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Marine non-native species

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EXECUTIVE SUMMARY

Species of fauna, flora or unicellular organisms that are not indigenous, and are introduced and become established in the waters around the British Isles by natural or human mediated transport, are termed marine non-natives. Some of these species can be considered to be invasive if they spread rapidly and cause economic or environmental harm, or harm to human health. Most introductions arrive *via* human intervention, intentional or otherwise (e.g. aquaculture, ballast water, fouling on yachts). More recently due to climate change some species, that in the past had ranges that were limited by temperature, have expanded their distribution to become established in new regions of the British Isles. Other non-native species have been able to take advantage of warmer conditions and have become more abundant. In the future an increase in introductions is anticipated, with unknown consequences for biodiversity, ecosystem functioning and living marine resources as a response to predicted rises in sea temperature (and possibly ocean acidification) and the opening of links between the Pacific and Atlantic Oceans due to melting of Arctic sea ice. Establishment of baselines and maintaining and funding an adequate monitoring programme to identify new non-native arrivals and to assess their impacts should have a high priority.

This paper reviews current information on non-native species found around the British Isles with two foci, planktonic (free floating in the water) plus meroplanktonic (benthic species that have a planktonic larval stage) and benthic (living on the bottom) introductions. Comment is made on the lack of information on the occurrence of non-native species in deep water environments. There is evidence to suggest that non-native species have been increasing on a global and European regional scale, although it is difficult to confirm the arrival dates of many introductions due to poor historical records and challenges with identification. It is surprising, given the many potential vectors that can distribute non-native species, that more have not become established. Often when successfully naturalised they become part of the normal seasonal cycle and may even improve ecosystem functionality by filling unused niches. There is little evidence to suggest that marine non-natives in the British Isles have caused extinctions of native organisms. Furthermore, few of the introductions to date appear to have caused large scale impacts. More localised impacts have included sporadic poisoning or smothering of farmed organisms in aquaculture,

clogging of nets, or fouling of structures – all events of considerable concern for the aquaculture industry in Scotland and Ireland. A future concern, given rising sea level, is the de-stabilising effect that burrowing Chinese mitten crab may have on sea defences. Many bloom species, including those causing Harmful Algal Blooms (HABs) are native or cosmopolitan species that can cause problems if they occur in excessive numbers in the environs of aquaculture ventures. The original source of these blooms may be offshore. For example, infrequent intrusion of oceanic water onto the shelf can result in swarms of gelatinous plankton arriving inshore as in the recent case of the jellyfish *Pelagia noctiluca* that resulted in fish kills in the North Channel, Northern Ireland.

A number of case studies of non-native species that have recorded impacts around the British Isles are described. These include the planktonic diatom *Coscinodiscus wailesii*, the planktonic comb jelly *Mnemiopsis leidyi*, the Pacific oyster *Crassostrea gigas*, the Chinese mitten crab *Eriocheir sinensis* and the Japanese wireweed *Sargassum muticum*. Reference is also made to the first evidence of a recent trans-Arctic invasion to the north-west Atlantic from the Pacific of the diatom *Neodenticula seminae*. This transfer, for the first time in 800,000 years, could mark the beginning of an invasion of Pacific organisms into the North Atlantic as last occurred in the Pliocene, and which could have profound impacts on Atlantic ecosystems.

Non-native planktonic species may expand to cover all coastal waters of the British Isles in a matter of only 25 years. Benthic organisms and especially intertidal species may extend over the same area within 50 years if conditions are favourable. Modelling studies of native zooplankton indicate that a northerly contraction of boreal species and expansion of warmer water species will take place at a rate of one degree of latitude per decade for typical mid range IPCC scenarios. Such a rapid rate of change will open up many new opportunities for the introduction of new non-native species.

1. HOW IMPORTANT ARE INVASIONS OF NON-NATIVE SPECIES?

Introduced species of fauna, flora or unicellular organisms that are not native and become established in the waters around the British Isles are termed ‘marine non-natives’. Some of these species can be considered invasive if they spread rapidly and cause economic or environmental harm, or are harmful to human health. Such species may be introduced by a wide range of human activities (either intentionally or unintentionally via aquaculture, or unintentionally via ballast water or fouling on ships), natural range expansions, or due to the availability of new niches as a consequence of climate change. A considerable evidence base is now available to show that many non-native species are increasing in abundance, and seasonal and range extent due to rising temperatures, although this may be partially a consequence of a greater interest in the problem (ICES 2007; Occhipinti-Ambrogi and Sheppard 2007). Gomez (2008) however, argues that many supposed non-indigenous species of dinoflagellates (including some Harmful Algal Bloom (HAB) species) and diatoms have been misidentified and are in reality synonyms of cosmopolitan species. Alternatively, the species may have extended their ranges as a response to cooling or warming events. By providing more favourable conditions for growth and expansion, rising temperatures may enable the transfer of pathogens from non-native species to indigenous populations. It is also clear that some introduced species may cause major changes to ecosystems, biogeochemical cycles, and fisheries and have large economic consequences in some parts of the world (Ruiz 1997; Ruesink 2006).

The presence of non-native species may go unnoticed until they reach nuisance status. As a result there are few case-histories that have been studied from their initial appearance and for their subsequent spatio-temporal development. In addition reporting of events has been slow through international journals, although the new on-line journal 'Aquatic Invasions' is helping to alleviate this situation. Exceptions include observations from the CPR survey of the development sequence of some non-native introductions by the CPR survey and tracking of large obvious species such as the spread of the seaweed *Sargassum muticum* in Scotland and the barnacle *Elminius modestus* (Crisp 1958; Crisp and Southward 1959). In Great Britain more than 80 marine species have been recorded as non-native introductions and a further 70 are of uncertain origin (Minchin *et al.* in prep.) However, only a few of these have caused large scale environmental impacts. The combined effects of predicted alterations in sea temperature and acidification with seasonal retraction of Arctic ice (Minchin 2006) are likely to lead to changes in ecosystems and an increase in the number of non-native species arriving in the waters around the British Isles.

This report has built on the 2008 MCCIP report by Elliott *et al.* (2008), the reports of two ICES working groups (ICES WGITMO (2007) and ICES WGBOSV Report (2006a)), the Marine Aliens Project, the EU DAISIE Project and a general literature search.

2. NON-NATIVE SPECIES AND CLIMATE CHANGE

Climate change has been proposed to affect marine invasions in a number of ways:

1. warm-water indigenous species may expand ranges to the warming higher latitudes and out-compete cold-adapted species through their greater growth rate and recruitment capability or the colder species may simultaneously retreat to the north, tracking their temperature niche (Carlton 2000; Stachowicz *et al.* 2002; Beaugrand *et al.* 2008);
2. climate change and associated ocean acidification may alter oceanography, as well as primary trophodynamic regimes, indirectly facilitating invasions (Carlton 2000; Hulme 2005);
3. successful invaders tend to be more resilient to disturbances than native species, and thus climate change could combine with other stressors to allow invaders to out-compete native species (Rogers and McCarty 2000).

It is worth stressing, however, that most of the non-indigenous marine species that are believed to have been introduced to the British Isles arrived through human activities and are spreading through natural processes independent of any contribution from climate change. Some species that arrived through natural range expansions now appear to have increased the speed of expansion due to direct physiological effects as well as environmental changes caused by rising temperatures attributable to climate change. The same appears to apply to some non-native introductions that had relatively static distributions, but have accelerated their expansion in recent years.

3. CURRENT STATUS AND POTENTIAL IMPACTS OF NON-NATIVE SPECIES

In terms of the vector of introduction/invasion, it is possible to separate non-native species into four categories: 1) those associated with the plankton (free drifting organisms in sea water) whose invasion may be linked to transport by currents or from ballast water in shipping [the plankton includes resting cysts and eggs that may be contained in the sediment at the bottom of ballast tanks as well as some larval stages of benthic organisms (animals living on or in the sea bottom) that can act as transport vectors]; 2) benthic organisms attached to the walls of ballast tanks and seawater piping and contained in the sediment at the bottom of ballast tanks (other than resting stages); 3) organisms attached as or within the fouling on the bottom of ships and yachts; 4) benthic organisms introduced with seed populations for aquaculture. Considerable research has been carried out into all of these categories on a global scale as part of the background and continuing work related to the IMO Ballast Water Convention. All of the introduced species described so far are from shallow coastal waters and estuaries. Until now there have been no records of introductions to deeper waters on the shelf and on the ocean floor in British and Irish waters.

Plankton

It has been suggested that non-native planktonic species that are introduced may have important ecological and economic consequences by out-competing native species and/or causing nuisance Harmful Algal Blooms (HAB) at local or regional scales. Such introductions have had major impacts on aquaculture through poisoning or smothering of the farmed organisms in many parts of the world (Smayda 2006; Wallentinus and Nyberg 2007). Concern over the inadvertent trans-oceanic transfer of plankton, their resting stages or benthic organisms in the ballast water of ships led to the adoption of the International Maritime Organisation (IMO) Ballast Water Management Convention in 2004. The effects of each new introduction are unpredictable and efforts to assess and monitor invasive planktonic species vary greatly between different countries. There is no formal monitoring system for new invasive plankton species in place in the UK, but as is indicated later, existing monitoring systems are probably adequate. This statement needs to be qualified, however, for phytoplankton; many species are difficult to identify just with light microscopy, are often poorly preserved and require electron microscopy or genetic analysis for definitive identification. Many species are not recognised until they become dominant in the plankton though they may have been present in the past in very small numbers. Evidence to date suggests that new species typically become part of the local biodiversity and do not have a major impact on planktonic diversity through local or regional extinction. However, there is so little historical information available that this latter point is largely based on hearsay.

The diatom *Coscinodiscus wailesii*

The case-history of *Coscinodiscus wailesii*, based on data from the Continuous Plankton Recorder (CPR) survey, has provided a unique insight into the progressive evolutionary expansion of an invasive plankton species. The geographical expansion of this species has been followed from its initial introduction in 1977 into European shelf seas to the present day (Figure 1) during which time it has become a persistent and significant member of the plankton community (Edwards *et al.* 2001). Gomez (2008) suggests that this species is cosmopolitan and not invasive. We on the contrary, believe that it is highly unlikely that the species was present in UK waters prior to 1977 as the plankton at Plymouth has been monitored on a weekly basis by an expert phytoplankton taxonomist (G. Boalch) for more than 40 years. Furthermore, the species is large and well sampled by the CPR and again it is unlikely that it would have been missed by the skilled taxonomists that work in this group.

When this species first appeared in the North Atlantic it had a detrimental effect on fishing operations through the production of copious amounts of mucus that clog fishing nets. The species also considerably reduces underwater visibility for divers. It has subsequently become, in the early spring and late autumn, a dominant member of the phytoplankton community in competition with indigenous species. Since its introduction it has spread throughout all waters around the British Isles. This information provides an invaluable model of how the pattern and rate of spread of an introduced species is likely to evolve in European waters.

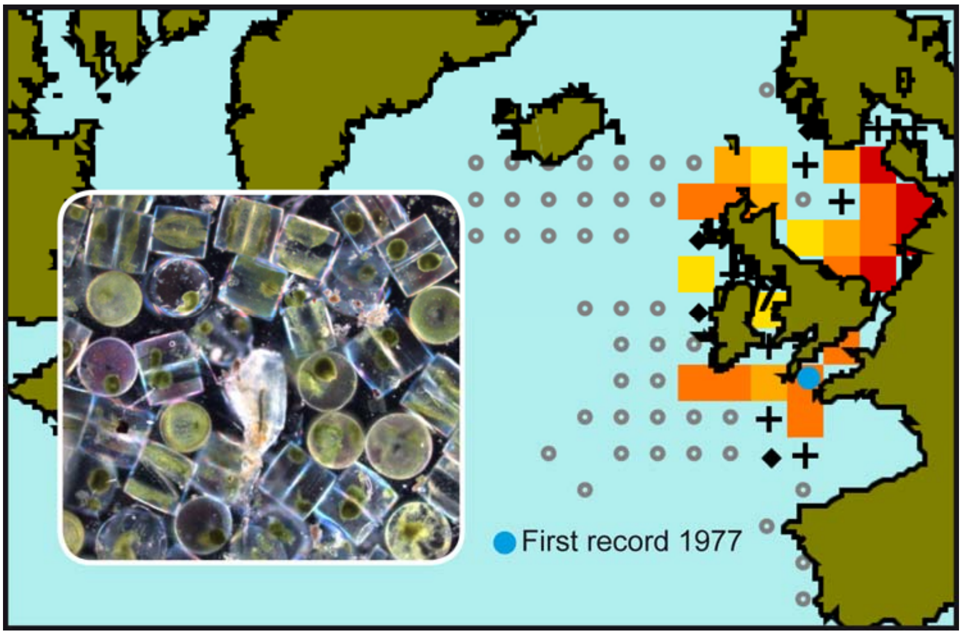

Figure 1. Map of the expansion of the non-native diatom Coscinodiscus wailesii from its initial discovery off Plymouth in 1977 to 2005 with a superimposed photograph of a collection of this 'pill box' diatom in different orientations. The intensity of colour indicates higher abundance. Grey circles show single sightings, diamonds indicate only one presence has been detected; crosses denote > 1 presence detected. Updated from Edwards et al. (2001).

A number of other non-native plankton species have been recorded in waters around the British Isles and in the North Sea over the last century, building on earlier introductions such as the diatom *Odontella sinenesis* that has become a routine member of the plankton since it was first recorded by Ostenfeld (1908) in 1889. Gomez (2008) also considers, and he may be correct here, that this species is cosmopolitan, as there were only limited studies of phytoplankton prior to 1889. It should be noted, however, that Ostenfeld gives a clear explanation of the expansion of this species in the North Sea and used it to measure the speed of currents. Other possible introductions include the cladoceran *Penilia avirostris* (Johns *et al.* 2005), and the copepod *Acartia tonsa* (Conover 1957) and some other species of diatoms (Eno *et al.* 1997). *P. avirostris* has a resting egg and had been found in the North Sea prior to its recent increase and its increased abundance may well be due to the presence of warmer temperatures allowing it to develop from a small residual population.

<u>The comb jelly *Mnemiopsis leidyi*</u>

In the Black Sea the introduction of the 'comb jelly' *Mnemiopsis leidyi* in the early 1980s had a pronounced impact on the ecosystem when massive blooms, circa 1988, coincided with the collapse of the anchovy fishery. Concurrently there was a large reduction in the biomass of the mesozooplankton and carrying capacity of the ecosystem that, in conjunction with overfishing and eutrophication, possibly led to a catastrophic failure in the fishery. The sudden occurrence also coincided with environmental changes and increases in temperature so that other factors may have been involved in the fishery collapse. *M. leidyi* is a voracious feeder on zooplankton (including meroplankton) and fish eggs and larvae and in favourable conditions can multiply rapidly. Its appearance and mass development in the Black Sea had a major economic impact on the whole region. Originating from estuaries on the western side of the Atlantic in North and South America the introduction of the species was attributed to ballast water transfer. *M. leidyi* subsequently spread to the Caspian Sea and into the eastern Mediterranean (Shiganova *et al.* 2001). Numbers of the species in the Black Sea have since reduced and now appear to be in balance possibly due to a later introduction of the comb jelly *Beroe ovata* that predates on *M leidyi* (Shiganova 2005).

By the early 1990s *Mnemiopsis leidyi* had probably spread through ballast water introduction, to near shore and estuarine waters of the North Sea (Faasse *et al.* 2006). However, positive identification by molecular analysis was only made in 2006, based on individuals taken from large blooms in Dutch estuaries in the summer and autumn of that year (Faasse *et al.* 2006) and it was recorded at Helgoland in November 2006 (Boersma *et al.* 2006). At approximately the same time the species was recorded for the first time in the Baltic (Javidpour *et al.* 2006). In the summer and autumn of the same year the species was found at many near coastal locations extending from the Netherlands, Germany, Denmark, Sweden and Norway as far as Bergen and into the western Baltic with the earliest confirmed record from Denmark in August 2005 (Tendal *et al.* 2007). The following year the species was recorded widely in the Baltic as far north as the Gulf of Finland.

The precise date when *M. leidyi* arrived respectively in the North Sea and Baltic, and if they were separate introductions or a consequence of progressive transfer from one sea to the other, is unclear. Its apparent mass occurrence over a very wide area in 2006 implies that it was already in place in low numbers and responded to an environmental cue like increased temperature. Its extension along the eastern seaboard of the North Sea and into the western Baltic implies that it was first distributed in the low salinity coastal currents into the Skagerrak and Kattegat and then in the Baltic outflow along the Norwegian coast. This fits with its apparent preference for lower salinity estuarine conditions. The route follows a similar path to the rapid spread of the diatom *Biddulphia. sinensis* from its first record in European waters in 1889. It is only a matter of time before *M. leidyi* is recorded in UK waters, although it is likely that it is already present. It is perhaps no coincidence that the unusual seasonal occurrence of a ctenophore that may have been *M. leidyi* in the summers of the early 90s occurred soon after the North Sea regime shift. The occurrence of mass blooms of *M. leidyi* in 2006 coincides with many other events that appear to be linked to changes in the circulation of the northern North Atlantic.

<u>First evidence of a trans-Arctic invasion in modern times</u>
Sea ice and ice shelves are melting at an unprecedented rate in the Arctic and extensive ice free conditions to the north of Canada are expected within a matter of decades. This means that the biological boundaries between the North Atlantic and Pacific Oceans are becoming blurred and an increase in trans-Arctic migrations is likely (Reid *et al.* 2007). The first recorded substantial retreat of summer ice from the whole coast of northern North America took place in 1998 at the same time as changes in wind patterns. This allowed the Pacific diatom *Neodenticula seminae* to be transferred in currents between the two oceans. In the cool sub-polar waters of the North Pacific and the Bering Sea the planktonic diatom *N. seminae* is abundant. It bloomed for the first occasion in modern times in the spring of 1999 in the Labrador/Irminger Seas, between Canada and Greenland, when it was first identified in samples from the CPR survey, and subsequently in 2001 in the Gulf of St Lawrence (Reid *et al.* 2007). Since then it has spread south to Georges Bank on the eastern coast of the USA and east to south of Iceland.

From records of the deep sea drilling programme we know that *N. seminae* was last resident in the North Atlantic between 1.2 million and 800,000 years ago. Its recent arrival in the North Atlantic, after becoming locally extinct 800,000 years ago, therefore could be the first evidence of a trans-Arctic migration in modern times and be the harbinger of a potential inundation of new organisms to the North Atlantic. The last time the Pacific and Atlantic were joined together during the Pliocene there was a major invasion of new species that caused large changes in the fauna of the North Atlantic. For most of the period since the Pliocene the two oceans have been isolated.

Harmful Algal Blooms

The introduction of non-indigenous marine plankton via ballast water may have a considerable ecological and economic effect on regional systems (Edwards *et al.* 2001). Some species can form Harmful Algal Blooms (HABs) and as a consequence of regional climate warming it is thought that more non-native species that are currently found in the warmer waters of southern Europe may become established in the British Isles in the future (e.g. *Gymnodinium catenatum*). One of the best known examples of a possible transplantation is the dinoflagellate *Karenia mikimotoi* which was recorded for the first time in 1966 off the southern Norwegian coast and at about the same time off Ushant in the English Channel (Pingree *et al*. 1975; Holligan 1979). The species has subsequently spread throughout the North Sea and around Ireland to become one of the most common toxin producing HAB species in northern European Waters. It is considered by Gomez (2008) and Davidson *et al.* (in press) that *K. mikimotoi* may not be non-native, but cryptogenic (a species of unknown origin and thus uncertain native or introduced status). A genetic analysis of the species complex is needed to confirm its origins. The species is now routinely recorded in phytoplankton monitoring programmes as blooms of *K. mikimotoi* have caused problems e.g. kills of benthic organisms and fish kills through the production of haemolytic cytotoxins and the hypoxic conditions that dense blooms can create (Davidson *et al.* in press).

Over the last few years *K. mikimotoi* has produced some exceptional blooms. During 2005 for example, particularly intense blooms formed in coastal waters off the west of Ireland leading to discolouration of water and foaming in coastal embayments. Major mortalities of both benthic and pelagic organisms, including farmed shellfish and fish, were associated with this bloom (Silke *et al.* 2005). There is some evidence to suggest that climate change has increased the bloom frequency of some HAB species in the North Sea although this may also be a consequence of a change in the focus of their centres of distribution (Edwards *et al.* 2006). Climate warming may open up new thermally defined habitats that were previously denied to non-natives (e.g. sub-tropical species in the North Sea) and invasive species allowing them to establish viable populations in areas that were once environmentally unsuitable.

Coastal and estuarine benthic non-natives

Marine Aliens Project

The occurrence, expansion, means of dispersal and impacts on biodiversity of seven key non-native marine species found in the UK are being closely monitored by the Marine Aliens project that is being led by the Scottish Association for Marine Science (SAMS) in Scotland with MarLIN at the Marine Biological Association (MBA) in Plymouth acting as the website host www.marlin.ac.uk/marine_aliens (Figure 2). The seven species are (1) *Caprella mutica*, the Japanese skeleton shrimp, first found in a Scottish fish farm in 2000 (Willis *et al.* 2004) and since found in over 120 locations throughout Europe, predominately in areas of human activity (Cook *et al.* 2007); (2) The invasive form of the alga *Codium fragile* was first found in Devon in 1939 and replaces native species of the same genus; (3) *Sargassum muticum* (wireweed) first recorded on the Isle of Wight in 1973 and now found extensively on the western margins of the Great Britain and Ireland (see below, Harries *et al.* 2007a); (4) *Undaria pinnatifida*, the brown seaweed Wakame first found in the Solent estuary in 1994 and now at sites along the south coast of England; 5) *Styela clava*, the leathery sea squirt first found in Plymouth in 1953 and now widespread in Europe (Davis and Davis 2004);6) *Perophora japonica* a colonial sea squirt first found in Plymouth in 1999 and since in the Channel Islands and further along the south coast; and 7) *Eriocheir sinensis* the Chinese mitten crab (see later).

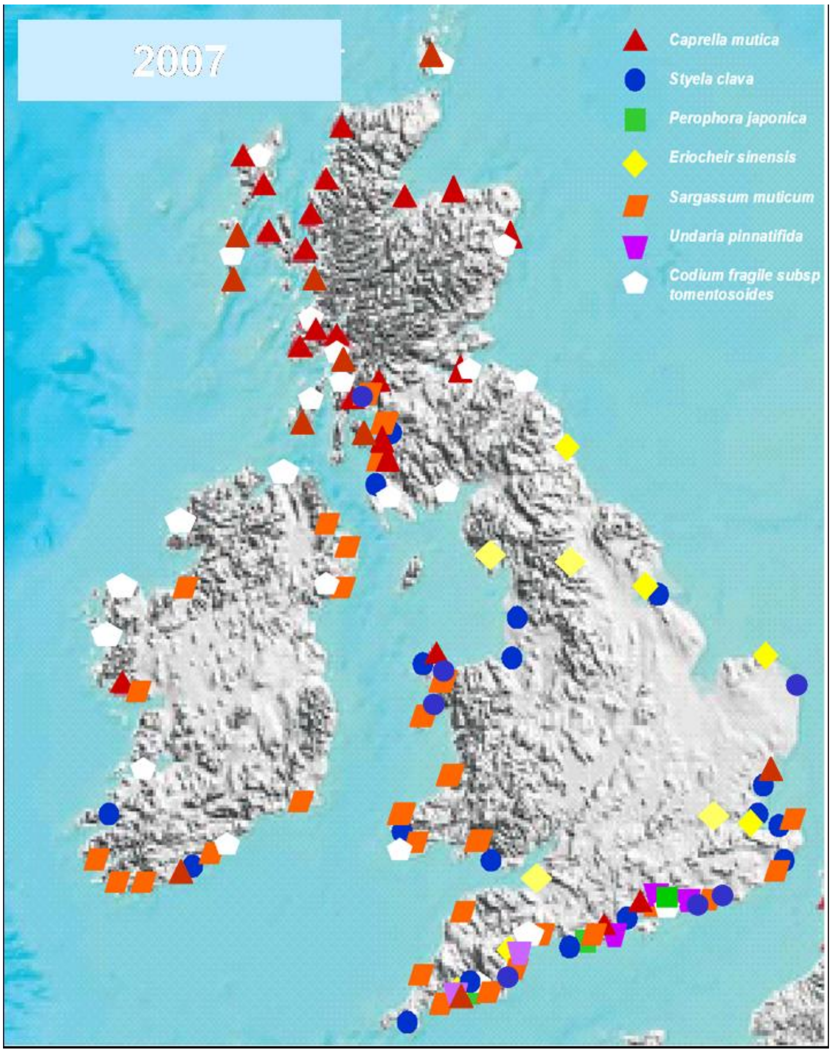

Figure 2. Distribution of the seven key non-native species featured in the Marine Aliens programme in 2007

The project has also been following the dispersal of more recent introductions such as (8) *Corella eumyota* a southern hemisphere cold temperature tunicate first found in Brighton, Gosport and Weymouth in 2004 (Arenas *et al.,* 2006) and subsequently elsewhere on the south coast of England and in south Wales; and (9) *Tricellaria inopinata*, a bryozoan native to the Pacific, first found in 1998 on the south coast of England (Dyrynda 2000) and recently found in marinas on the west coast of Scotland in 2007 (E. Cook, pers. obs.). Other non-native species that have been resident for some time, but are continuing to expand their range and numbers are also being followed e.g. (10) *Crepidula fornicata* the slipper limpet, (11) *Dreissena polymorpha* *the* zebra mussel in both freshwater and estuarine environments, (12) *Crassostrea gigas*, the Pacific oyster (see below), (13) *Elminius modestus*, the Australasian barnacle and (14) *Botrylloides violaceus*, a brightly coloured colonial tunicate from the north-west Pacific.

In the last three years, the Marine Aliens project has recorded the widespread distribution of *Caprella mutica* and *Codium fragile* throughout Ireland, Scotland and on the south and west coasts of England, the appearance of the mitten crab *Eriocheir sinensis* in apparently random 'inland' sites throughout England and the rapid northwards spread of *Sargassum muticum* (Figure 2). All seven of the key species are found along the south coast of England, but appear to be rare along the east coasts of England and Scotland. The apparent paucity of non-native species on the east coast of Great Britain, however, may be attributed to a lower sampling effort compared to elsewhere and highlights the need for a concerted monitoring programme for non-native species throughout the UK.

<u>The Pacific oyster, *Crassostrea gigas*</u>

Crassostrea gigas was first introduced from Portugal for use in commercial aquaculture to the Blackwater Estuary, England in 1926 with a second introduction to Conwy, North Wales in 1970 (Eno *et al.* 1997). At the time of these early introductions there was limited reproduction and recruitment of young oysters in British waters and commercial oyster farms used hatchery produced seed. By the 1970s the Pacific oyster was more generally distributed in NW Europe and was found to recruit successfully in Arcachon and Marennes-Oleron, France. Subsequently settlements were noted elsewhere in northern Europe in small amounts. Higher summer temperature in the mid 1970s and 1980s enabled *C. gigas* to recruit intensively in some shallow embayments and lagoons, in particular in the southern North Sea (Nehls *et al.* 2006). In the 1990s recruitment was sustained and occurred at higher levels (Gollasch *et al.* 2007). Very often the recruitment of small numbers of individuals, some decades previously, preceded the more intensive settlements that followed (Reise *et al.* 2005). At some locations in the Yealm estuary densities of *C. gigas* now exceed 150 per square metre (Hiscock pers. comm.) and in the Wadden Sea densities of > 1000 per m^2 are the rule (Reise pers. comm.).

The Pacific oyster is becoming more common in estuaries along the south coast of England between the Thames and Plymouth Sound and there are occasional settling individuals as far north as in North Wales (Spencer *et al.* 1994). The increase in abundance is attributed to sustained higher water temperatures following spawning events and milder winters. In Ireland, since the 1990s small numbers were found to recruit within Irish bays extending from Cork Harbour to Donegal Bay (south to north-west Irish coast) (Boelens *et al.* 2005) and recently recruiting in Lough Swilly, NW Ireland (E. Sides, pers. comm.) and in the NW Irish Sea in Strangford Lough.

In some regions hatchery produced spat are no longer needed due to the intensity of natural settlement. Indeed, the settlements in some areas are sufficiently intense to cause a fouling problem. For example, in the northern part of the Wadden Sea native blue mussel beds are declining and are being overgrown by *C. gigas* and *Crepidula fornicata* (see also Nehls *et al.* 2006; Nehls and Buttger 2007). These authors conclude that the disappearance of the mussels is due to poor mussel spatfalls as a consequence of warmer conditions that have favoured the growth of the other two species. See Figure 3 for the pattern of spread of *C. gigas* in the Wadden Sea.

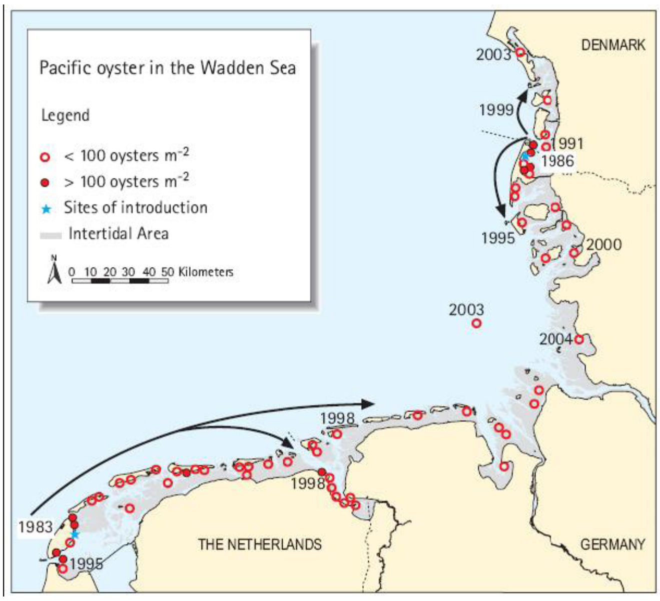

Figure 3: Crassostrea gigas in the Wadden Sea. Asterisks indicate introduction sites (Texel, The Netherlands and Sylt, Germany). Years indicate first records of settlement. Circles refer to mean Pacific oyster abundance in 2003 (from Reise et al. (2005)).

<u>Chinese mitten crab, *Eriocheir sinensis*</u>

The Chinese mitten crab lives in both estuaries and rivers and is becoming a major pest and predator on native species (Gilbey *et al.* 2008)., including young fish. It is reported that *E. sinensis* is burrowing extensively in both the river banks and estuary of the Humber area, gradually weakening the flood defences (Herborg *et al.* 2005). Colonisation by mitten crabs has greatly increased in the UK in recent years from its first record in the Thames in 1935. The invasion pattern of the crabs in the UK is similar to the expansion of its populations in Europe earlier in the last century, most likely because their settlement is comparatively new. Attrill and Thomas (1996) postulated that their delayed success was due to drought conditions restricting the flow of the river. Chinese mitten crabs are now present in the Thames, Humber and Tyne rivers and parts of the North Sea and Channel coasts. By 1998 the species had reached the Teign Estuary (Herborg 2005) and was recently recorded in the River Dee (Wales) (ICES 2007), which suggests a clockwise extension around the UK. A few individuals of the species were also caught in the Waterford Estuary on the south Irish coast during 2006 (Minchin 2007a). It has been suggested that some of these more recent records are actually deliberate introductions (Herborg *et al.* 2005). Recently, *E.sinensis* has been spreading at a very fast rate. From 1997–1999 the spread along the coast was 448 km per year, nearly six times the average spread of 78 km per year from 1976–1999. This increase in the rate of spread may be because the breeding stock in and adjacent to the Thames has reached a critical level of population that encourages migration. In rivers, the increased spread from 1995–1998 was 49 km per year, around three times the average spread of 16 km per year from 1973–1998 (Herborg *et al.* 2005). It is not thought that rising temperature has contributed to the spread (Attrill pers. comm.) although temperature does feature in the modelling of the invasion by Herborg *et al.* (2007). It is predicted that the mitten crab has the potential to establish itself in all major UK estuaries and possibly throughout Ireland in several years time. A survey of mitten crabs from the River Thames found no evidence of infection with the human lung fluke (*Pseudamphistomum truncatum*), which is sometimes carried by these crabs in their native range. This finding is important, as it is possible that a fishery for these crabs will develop in the UK, to supply ethnic markets (ICES 2007). It was reported by (Nehls *et al.* 2006) that more than 200 tonnes of these crabs were harvested per year from the river Elbe in Germany where it can be found (Figure 4) more than 700 km upstream from the estuary. This may have been the case in the 1930s, but today the species is not a regular food item in Germany because of its high chemical contamination load as well as it being not an attractive food item for the German palate. The current annual catch is estimated as less than 1 tonne per year by S. Nehring (pers. comm.) based on purchases from fishermen by Chinese people.

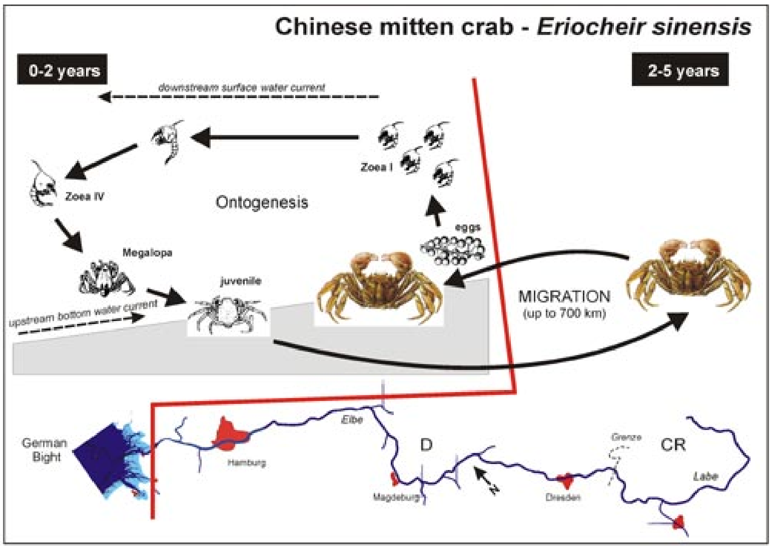

Figure 4 showing the life cycle of the Chinese mitten crab and how it can migrate inland up to 700 km from the sea in the adult stage of its life cycle, returning to the sea to reproduce. The bottom part of the figure shows a map of the River Elbe with the border between Germany and the Czech *Republic marked as a dashed line. Modified and redrawn by Stefan Nehring from:* www.aquatic-aliens.de/habitats.htm

<u>Japanese wireweed, *Sargassum muticum*</u>

This successful invasive algal species (Critchley *et al.* 1990) (Figure 5) is native to the waters around Japan and the north-west Pacific (Critchley 1983). *S. muticum* was first recorded in UK waters at Bembridge on the east coast of the Isle of Wight in 1973 (Farnham *et al.* 1973) and subsequently extended its range along the entire south coast of England (Critchley 1983). Over recent years, a rapid northerly expansion of its range has been recorded along the western coasts of England, Wales and Scotland: north coast of Cornwall in 1991 (Eno *et al.* 1997), Pembrokeshire in 1998 (Davison 1999), Anglesey in 2001 (ICES 2006b) and Scotland (see later). The species extended to Northern Ireland, Strangford Lough, in 1995 (Boaden 1995; Davidson, 1999) and western Ireland to Cashel Bay, Co Galway, in 2001 (Loughnane and Stengel 2002). It is now known to occur at several other locations on the south and west coasts of Ireland (Loughnane and Stengel 2002; ICES 2006b).

This seaweed has a broad tolerance range for temperature (Norton 1977), *S. muticum* has become successfully established in the cold waters of southern Alaska (Hales and Fletcher 1989) and Scandinavia (Karlsson and Loo 1999), as well as in the warmer waters of the Mexican Pacific and the Mediterranean. Experimental evidence indicates that the optimal temperature for growth and reproduction is about 25˚C (Hales and Fletcher 1989), which suggests that increasing temperatures may favour higher rates of growth and its spread along much of the remaining uncolonised coastline of the British Isles.

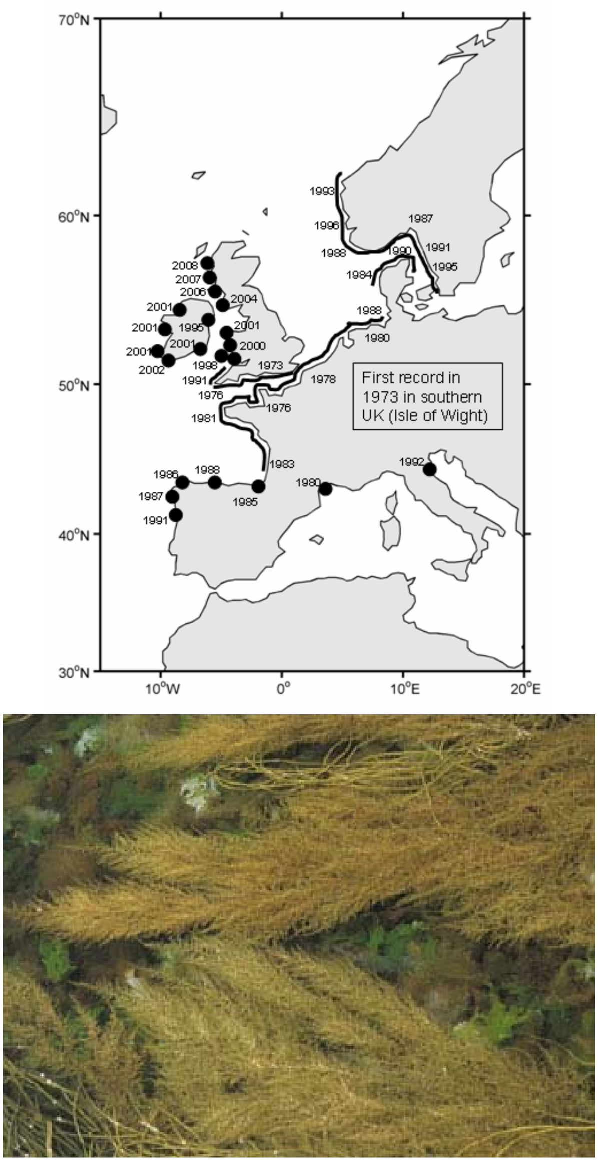

Figure 5. Map of the distribution of Sargasssum muticum in Europe up to 1998 from Wallentinus www.aqualiens.tmbl.gu.se/Sargassum-muticum.pdf,, updated for the UK and Ireland to 2008, and a photograph of S. muticum (courtesy Keith Hiscock, MarLIN).

It is not expected that *S. muticum* will cause widespread ecological damage, but it may, particularly in Scotland and possibly in Ireland, result in dense growths on aquaculture structures (Harries *et al.* 2007a). Tourism may also be affected through an aesthetic impact on coastlines and potential ecological effects on conservation sites. At low tide when the species is laid out on sediment it appears to dominate; in contrast when fully upright at high tide, and observed by divers, an extensive flora may be present beneath.

<u>Other non-native species</u>
Many other non-native benthic organisms have been recorded in waters around the British Isles and in the North Sea over the last century. See Elliott *et al.* (2008) for information on species not covered here, including those whose distribution range is

sensitive to temperature. New records include confirmed sightings of the kuruma prawn, *Marsupenaeus japonicus* from off Start Point (ICES 2007), Looe and the Lizard on the south coast of England in 2007. At least nine confirmed records of this prawn have been made in the Channel and one off the south coast of Ireland from 1989 to 2007 (pers. comm. Paul Clark, Douglas Herdson). They are believed to be escapees from French prawn aquaculture sites. A number of non-native species have been found in adjacent European countries, but have not yet reached the British Isles. Of some concern in this list are records of *Homarus americanus*, the American lobster, in Norway because they are a potential source of a lobster disease and may hybridise with native lobsters with unknown consequences.

4. TIMESCALES

On the basis of extrapolation from planktonic introductions such as *C. wailesii* new planktonic species may extend their ranges around Great Britain and Ireland within 25 years. This rate of expansion depends on current movement and where the species first arrives; it is likely to be even faster with warmer temperatures and higher growth rates. The rate of colonisation by benthic non-native species appears to be much slower although it may be faster if the species has a planktonic larval stage or it disperses through fragmentation or by attachment to ship hulls. A period of initial establishment in some species appears to be followed by subsequent rapid colonisation and expansion. This initial period of rapid growth and dominance is followed by a decline and accommodation within the existing community. In the case of the Pacific oyster the species has continued to expand in concert with warmer sea temperatures. The Chinese mitten crab showed an increase in abundance in the 1980s reflecting higher summer temperatures, which was followed by a rapid increase from ~1997. In Germany, however, where the species has existed over a longer period, cycles of abundance have been noted. It is likely that crabs, as per the occasional records found in Ireland, may have been transferred with shipping from infested areas.

The distribution and abundance of northern and southern native species of intertidal barnacles have been studied extensively in the British Isles for many decades (Mieszkowska *et al.* 2006) and may be used as surrogate examples of how an equivalent non-native species might spread on intertidal rocky shores. Their distribution and that of the top shell *Osilinus lineatus* has been modelled against sea temperature, wave action and competition for a UKCIP02 Medium-high scenario in the 2080s (Mieszkowska *et al.* 2005). The northern species *S. balanoides* is expected to be very rare in the south-west of England as early as 2025 and will retreat north at the same time as the 'southern' chthamalid barnacles increase and spread around the top of Scotland into the North Sea by the 2080s. There is already evidence that the range of *S. balanoides* has retracted to southern Brittany from northern Spain over the last century (Wethey and Woodin 2008).

Of the 51 non-native species examined by Eno *et al.* (1997), most had spread throughout the British Isles within 50 years. The majority are believed to have originated from similar latitudes to the UK, especially from the east coast of the USA (mainly fauna) and the Western Pacific (mainly flora). For example, *C. fornicata* and the American oyster drill, *Urosalpinx cinerea* are thought to have arrived accidentally with American oysters imported for culture and *Sargassum muticum* is believed to have been imported with Pacific oysters, either as packing or as microscopic early life-history stages attached to shells. It is likely that most species made the journey to Britain via deliberate and unintentional introduction (often in association with aquaculture), by attachment to hulls, or in the ballast water of ships.

Studies in the pelagic realm using data from the CPR survey have demonstrated that the distribution and seasonal to decadal variations in abundance of a number of zooplankton species is closely linked to temperature, and in some cases combined with the timing, abundance, composition and distribution of phytoplankton food (e.g. Beaugrand *et al.* 2007). Rapid progress has been made recently in the further development of this approach to understand the spread of marine planktonic organisms using niche theory (Helaouët and Beaugrand 2007; Beaugrand *et al.* 2008; Beaugrand and Helaouët 2008). A similar approach has been used by McMahon and Hays (2006) by using a 'climate envelope' based on temperature to help explain an observed northerly range extension of the leatherback turtle. Ecological niches are the set of physiological, competition and environmental conditions under which a species can maintain populations in its native area in the long term without an in-migration of individuals (after Peterson 2003). Extrapolation of this concept to new range expansions implies that the species can only live within the conditions that characterise its native location, with the exception of competition, which may be different. Hulme (2005) for example comments that effects from non-native introductions may be indirect and result from changes in the availability of natural resources and mutualistic and antagonistic interactions between species.

In an application of the niche approach, Helaouët and Beaugrand (submitted) have modelled changes in the distribution and abundance of the copepod *Calanus finmarchicus* against temperature scenario projections from AO-GCMs based on ECHAM 4 data for two moderate IPCC scenarios, A2 and B2. The modelled results for 2050-2059 and 2090-2099 show a substantial poleward movement of the species by one degree of latitude per decade to 2100. The projected changes in this key pelagic species mean that there will be substantial alterations to polar pelagic ecosystems and biogeochemical cycles. Applying these results to spatial patterns in egg production (Beaugrand and Helaouët 2008) have shown that regions characterised by high abundance and reproductive rate at the present day (and modelled) are just below the isotherm 9-10°C. This isotherm is shown to be a key biogeographical boundary between Atlantic Arctic and cold temperate biomes and is projected to move north at the same rate as the modelled data for *C. finmarchicus*.

5. NATURAL VARIABILITY VS HUMAN INDUCED CLIMATE CHANGE

It is notable that relatively few protist, bacterial or viral introductions have been recorded globally and there are few new plankton invasions despite the very large number of individuals and their resting cysts found in ballast water and its associated sediment (Drake *et al.* 2007). The majority of non-native species are benthic organisms and have reached their new localities by anthropogenic dispersal through deliberate and unintentional introduction for aquaculture, fouling on the bottom of ships, or through the release of organisms in ballast water (Eno *et al.* 1997). We know of no marine fish non-natives in UK waters, although there are known to be more than 200 introductions elsewhere in the world, especially in tropical regions (Semmens *et al.* 2004). Nehring (2006) argues that estuaries, where the greater proportion of non-native species are first detected, provide ideal conditions for establishment due to four factors: 1) the frequent shipping transport of salt-tolerant limnic species; 2) the presence of major harbours where intercontinental shipping takes up ballast water of estuarine origin; 3) that brackish water species are already tolerant of estuarine conditions; and 4) the common presence of vacant ecological niches in estuaries. The international transport of organisms on the hulls of vessels may increase in the future due to the introduction of a ban on Tributyltin (TBT) antifoulants by September 2008. Furthermore, there is some evidence that non-native species will take advantage of these less toxic conditions in port regions and together with climate change this may lead to an increase in invasion rates (Carlton 2000; Stachowicz *et al.* 2002).

Against this background there is clear evidence for large annual, decadal and long-term variability in the seas around the British Isles, with the ~1988 regime shift in the North Sea standing out as a major hydroclimatic event. A step-wise change in marine pelagic and benthic ecosystems, hydrography and climate occurred at this time, associated with warming temperatures (Reid *et al.* 2001; Beaugrand 2004). A recent paper has shown that the hybrid non-native cordgrass *Spartina anglica* showed a marked increase in growth and expansion during the same period ~1988 in the Wadden Sea (Loebl *et al.* 2006). More remote oceanographic changes associated with sub-polar gyre and northerly extensions of the biogeographic 10°C boundary (Beaugrand *et al.* 2008) are also likely to contribute to conditions that may favour new introductions.

6. REGIONAL CASE STUDIES

A report by Eno *et al*. (1997) summarised the distribution and invasive characteristics of 51 non-native species in British waters. The species included 15 marine macroalgae, five diatoms, one flowering plant and 30 invertebrates. There is little common pattern in the distributions, but there appears to be a higher proportion of invasive species on the south and west coasts of Britain, especially in the Solent and along the Essex Coast. This increased frequency is likely to be a consequence of multiple factors including increased shipping, Second World War activities and the junction of two biogeographic zones in this region as well as the location of marine laboratories in the area, which means that non-native species are more likely to be recognised.

Ireland

The jellyfish *Pelagia nocticula* (Figure 6) is not strictly an invasive species as it is widely distributed in warm and temperature waters of the North Atlantic and occurs at times in deep waters off the north and west coasts of the British Isles (Doyle *et al.* 2008). However, it is only occasionally found in shallower shelf waters so that a massive swarm of this species off the coast of Northern Ireland, north of Belfast in November 2007 (Doyle *et al.* 2008) was exceptional. The bloom moved inshore onto a salmon farm, killing by smothering or stinging ~200 tonnes of salmon worth more than £1 million. Such inundations by jelly fish can be a major problem for aquaculture facilities and infrequent events of this nature may be copied by some non-native introductions.

Figure 6. Pelagia noctiluca (image courstesy of Paul Newland, MarLIN)

To the present there is no evidence to suggest that new non-native species of jelly fish have been found in UK waters, but there are examples from other regions of the world. However, results from the CPR survey show an increase in the frequency of the presence of the stinging cells (nematocysts) of jelly fish from the mid-1980s within the central North Sea (Attrill *et al.* 2007). The increase coincided with a range of changes in phytoplankton biomass, zooplankton abundance and composition and hydrography that has been described as a regime shift (Reid *et al.* 2001; Beaugrand 2004). The rise in incidence was positively correlated with the North Atlantic Oscillation (NAO) and inflow of Atlantic water from the adjacent ocean (Attrill *et al.* 2007) and from other evidence with rising sea temperatures. In a review of the effects of climate on the formation of jellyfish and ctenophore blooms Purcell (2005) concluded that "ocean warming may shift the distributions, expand the seasonal occurrence and increase the abundances of temperate-boreal species". Populations living near their thermal maximum may suffer negative consequence of warming and in the case of the UK are likely to move further to the north. Doyle *et al.* 2008 consider that the predominantly warm water species *P. noctiluca* will expand its range.

Republic of Ireland

In a rapid assessment survey for non-native species along all Irish coasts 29 sites, mainly in marinas, were sampled in the summer of 2006. Twenty species were targeted in this study. Ten of these were already known to occur in Ireland and a further ten were known only from Europe or Britain. New range extensions within Ireland were found including *Caprella mutica* from Cork on the south coast and in the northern Irish Sea. Four species not previously found in Ireland included (1) the amphipod *Corophium insidiosum* from Belfast Lough, (2) the southern hemisphere tunicate *Corella eumyota* from the Irish Sea and the south coast, (3) the colonial tunicate *Botrylloides violaceus* from the Irish Sea, and (4) the colonial tunicate *Didemnum vexillum* from the Irish Sea.

There are several other range extensions and arrivals of species to Ireland (Minchin 2007a; 2007b) but whether these represent new opportunities provided by climatic windows or a change in the local environment is not known. Examples of the latter include movement of port berthing areas from brackish to more marine conditions and changes due to a higher turnover and more frequent movement of vessels (Minchin and Gollasch 2003). The increase in the numbers of small craft, development of marinas and plying of such craft worldwide to many more remote areas may also be important in species dispersal (Minchin 2006).

Scotland

A number of non-native species that are established elsewhere within the UK (Ashton *et al.* 2006), as well as others that are responding to the warmer conditions found from the 1980s onwards are spreading northwards to become established in Scotland. A survey of ten marinas in Scotland for seven well established non-native species in the UK outside Scotland (*Caprella mutica, Eriocheir sinensis, Perophora japonica, Styela clava, Codium fragile,, Sargassum muticum* and *Undaria pinnatifida*) was carried out in 2006 (Ashton *et al.* 2006). Seven of the marinas had one or more of the selected species and only three were not found (*E. sinensis, P.japonica* and *U. pinnatifida*).

Recently, the Mediterranean mussel *Mytilus galloprovincialis* and the Baltic mussel *Mytilus trossulus* have been reported in cultivation on the west of Scotland (Beaumont *et al.* in press; Dias in press). Using genetic markers, *M. galloprovincialis* was detected extensively throughout the north-west and north-east of Scotland, extending its range north and eastwards from previously reported sightings (Skibinski

1983), which the authors suggest may be attributed to climate change (Dias in press). *Mytilus trossulus* alleles were also identified in natural populations in the Argyll and Clyde areas of south-west Scotland (including two marinas; Dunstaffnage and Inverkip) (Dias in press) considerably extending the recent sighting of *M. trossulus* in Loch Etive, near Oban, west coast of Scotland (Beaumont *et al.* in press). This discovery suggests that aquaculture transfers may play an important role in the introduction and dispersal of these species in the UK.

A special effort is being made in Scotland to monitor the occurrence of the Japanese wireweed, *S. muticum* (Figure 7) and develop management procedures for mitigation. From its first introduction on the south coast of England in 1973 the species has spread rapidly, extending to the west coast of Scotland at Loch Ryan, Wigtownshire in 2004. Other established populations have been recorded subsequently as unattached fronds on the east coast of the Isle of Cumbrae (Harries *et al.* 2007b) , along much of the south-west coast of Scotland from other observers and as far as the southern coast of the Isle of Skye by September 2008 (F. Manson, SNH pers. comm.). The latest sighting is a considerable distance north of the last record and equates to a dispersal rate of approximately 50 km yr^{--1} since the early 1990s. Dispersal appears to be predominantly by natural drift in currents, but supplemented by human vectors (Harries *et al.* 2007a). Further dispersal is likely to be influenced by the strong near surface water currents which travel in a clockwise direction around the Scottish coast although fewer suitable sites are found along the east coast of Scotland due to the more exposed conditions and its spread there is expected to be slower.

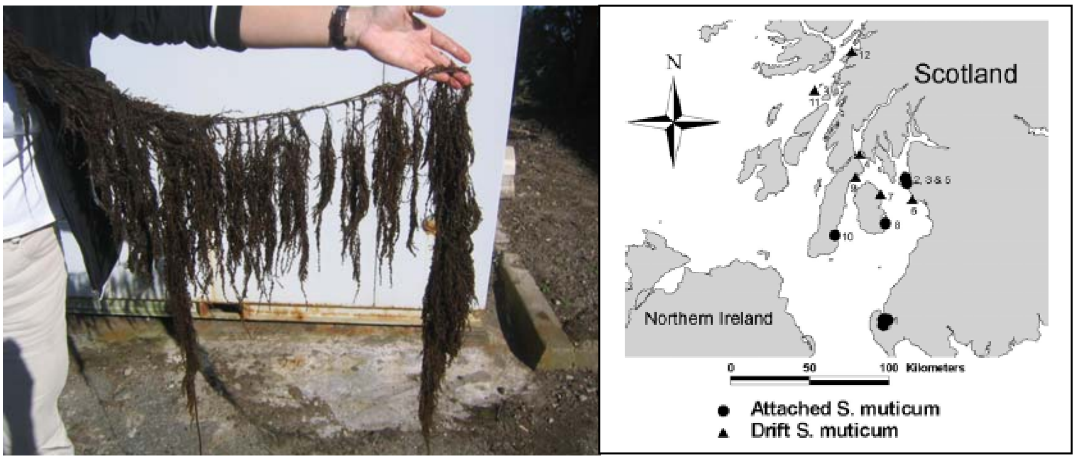

Figure 7. Photograph of Sargassum muticum collected from Campbeltown, Mull of Kintyre (Image E. Cook) and map of distribution in Scotland to 2007 (From Harries et al. 2007a).

Wales

Like *C. gigas*, the Manila clam *Venerupis philippinarum* was originally introduced for cultivation (ICES 2006b). Occasional reports of individual specimens found further along the coast have been made, mainly in the Thames area near the hatchery. A flourishing fishery in Poole Harbour on the south coast of England harvested 350 tonnes in 2005 (ICES 2007). Naturally recruited Manila clams have recently been found about 35 miles to the east of Poole in Southampton Water and in Wales representing a considerable expansion of its distribution. Further dispersal is likely under prevailing conditions as the species grows well at sea temperatures up to 26° C. The potential impact on native fauna is unclear at this time. The slipper limpet

Crepidula fornicata was also recently found in the Menai Strait, North Wales, most likely introduced with mussel seed.

England

Coastal developments such as marinas provide artificial habitats that appear to be important for the establishment and spread of marine non-natives, and are often close to sites of primary introduction such as ports. A rapid survey in 2004 of 12 localities on the south coast of England, mostly marinas, recognized 20 non-native species of alga and invertebrate amongst a total of 80 taxa encountered (Arenas *et al.* 2006). On average, nine non-native species were found per locality. Two species of non-native sea-squirt (ascidian) new to the UK were recorded during the survey, and significant range extensions were noted for three other non-native organisms. The number of non-native sea-squirts known in the British Isles rose from one in 1997 (Eno *et al.* 1997) to six by 2005 (Nishikawa *et al.* 2000; Arenas *et al.* 2006; Minchin and Sides 2006), suggesting a much faster rate of arrival compared to previous decades for this group.

7. PREDICTION

There has been limited modelling of the effects of climate change on non-native species around the British Isles. As indicated earlier, most relevant modelling is on native species and may be extrapolated to introductions. An exception was the modelling undertaken within the MarClim project which examined potential range expansions for two algae (*Codium fragile* and *Sargassum muticum*) and one barnacle (*Elminius modestus*). The models predicted that the three species are likely to extend their range with rising temperatures. At present there are no international standards for Ecological Risk Assessment (ERA) of marine invading species. Recent UK studies have adapted and extended a risk assessment scheme to all non-native species, including marine invertebrates and fish (Baker *et al.* 2008) and a number of equivalent European programmes have been addressing non-native species. New procedures for reporting (including location and time information for incorporation in an international database and mapping system) are being proposed by ICES to monitor the occurrence of non-natives (see ICES 2008).

8. KEY LINKAGES

Introductions of non-native marine species to the British Isles have been recorded since the end of the 19^{th} century although some species are likely to have arrived before then attached to sailing boats. There is moderate confidence that the major vectors of introduced species in the past, in order of importance, were attachment to ships in the fouling community, presence in ship ballast water and as organisms imported deliberately or unintentionally for aquaculture ventures (moderate confidence). Since the 1980s there has been an increase in abundance and a northerly extension of the range of many introduced species that were increasing previously at a much slower rate (high confidence). This change has been attributed to higher temperatures and a longer growing season caused by climate change (moderate confidence). To our knowledge there has been no statistical analysis of the timing, development and expansion of all non-native species introduced since the 19^{th} century to the British Isles. It is believed that there has been an increase in the occurrence of non-native introductions (low confidence), but as there has been no full analysis this cannot be confirmed. It might be expected that a rapidly growing trend in the tonnage and activities of shipping and in the development of aquaculture might have led to a proportional increase in introductions, but this does not appear to be the case (low confidence). It is clear, however, that warmer water species of the plankton, benthos and fish, including non-natives are expanding northward and colder water equivalents are retreating to the north (high confidence). However, in the plankton at least, a colder period in the late 70s early 80s may have reintroduced colder water species.

Evidence that Pacific organisms may have invaded by a trans-Arctic migration has major implications for biodiversity and biogeochemical cycles in the North Atlantic (low confidence). On the last occasion that such an event took place in the Pliocene there was a complete reorganisation of the Atlantic benthic fauna (high confidence). Ocean acidification is expected to have a large impact on calcareous plankton and benthic organisms with species that have Mg calcite and aragonite body parts likely to be particularly vulnerable (moderate confidence). Potential large changes in community structure due to acidification are likely to alter and possibly reduce the magnitude and direction of ocean/atmosphere CO_2 fluxes (moderate confidence). The productivity and possibly even survival of many organisms presently farmed in aquaculture ventures may reduce due to ocean acidification (low confidence) with potential large social and economic consequences. Hybridisation between native and non-native species is considered a low probability event even though there is a good historic example within the genus *Spartina*. However, if such an event did occur it could have a major impact on marine ecosystems (high confidence). Reproduction between possible escapees of cultured tetraploid species produced for aquaculture and native congeneric species, considered to be a low probability event could lead to sterile populations in the wild. Non-native species may act as vectors for parasites (high confidence) that can have a severe impact on aquaculture and native populations (medium confidence).

A number of occurrences of new invasive species appear in quick succession in distant locations implying that they have been present with a wide distribution for some time and their sudden appearance in noticeable numbers is a response to some environmental cue (low confidence). Alternatively, their simultaneous appearance may be due to an increase in survey activity or an increase in awareness (low confidence). The speed of expansion of most species indicates that present monitoring based on surveys for the benthos and single point regular monitoring for plankton as well as the extensive spatial coverage of the Continuous Plankton Recorder is adequate for purpose (moderate confidence). This may not apply for some of the smaller protists/phytoplankton that require special collection, preservation and electron microscopy techniques and/or molecular analysis for identification. It is also worth emphasising that there is much less surveying for non-native species in the marine compared to terrestrial environments and that funding for monitoring is often insecure and short term.

9. KEY LINKS TO OTHER ECOSYSTEM LINKAGES REPORT CARD REVIEWS

Arctic sea ice: As Arctic sea ice retreats due to rising global temperatures there will be profound impacts on Arctic marine ecosystems with an expansion of species at present restricted to the adjacent oceans into the Arctic. Impacts on the British Isles are likely to be restricted to the consequences of any changes to circulation as part of the Meridional Overturning Circulation. As described above the introduction of Pacific species to the North Atlantic could also have an impact in the longer term through competition and hybridisation of the fauna and flora native to the British Isles.

A view from above: changing seas, seabirds and other food sources: To the present there is little evidence of major ecosystem or food web effects from the introduction of non-native species. However, the projected large changes in sea temperature over the next century combined with acidification effects may lead to an increase in the rate of introductions and it is difficult to forecast potential consequences. As sea temperatures rise over the next century the waters around the British Isles are likely to become less productive with consequent effects for the food web, birds and living marine resources. Introduction of new non-native species may exacerbate these effects.

Coastal economies and people: Increased growth of existing non-native species on aquaculture structures may impact coastal economies. There may also be an increase in the occurrence of bloom events impacting fish farms and fisheries. On past experience there would appear to be few other large impacts from introductions under this heading, but any impact will be highly dependent on the species that is introduced. On the contrary, growing economies with increases in population and development can act in another way by providing artificial 'islands' of hard substrate (e. g. sea defences, harbour developments, marina developments) which may act as stepping stones for the spread of hard-bottom fauna and flora, including native and non-native species, responding to climate change. The increase in the growth of marinas, especially on the south coast of England may be providing a substrate for the spread of organisms in exactly this way. Such sites are also potentially interlinked by movements of boats carrying adult sessile biota as hull fouling.

Acidification: See Conclusions below.

10. CONCLUSIONS

Evidence from introduced plankton and benthic species indicates that non-native organisms can expand rapidly in range reflecting and following the general circulation of waters adjacent to the British Isles. To some extent incursions of oceanic water onto the shelf may impact pelagic systems, as appeared to have happened in the recent bloom of the jelly fish *P. noctiluca*. This route also appears to be an important vector of non-native phytoplankton, which could potentially include HAB species such as the dinoflagellate *Karenia mikimotoi*. New immigrants appear to integrate into the existing seasonal succession, possibly occupying a previously unused niche, but there is little or no evidence that they replace or eliminate other species. However, when they first appear they may occur in large numbers and cause major changes in the ecosystem with downstream consequences for the food web and living marine resources. The occurrence and abundance of many species is linked to temperature through physiology and the effects of temperature on the physical and chemical environment. As a consequence the abundance of both native and non-native warm temperate species around the British Isles is likely to increase over the next century with warmer water species moving northwards and boreal species retreating to the north. Exactly this pattern has been found for many species of zooplankton that have moved north by over 1000km in the last 50 years (Beaugrand *et al.* 2002). There is also evidence for an increase in the occurrence of warm temperate species of the plankton in British waters including for example *Euchaeta hebes*, *Clausocalanus* and *Ceratium hexacanthum*. These species occurred in the North Sea in 2005 at six standard deviations above their normal level of abundance over the period 1946-2004. There are many similar observations for benthic organisms (Mieszkowska *et al.* 2006), fish (Brander *et al.* 2003) and turtles (McMahon and Hays 2006) of a northerly movement of warmer water species and retreat to the north of species favouring colder water conditions, a process that is also likely to influence the introduction of non-native species.

The reappearance of *N. seminae* in the North Atlantic, and its subsequent establishment over a large area of the sub-polar biome, could be an indicator of the scale and speed of changes that are taking place in the Arctic and North Atlantic oceans as a response to climate warming. The consequences of such changes to the function, carbon cycle feedbacks and biodiversity of Arctic and Atlantic sub-polar systems are at present unknown. It is also not known if Pacific non- native species will extend into the shelf seas around the British Isles. If and when they do they are likely to have a large impact on existing communities.

The potential for hybridisation between native and non-native species and possible escapees of tetraploid species produced for aquaculture that could lead to sterile populations in the wild are concerns for the future. Non-native species may act as vectors for parasites that can have a severe impact on aquaculture and native populations that can last over decades, e.g. recent expansions to Scotland and Ireland of the protozoan parasite *Bonamia ostreae* to native oysters (ICES 2007).

A further major unknown is the effect of ocean acidification on native and non-native plankton, both calcareous and non-calcareous forms (Turley *et al.* 2009) If carbon emissions continue at their present rate it is expected that the oceans will be less alkaline within 100 years than since the middle Jurassic and the change in pH will have taken place over a century compared to thousands to possibly a million or more years. Many planktonic organisms and especially those with calcareous body parts and most particularly those with aragonite are likely to become vulnerable and some species may become extinct. The larvae of many benthic organisms such as sea urchins (echinoderms) and shellfish (bivalves and gastropods) also have calcareous body parts and may be particularly vulnerable to acidification. Unlike corals, the effect of ocean acidification on calcium carbonate-producing phytoplankton is, however, unclear, and shows a non-uniform response across species in laboratory experiments (Riebesell *et al.* 2000; Langer *et al.* 2006; Iglesias-Rodriguez *et al.* 2008). The balance between calcification and photosynthetic carbon fixation controls whether calcifying phytoplankton represent a sink or a source of CO_2 to their surrounding environment (Frankignoulle *et al.* 1994). Potential large changes in community structure due to acidification could change the magnitude and direction of CO_2 fluxes and likely reduce or possibly increase the extent to which the ocean can take up anthropogenic CO_2 from the atmosphere.

In a recent review Reise *et al.* (2006) consider that one of the reasons why European coasts have acquired a large number of non-native species in a global perspective is a consequence of the changeable environments during the Pleistocene so that climax conditions have not been reached with low diversity fauna and flora. This may apply to the benthos, but does not fit with information from the plankton, where species have wider distributions. There is little evidence for pronounced negative effects on biodiversity and ecosystem functioning, other than possibly fouling of structures by excessive growth. More often, invaders expand ecosystem functioning by adding new ecological traits, intensifying existing ones and increasing functional redundancy (Reise *et al.* 2006). Observed impacts vary between habitats, the phase of the invasion and local climate variability. Cold winters for example may retard the development and spread of some non-native species. Finally, there are a number of non-native species that have already reached adjacent shores to the British Isles that are waiting in the wings to arrive in the UK.

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