biofouling • Ballast water • Natural dispersal</td>
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<tr>
<td></td>
<td></td>
<td>• Adhering</td>
<td></td>
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<tr>
<td><em>Caprella mutica</em></td>
<td>Crustacea</td>
<td>• Adhering</td>
<td>• Biofouling • Unintentional introduction via contamination of aquaculture stock</td>
<td>(Willis et al. 2004)</td>
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<td></td>
<td></td>
<td>• Contaminating</td>
<td>• Ballast water • Natural dispersal</td>
<td></td>
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<tr>
<td><em>Mnemiopsis leidyi</em></td>
<td>Jellyfish</td>
<td>• Waterborne</td>
<td>• Ballast water</td>
<td>(Fasse and Bayha 2006, Molnar et al. 2008)</td>
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<td><em>Microsporangium globosum</em></td>
<td>Algae</td>
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<td>• Ballast • Unintentional introduction via contamination of aquaculture stock</td>
<td>(Molnar et al. 2008)</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>• Contaminating</td>
<td>• Natural dispersal</td>
<td></td>
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<td><em>Charybdis japonica</em></td>
<td>Crustacea</td>
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<td>• Ballast water • Biofouling</td>
<td>(Molnar et al. 2008)</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>• Contaminating</td>
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</table>

Table 6. Introduction risk tool matrix detailing the relative importance of species characteristics for introduction mechanisms associated with key pathways. A score of 1 means that presence of the characteristic increases the risk of introduction by the specific introduction mechanism. A score of 0 means that presence of the characteristic does not impact on the risk of introduction by the specific introduction mechanism. Total risk scores indicate the overall risk of introduction by all mechanisms associated with each species characteristic. To calculate the overall risk associated with a species exhibiting multiple characteristics the total relative score for each characteristic can be summed.
(N.B It is assumed that each pathway mechanism is equally as likely to result in an introduction of NIS).

<table>
<thead>
<tr>
<th>Introduction pathway</th>
<th>Pathway mechanism</th>
<th>Characteristic</th>
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<tbody>
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<td></td>
<td>Biofouling</td>
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</tr>
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<td>Recreational boating</td>
<td>Biofouling</td>
<td>0</td>
</tr>
<tr>
<td>Aquaculture</td>
<td>Unintentional</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>(contamination)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intentional</td>
<td>0</td>
</tr>
<tr>
<td>Natural dispersal</td>
<td>Ocean current</td>
<td>1</td>
</tr>
</tbody>
</table>

| Total Score          | 2/6                  | 4/6        | 1/6      | 1/6           | 0.33       | 0.67       | 0.167     | 0.167       | 0.25       | 0.5        | 0.125     | 0.125     |

3.3 Case Studies: Species Characteristics and Introduction Pathways.

Using the pathway intensity scores and the risk tool, the likelihood of introduction of species with certain characteristics into coastal areas around GB and Ireland can be determined. The likelihood of introduction heatmap for species which are waterborne was constructed by combining the commercial shipping pathway intensity scores with the natural dispersal pathway intensity scores for each coastal grid (Figure 24). Hotspots of introduction for waterborne species are the regions around Southampton, Dover and Immingham. The likelihood of introduction of adhering species into coastal grid squares can be determined by combining intensity scores for all pathways considered in this study (Figure 25). Hotspots of introduction for species which are adhering are in the regions around Dover, Isle of Man and in South-East Ireland, south of Waterford. Areas where the likelihood of introduction is generally high for species which are waterborne or adhering are around the east, south and north-west coast of England the west coast of Scotland and the east and south-west coast of Ireland. The likelihood of introduction of species which are both contaminating (Figure 26) and have food value (Figure 27) can be estimated using the intensity scores for the aquaculture pathway. Therefore for species which are either contaminating or have food value or have both
characteristics, areas where introduction is most likely are located in Ireland, specifically in the north around Milford, Cardonagh and Carlingford loch and on the south-east coast, south of Waterford.

Figure 24. Likelihood of introduction of waterborne species into coastal grid squares around GB and Ireland. Scores are based on the intensity of the commercial shipping pathway and the natural dispersal pathway.
Figure 25. Likelihood of introduction of species which are adhering into coastal grid squares around GB and Ireland. Scores are based on the intensity of all four introduction pathways.
Figure 26. Likelihood of introduction of contaminating species into GB and Ireland. The scores are based on the intensity of the aquaculture pathway.
Figure 27. Likelihood of introduction of species which have food value into coastal grid squares around GB and Ireland. Scores are based on the intensity of the aquaculture pathway.
The risk matrix and pathway intensity scores can also be used to determine the likelihood of introduction of specific species, which may have more than one of the characteristics presented in the risk matrix. Four species; *E. sinensis*, *C. fornicate*, *S. muticum* and *D. vexillum* were used as case studies to illustrate the use of the introduction risk tool in combination with the introduction pathway intensity analysis to inform the likelihood of introduction of these species into different coastal regions of GB and Ireland. The risk scores were calculated for each species using the risk matrix (Table 7). In addition, the introduction pathways which are likely to be important based on the species characteristics are listed.

Based on its characteristics *E. sinensis* has the lowest risk score (0.5) and is likely to be introduced by three out of the four pathways considered; commercial shipping, aquaculture and natural dispersal. *E. sinensis* does not have the ability to adhere to surfaces and is therefore unlikely to be introduced by the recreational boating pathway. *C. fornicate*, *S. muticum* and *D. vexillum* all have the same risk score of 0.875 and based on their characteristics, are likely to be introduced by all four pathways considered in this study.

Species heat maps were created using the introduction pathway intensity scores previously calculated. For *E. sinensis* the heat map was constructed by combining intensity scores for the commercial shipping pathway, the aquaculture pathway and the natural dispersal pathway (Figure 28). From this heat map it is clear that there are two regions into which *E. sinensis* is most likely to be introduced, based on the analysis conducted. These are the Dover region and the region in south-east Ireland, south of Waterford. *E. sinensis* was thought to be first introduced into the Thames region around 1935 and then subsequently into the Humber region. The heat map for *E. sinensis* shows intermediate likelihood of introduction in the Thames region and a hotspot of introduction in the Humber catchment region around Immingham. The map detailing the distribution of *E. sinensis* (Figure 29) highlights that in addition to colonisation of the Thames and Humber catchment region there are also colonies in East Anglia, around Liverpool and North Wales and also around Tees and Southampton. While it is not clear whether these colonies are the consequence of introductions or subsequent spread following introduction elsewhere, the heat map for the likelihood of introduction does indicate, that according to our analysis, these areas have an intermediate or high likelihood of introduction of *E sinensis*. However, while there the heat map indicates that the region on the south east corner of Ireland is an introduction hot spot for *E sinensis*, there is no data to support the presence of *E sinensis* in this region.
Table 7. Calculation of introduction risk scores for four case species using the introduction risk tool matrix. Important species characteristics were identified and the scores for these characteristics read from the risk matrix. Overall species scores were then determined by addition of scores associated with species characteristics. Using the risk matrix for reference, the introduction pathways associated with species characteristics were also listed.

<table>
<thead>
<tr>
<th>Species</th>
<th>Important Characteristics</th>
<th>Characteristic score (from risk matrix)</th>
<th>Overall Species score (based on all characteristics)</th>
<th>Important pathways (based on characteristic)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Eriocheir sinensis</em></td>
<td>Waterborne</td>
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<td>0.5</td>
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</tr>
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<td></td>
<td>Contaminating</td>
<td>0.125</td>
<td></td>
<td>Aquaculture</td>
</tr>
<tr>
<td></td>
<td>Economic/food value</td>
<td>0.125</td>
<td></td>
<td>Natural dispersal</td>
</tr>
<tr>
<td><em>Crepidula fornicata</em></td>
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<td>0.25</td>
<td>0.875</td>
<td>Commercial shipping</td>
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<td>Adhering</td>
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<td>Recreational boating</td>
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<td>Contaminating</td>
<td>0.125</td>
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<td>Aquaculture</td>
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<td>Natural dispersal</td>
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<tr>
<td><em>Sargassum muticum</em></td>
<td>Waterborne</td>
<td>0.25</td>
<td>0.875</td>
<td>Commercial shipping</td>
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<tr>
<td></td>
<td>Adhering</td>
<td>0.5</td>
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<td>Recreational boating</td>
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<td><em>Didemnum vexillum</em></td>
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<td>0.875</td>
<td>Commercial shipping</td>
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<td></td>
<td></td>
<td></td>
<td>Natural dispersal</td>
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</table>
Figure 28. The likelihood of introduction of *E. sinensis* into coastal grid squares around GB and Ireland.
Figure 29. The distribution of *E. sinensis* (NBN via MarLIn - http://www.marlin.ac.uk/).

A heatmap was also constructed for *C. fornicata*, *S. muticum* and *D. vexillum* as all three species are likely to be introduced by all four pathways considered in this study. The areas of high risk of introduction are those areas where the intensity of all pathways is high. These are in the Dover area, the south-east of Ireland, south of Waterford and around the Isle of Man.

The first *D. vexillum* colony was found in Holyhead marina in North Wales in 2008 (Griffith et al. 2009). From photographic evidence taken in 2005, *D. vexillum* was also suspected in Dartmouth area. The presence of *D vexillum* in this area was confirmed in 2009 (Griffith et al. 2009). The heat map for *D vexillum* introduction (Figure 30) does not indicate either the Holyhead region or the Dartmouth region as an introduction hotspot. However, these initial introductions were found in marinas and thought to be the consequence of the recreational boating pathway. The Holyhead
Figure 30. Likelihood of Introduction of *D. vexillum, S. muticum and C. fornicata* into coastal grid squares around GB and the Ireland.

area and the Dartmouth area are both hotspots of recreational boating activity (Figure 15). The current distribution of *D. vexillum* is shown in Figure 31. The locations of this species does not
coincide with introduction hotspots identified in the *D. vexillum* heatmap, though many colonies are located in regions which have intermediate to high likelihood of introduction. It is not certain whether the current locations beyond Holyhead and Dartmouth are the consequence of spread. If this is the case we would not expect a correlation between the distribution of this species and the likelihood of introduction scores.

*S. muticum* was first found in the Isle of Wight and then subsequently identified in a number of locations including the Isles of Scilly, the south coast of England, the north Cornish coast, Welsh coast and the Isle of Man in addition to many locations along the coast of Ireland and the south-west coast of Scotland (Figure 32). Colonies are found in 2 regions highlighted on the heat map as introduction hotspots for this species (Figure 30), namely the Dover region and the Isle of Man. It is

![Figure 31. The distribution of *D. vexillum*.](image)
not known whether the colonies in these two regions are the consequence of introductions or subsequent spread following previous introductions elsewhere. While our analysis suggests that these colonies may be the results of introductions; without conducting analysis on

Figure 32. Distribution of *S. muticum* (NBN via MarLIN - http://www.marlin.ac.uk/).

the spread of this species, this is an assumption. The primary route by which the initial introductions of *S. muticum* where thought to occur is contamination of aquaculture stock, namely oysters.
However, there does not seem to be clear correlation between the heat map illustrating the intensity of the aquaculture pathway activity (Figure 16) and the distribution of *S. muticum*.

*C. fornicata* was thought to be first introduced into the Liverpool region where the colony later died out and then subsequently into the Essex region. Although the heatmap for the likelihood of introduction of this species does not indicate that the Essex region is a hotspot of introduction this region does have an immediate score for the likelihood of introduction of *C. fornicata*. In addition although it is uncertain as to whether the colonies of *C. fornicata* located outside Essex (Figure 33) are the consequence of introduction or subsequent spread, the distribution is correlated with regions of high to intermediate likelihood of introduction.

Figure 33. Distribution of *C. fornicata* (NBN via MarLIN - http://www.marlin.ac.uk/).

### 3.4 Assessment of the Merit of Risk Based Monitoring
The results of the simulation show that NIS may be detected more quickly with risk based monitoring than with random, non risk based monitoring (Figure 34). However, the results of the simulation clearly demonstrate that by focusing too much on high risk areas (heavy risk based monitoring), it may take longer to detect an introduced NIS and the probability of detecting an introduction within a certain time frame is reduced. The consequence of increasing the frequency of visits to high risk sites is that visits to low risk sites are less frequent or excluded. In the event of an introduction to a low risk site, detection using a monitoring strategy heavily focused on high risk sites would take a long time or, if the site is not visited under this strategy, the introduction may go completely undetected. It is therefore clear that the most effective monitoring approach will be a balance between increasing frequency to high risk sites while maintaining visits to low risk sites to avoid an introduction, if at a low risk site, going undetected.

The time to detection for all monitoring approaches varies for simulations for the different pathways considered. It is likely that this is due to the variation in the distribution of pathway activity intensity scores between each pathway (Figure 35). For pathways which have few high and few intermediate pathway intensity scores, with most scores being very low, the advantage of risk based monitoring is greater. For example, for the commercial shipping pathway there is a 90% chance of detecting a NIS in less than one year using light-risk based surveillance whereas there is only a 50% chance of detecting an introduction using a random, non risk based approach. For this pathway there are very few high scoring and intermediate scoring grid squares. However, considering the detection of NIS into grid squares based on the number of offshore structures in close proximity, the relative merit of risk based, while still clear, is smaller. There is only a 20% increase in probability of detection with light risk based monitoring compared to non risk based monitoring in the first year following an introduction. This is likely the consequence of the greater number of coastal grid squares with intermediate scores relating to offshore structures, where introduction may occur but where risk based monitoring will not focus.

The simulation conducted on scores for all pathways combined further illustrates this point. There are very few high scoring grids but a number of grids with intermediate scores. So, while introduction into intermediately scoring grid squares is possible, light risk based monitoring will not focus on these and therefore will only slightly increase the probability of detecting an NIS following introduction compared to non risk based monitoring.
Figure 34. Monitoring simulation model results. Comparison of time taken to detect a NIS following introduction using random, non risk based monitoring (solid line), light risk based monitoring (dashed line) and heavy risk based monitoring (dotted line). Each plot illustrates model outputs based on introduction scores determined previously for each introduction pathway.
Figure 35. The distribution of pathway intensity scores (determined previously) on which the monitoring simulation for each pathway is based.
4 Discussion

4.1 How does this work aid in developing risk based monitoring and measures?

The results from this study will aid in the development of a risk based approach to the management of NIS in the marine environment. A risk based approach to monitoring is proposed in the indicators developed for descriptor 2 of the MSFD, and is generally considered the most cost effective means of implementing monitoring programmes. Targeted monitoring at locations where introductions are most likely to occur will increase the speed and probability of detection of NIS. This will facilitate rapid response allowing for control/eradication measures to be implemented before further spread can occur. This study will aid in developing a risk based approach to the delivery of descriptor 2 through the following outputs:

- The pathway assessment provides a quantified method that identifies areas at high risk from introduction of NIS through the main pathways and vectors. Through this process high risk locations have been identified for each individual pathway in addition to all pathways combined. These high risk locations should be the focus for future monitoring and measures programmes. Using the process developed, an summary of locations at high risk of introduction is presented in appendix 3 in relation to the development of a monitoring programme for the UK.

- A simple tool has been developed using species characteristics allowing for the estimation of points of introduction for specific species. In combination with a target species list this provides a mechanism by which high risk locations for individual species can be identified. This facilitates the identification of locations where targeted monitoring for individual species can be focused. This will be important in ensuring that monitoring conducted in a location will be capable of detecting species that are most likely to be introduced there. This tool will be of use when dealing with rapid responses to new introductions and horizon species (i.e. species not yet found within the UK). For example with the introduction of a new species into the UK this tool can be used to identify locations where additional monitoring should take place as part of the rapid response process.

- The monitoring simulation developed in this study provides clear evidence that a risk based approach to monitoring is most beneficial in reducing time to detect NIS at points of introduction. Although the simulation demonstrates that monitoring should also be conducted at locations at low risk of introduction as well, but with a lower frequency than monitoring a high risk locations.
The following sections provide a critic and further explanation of the main findings of this report.

4.2 Introduction Pathway Assessment

The introduction pathway assessment and construction of heatmaps undertaken in this report enables the relative intensity of pathway activity between coastal grid squares to be visualised and the location of pathway activity hotspots to be highlighted. Although scores are scaled between 0 and 100 for all pathways, comparison of activity intensity scores between pathways is problematical given that the same score may represent a different level of activity for each pathway and scores are based on data of different resolution. For example, a score of 100 for the commercial shipping pathway represents much higher activity than a score of 100 for the recreational boating pathway. In addition, the commercial shipping data represents actual shipping traffic whereas the recreational boating data is only indicative of recreational cruising routes and their intensity. So, while combining intensity scores for multiple pathways enables general examination and indication of the activity coastal areas experience from multiple pathways, a more accurate appreciation of pathway intensity is gained from individual pathway intensity scores and heat maps.

Analysis and consideration of temporal variation in pathway intensity was conducted where data allowed and information was available. This highlighted that different pathways may show different levels of temporal variation. For example, our analysis indicates that variation in commercial shipping activity is likely to be less than variation in recreational boating activity throughout the year. Temporal variation in pathway activity will result in different pathway intensity scores at different times of the year therefore altering the likelihood of introduction by that pathway at different times of the year. This will have important implications, for example, when developing the most cost effective monitoring strategy for NIS.

The pathway intensity scores estimated in this study are based on data acquired. While every effort was made to acquire as much information as possible, additional information may be available which could further inform pathway intensity scores and the likelihood that a pathway will result in an introduction of a NIS. For example, for the commercial shipping and recreational boating pathway it is likely that the time in mooring, at both origin and destination, will impact on the likelihood of introduction of a NIS (Ashton et al. 2006). In addition, the presence of a NIS at the pathway origin will influence how likely it is that pathway activity will result in an introduction of a NIS. With increasing levels of monitoring for marine NIS (specifically within EU Member States under the MSFD) this information will be more readily available and its incorporation into further introduction pathway activity analysis will strengthen the assessment of risk.
The data used in this study is for the year 2012. When the project commenced (in 2013) 2012 was the most recent year for which data was complete and available. It is unknown whether the pathway activity and temporal variation in activity demonstrated in 2012 is typical of other years. A more robust analysis of pathway intensity would incorporate multiple years. Analysis of multiple years may also enable extrapolation in order to make predictions about likely future activity. However, caution needs to be exercised when extrapolating data. Although it is likely that activity associated with commercial shipping and recreational boating will remain largely consistent throughout coming years the risk associated with these pathways may change. For example, if the International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM) is implemented, the likelihood of introduction of NIS associated with commercial shipping may be reduced even if the activity of this pathway remains the same. The incorporation of biosecurity/mitigation into the model will be an important element of future risk analysis. It is also possible that activity associated with the aquaculture pathway may change markedly for example, as a result of shellfish farm site openings or closures, breakdown of links with colleagues from which sites are importing and the formation of new import connections. It is thought that offshore structures may aid the introduction of NIS into coastal waters by providing stepping stones to reduce the distance required to travel on ocean currents (Page et al. 2006, Wilhelmsson and Malm 2008). Renewable energy is topical and investment in this form of energy may increase over coming years resulting in an increase in offshore structures and therefore a change in scoring associated with the number of offshore structures located in close proximity to coastal regions around GB and Ireland.

This study has provided an assessment of NIS introduction pathway activity intensity in coastal grid squares around the coast of GB and Ireland. The data on which the assessment is based is from a range of sources and is of highest quality available. This assessment will be valuable in the development and implementation of a monitoring programme and programme of measures to reduce the impact of NIS. However, it is clear that to improve the accuracy and maintain the application of the pathway assessment conducted here, new data should be incorporated into the assessment as it becomes available and pathway intensity scores updated accordingly.

4.3 Non-Indigenous Species Introduction Risk Tool: Species Characteristics and Introduction Pathways

This project involved the development of a simple tool, which in combination with pathway intensity scores, allows quick assessment of the likelihood of introduction of species into different locations based on specific, easily identified characteristics. This tool requires no expert knowledge of
taxonomic classification or physiological and behavioural characteristics making it widely accessible and easily applied.

The tool was applied to four case study species; *Eriocheir sinensis*, *Crepidula fornicata*, *Sargassum muticum* and *Didemnum vexillum*. The correlation between current distribution of these species, with focus on the first known sites of introduction, and the heatmaps indicating the relative likelihood of introduction of these species into different coastal regions was examined. While some correlation was seen, most species were distributed outside the coastal areas considered to be high risk based on the species characteristics and the intensity of the activity of pathways associated with these characteristics. There are a number of reasons for this. It is likely that many of the species colonies are the result of subsequent spread following initial introduction and therefore would be correlated with spread pathway activity rather than introduction pathway activity. In addition, colonies may be the result of historic introductions. Therefore examining correlation between areas predicted to have a high likelihood of introduction based on pathway activity in 2012 and species distributions will be problematic as at the time of initial species introductions the pathway activity may have been markedly different. Validation of the species risk assessment tool may therefore not be possible using species distribution data. Assessment of correlations between future introductions and maps indicating the likelihood of introduction of that species into coastal regions may be more beneficial than the assessment of correlations between historic introductions and likelihood of introduction scores estimated in this study.

For each of the four case study species, the likelihood of introduction into coastal grids was displayed in one heatmap based on combined intensity scores for the different introduction pathways linked to characteristics of the species. It is possible that some pathways are more important for the introduction of species than others. This may be confounded by combining multiple pathways into one heat map to illustrate the likelihood of introduction of that species into coastal areas. So, while a single heat map provides a general overview of areas where the species are more likely to be introduced than others, it may be advantageous to examine individual heatmaps for each introduction pathway linked to the species. Further examination of evidence to support a greater role of certain pathways for species introduction compared to other pathways may enable pathways to be weighted according to their importance. Literature searches will provide information on the pathways associated with previous introduction of specific NIS. However, weighting the importance of introduction pathways, based on pathways associated with previous introductions has limitations as future introductions may be facilitated by a different pathway. In addition, the availability of irrefutable evidence demonstrating that a particular species has been introduced by a specific pathway or pathways is rare. In the majority of cases where the introduction of a species is accredited to a pathway it is through supposition and professional judgement. As a
result of the analysis of pathway activity undertaken in this study it may be possible to make some predictions about the relative importance of different pathways in the introduction of NIS which can then be applied across different species. Both the commercial shipping and recreational boating pathway are associated with introduction of adhering species. Based on the volume of traffic, the level of connectivity between ports and the larger surface area of commercial ship hulls, it is possible that commercial shipping is more important than recreational boating, for the introduction of adhering NIS. However, recreational boating vessels may be moored for longer than commercial shipping vessels, increasing the likelihood of attachment of NIS at origin and detachment of NIS at destination. Also, recreational cruising vessels travel slower than commercial shipping vessels thereby reducing the probability of the attached species becoming detached before reaching the destination. It is clear that weighting introduction pathways is a complicated process and requires consideration of a large number of variables, some of which would be impossible to quantify (i.e. time spent in port by recreational vessels). In this study we weight all introduction pathways associated with the characteristics of each species equally. We do this to provide a conservative estimate of likelihood of introduction and avoid the risk of weighting different pathways wrongly and miscalculating areas associated with high likelihood of introduction. With further information relative weightings may be adjusted.

Additional species information may increase the applicability of the NIS introduction risk tool developed. It is possible that additional high quality data may become available with the intervention of NIS monitoring and management programmes required by all member states under the MSFD. For example, monitoring programmes may provide information on the location of NIS populations outside the pathway assessment areas. These species locations could be incorporated as high risk origins and focus the assessment of introduction hotspots, with movements into regions from origins where the species has been identified, highlighted as increased risk.

4.4 Non-Indigenous Species Monitoring simulation

The results of the monitoring simulation highlight that risk based monitoring is advantageous for the detection of NIS. Specifically, the model output suggests that the time taken to detect a NIS introduction is reduced under a light risk-based monitoring programme compared to a random, non risk based monitoring programme. Crucially, the simulation outputs also indicate that focusing too strongly on high risk sites (those which have high pathway intensity scores) may increase the time taken to detect an introduction and reduce the probability of detecting an introduction within a given time frame.

Monitoring and early detection is fundamental to the management and control of NIS. The results of this study can be used to aid development and implementation of an initial monitoring
programme. Outputs from the model simulation highlight that a monitoring programme which includes more frequent monitoring at high risk sites with less frequent monitoring at low risk sites, but crucially, includes monitoring of all sites will be optimum for the early detection of NIS.

Pathway activity intensity scores are incorporated into the simulation so that the simulation results are directly dependent on the pathway intensity scores calculated in this study. As discussed previously, there may be limitations associated with the data used to estimate the pathway intensity scores. As pathway intensity scores are updated, the simulation should be repeated and conclusions drawn from simulation outputs fed back into monitoring programme development and improvement.

Optimisation of NIS monitoring will enable maximum utilisation and benefit from available resources. As discussed previously, results from this study suggest that risk based monitoring may act to optimise the detection of NIS. Additional results from this study may also inform further optimisation of a monitoring strategy by enabling monitoring for species with specific traits to be focused on in particular locations. For example, monitoring in areas with high recreational boating activity should be focused on species which are adhering. Temporal analysis conducted in this study highlights that optimisation of a monitoring programme may also involve varying monitoring effort through the year. For example, monitoring programmes developed to detect introduction of NIS by the recreational boating pathway may benefit from being down regulated in the winter and spring and up regulated in the summer and autumn in accordance with an increase in recreational boating activity. In contrast, monitoring for species which are likely to be introduced by commercial shipping should be undertaken at the same rate throughout the year.

4.5 Conclusions and Future Directions

Following estimation of introduction pathway activity, this study has highlighted coastal areas where the activity of pathways associated with introduction of NIS is high. In addition, this study has proposed an introduction risk tool which can be used in addition to the pathway assessment to determine the likelihood of introduction of species, based on their characteristics into different coastal regions around GB and Ireland. Finally, a mathematical modelling approach was taken to investigate the relative merit of risk based monitoring compared to non risk based monitoring.

Clearly, taken together, the result of this study will be essential for the development and implementation of a risk based monitoring and measures programme aimed at the management of NIS. A dynamic approach to pathway assessment using additional and updated information will enable regular refinement and optimisation of an NIS monitoring strategy. As additional information
becomes available on global distribution of NIS it would be possible to factor this information into the assessment of risk. For example, the recent introduction of the Asian shore crab (*Hemigrapsus sanguineus*) into the UK may have occurred through a number of pathways, such as ballast water, natural dispersal and movement of aquaculture animals. Considering the species native range (Western Pacific Ocean from Russia, along the Korean and Chinese coasts, to Hong Kong, and the Japanese archipelago) ballast water would be considered the most likely route of introduction into the UK. Populations of Asian shore crabs, however, are found in mainland Europe (including the French Atlantic coast in addition to the Netherlands and Germany) from which the UK receives shellfish and is in close proximity. It is therefore more likely that this species was introduced as a result of aquaculture movements or natural dispersal than ballast water movements. A more species specific method of assessing risk will be facilitated by knowing current distribution in relation to pathway intensity. In addition, incorporation of bio security and mitigation measures and interventions into pathway assessment will be required in the future to provide the most accurate assessment of NIS introduction risk into coastal areas. For example, implementation of the ballast water convention may have a significant impact on the location of high risk areas of introduction by the commercial shipping pathway. The present study weighted the risk of introduction associated with each introduction pathway equally. While this approach provides a conservative estimate of likelihood of introduction and prevents the miscalculation of risk, more detailed information regarding the relative contribution of different pathways to specific species introductions will allow weightings to be incorporated into the assessment of high risk locations in the future.

The focus of this study was assessment of pathways associated with the introduction of NIS, however, to aid a more accurate understanding of the threat posed by NIS to coastal waters around GB and Ireland it is necessary to consider the subsequent spread of NIS. Future work should therefore aim to acquire detailed information regarding pathways which may contribute to the spread of NIS and identify areas of where activity which may contribute to the spread of NIS is high. Without detailed information regarding potential pathways by which NIS are likely to be spread it is unclear whether areas where the likelihood of introduction of NIS is low are also areas where, given an introduction, the likelihood of spread is high, something which has implications for the monitoring and management of NIS.
References


International convention for the safety of Life at Sea (SOLAS). 1974 Chapter 5.


Appendix 1 – Score Scaling Method

Scaling of pathway activity intensity scores and likelihood of introduction scores to 0-100:

Scaled $x_i = \left( \frac{x_i - X_{min}}{X_{max} - X_{min}} \right) \times 100$

Where:

$x_i$ = the variable $x$ in the $i^{th}$ row.

$X_{min}$ = the minimum value of the variable $X$.

$X_{max}$ = the maximum value of the variable $X$.

Note on $X_{max}$:

Where the maximum unscaled score is much higher than the second highest unscaled score, the second highest unscaled score was used as $X_{max}$ and the highest score capped at 100. This approach was taken in order to avoid over influence of the maximum value (an outlier) on the scaled pathway activity intensity scores and likelihood of introduction scores for coastal grid squares.

For example, for the commercial shipping introduction pathway the distribution of unscaled pathway activity intensity scores is shown in Figure A 1.
Figure A 1. The distribution of unscaled activity intensity scores for the commercial shipping pathway.

The highest unscaled score is 1034670 and the second highest unscaled score is 487360. The score of 1034670 was capped at 100 and the scaled score for other coastal grid squares calculated by using $X_{\text{max}} = 487360$. 
Appendix 2 – Method to Calculate the Number of Offshore Platforms in Close Proximity.

Method to determine the likelihood of introduction of NIS into grid square being facilitated by offshore structures (section 2.1.4).

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Offshore structure count given to cell x (hatched) is the sum of the number offshore structures in cell x, a, b, c, d, e, f, g, and h.

N.B. offshore platforms in cells which are on opposite coastlines are not counted (Figure A 2).
Figure A2. Example to show how offshore structures in grids which are not on the same coastline as grid X are excluded in the count for grid X.
Appendix 3- Identification of locations considered at high risk of introduction of non-indigenous species and the development of a monitoring programme for the UK.

Locations at high risk of introduction of NIS have been identified to assist in the development of a risk based monitoring programme. In the context of this section ‘high risk’ is defined as those sites that fall into the 75 – 100 score category. Locations fall into 2 general categories, nodes or specific points such as ports and marinas, and areas (larger geographical locations). The classification of locations as nodes or areas will depend on which pathways enter those locations. For example, nodes are locations where commercial shipping and recreational boating may result in introductions, while areas are those locations where natural spread and introduction from off-shore platforms may occur. Given the open nature of aquaculture sites that would receive movements of animals from outside the UK (i.e. shellfish harvesting areas), locations that are considered at high risk of introduction from movements of aquaculture animals have been classified as areas as well. This classification is also a function of the geographical area that introduction may occur over. In the case of commercial shipping and recreational boating, introductions may occur at a single point where boats are moored or ballast water is discharged. With natural spread and proximity to off shore platforms introductions may occur at multiple locations over a stretch of coastline. This will in turn affect the nature of the monitoring required at these locations, with nodes requiring intensive monitoring and areas requiring extensive monitoring.

In total 59 nodes and 33 areas have been identified as high risk of introduction (see below). It is recommended that these sites are monitored at least once a year. Existing monitoring programmes are likely to be sufficient in scope and scale to monitor the areas sufficiently, but there is no monitoring conducted at the identified nodes.

Nodes:

There are 3 shipping ports within the UK that fall into the activity score category described as high risk (see figure 36). These are Thames, Immingham and Liverpool. The total number of marinas located within regions with high recreational boating pathway activity (>75) is 56 (see figure 37 and 38).
Figure 36. Shipping ports colour coded by their shipping activity intensity score. 3 ports have a score >75, these are Thames, Immingham and Liverpool.
Figure 37. The location of marinas in relation to regions of high recreational boating activity.
Figure 38. Recreational boating pathway intensity with numbers referring to the number of marinas located within the coastal grid squares scoring >75 for activity intensity.
Areas

No areas within England, Scotland or Wales were considered to be at high risk of introduction as a result of aquaculture activity (see figure 16). A total of 11 areas were considered to be at high risk from introductions as a result of natural dispersal (figure 18) and 22 areas were considered to be at high risk from introductions as a result of their proximity to off-shore platforms (see figure 22).
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