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Impacts of climate change on non-native species

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EXECUTIVE SUMMARY

Anthropogenic changes to climate and extreme weather events have already led to the introduction of non-native species (NNS) to the North Atlantic. Regional climate models predict that there will be a continuation of the current trend of warming throughout the 21st century providing enhanced opportunities for NNS at each stage of the invasion process.

Increasing evidence is now available to show that climate change has led to the northwards range expansion of a number of NNS in the UK and Ireland, such as the Asian club tunicate *Styela clava* and the Pacific oyster *Crassostrea gigas*.

Providing definitive evidence though of the direct linkage between climate change and the spread of the majority of NNS is extremely challenging, due to other confounding factors, such as anthropogenic activity.

Localised patterns of water movement and food supply may also be complicating the overall pattern of northwards range expansion, by preventing the expansion of some NNS, such as the slipper limpet *Crepidula fornicata* and the Chilean oyster *Ostrea chilensis*, from a particular region.

A greater understanding of the other aspects of climate change and increased atmospheric CO_2, such as increased rainfall, heat waves, frequency of storm events, and ocean acidification may aid in increasing the confidence that scientists have in predicting the long term influence of climate change on the introduction, spread and establishment of NNS.

1. WHAT IS ALREADY HAPPENING?

Introduction

Non-native species (NNS) are those that have been intentionally or unintentionally introduced outside their native range and provided with greater dispersal potential as a consequence of human activity (Maggs *et al.*, 2010; CBD, 2012). Once established, if these species then threaten biodiversity and/or cause economic damage they are referred to as 'invasive' (Wilcove *et al.*, 1998; CBD, 2012). Biological invasions are not only one of the greatest threats to marine biodiversity (Molnar *et al.*, 2008), but they can also cause massive economic and ecological damage (Vitousek *et al.*, 1997; Pimentel *et al.*, 2005). Increased international trade has caused an exponential increase in the spread of NNS around the world over the last few decades (Carlton and Geller, 1993; Hulme, 2009) and this trend has been observed in Britain (Roy *et al.*, 2012; Minchin *et al.*, 2013). The estimated cost of NNS to the economy in Great Britain is £1.7 billion a year (Williams *et al.*, 2010). The annual cost to 'marine-based' industries (e.g. shipping and aquaculture) in GB is estimated to be £39.9 million, although this is probably an underestimate, as there is little distinction made between native and non-native species during pest control operations (Williams *et al.*, 2010).

More than 90 NNS have been identified from British and Irish (including Republic of Ireland and Northern Ireland) marine and brackish environments, of which over 60 are now established (Minchin, 2007; Roy *et al.*, 2012; Minchin *et al.*, 2013). Their arrival has been principally due to shipping, including ballast waters and sediments, fouling of

Figure 1: Fouling of a yacht hull with Didemnum vexillum, Botrylloides violaceus *and mussels (courtesy D. Offer).*

hulls (Figure 1) and other associated hard structures, and imported consignments of cultured species (Holmes and Minchin, 1995; Minchin *et al.*, 2013). The majority of marine NNS in Britain originate from the North Pacific, followed by the North-west Atlantic (Minchin *et al.*, 2013). Many are initially reported from sites of anthropogenic activity, such as ports, marinas and aquaculture facilities, particularly in the English Channel, with a number subsequently spreading northwards to the North or Celtic Seas (Minchin *et al.*, 2013). Only a small proportion of the NNS established in the UK are known to have had a significant impact on existing communities (e.g., the slipper limpet *Crepidula fornicata*) (Bohn *et al.*, 2012) and to date these impacts have typically been species-specific or localised to a particular region (Minchin *et al.*, 2013).

Human-mediated changes to climate and extreme weather events have already led to the introduction of NNS to the North Atlantic (Reid *et al.*, 2009; Pederson *et al.*, 2011) and regional climate models predict that there will be a continuation to the current trend of warming throughout the 21st century (IPCC, 2007). Climate change can influence every stage of the invasion process, including introduction, establishment and secondary dispersal (Chapman, 2000; Colautti and MacIsaac, 2004; Maggs *et al.*, 2010; Pederson *et al.*, 2011), although it is often difficult to attribute, for example, shifts in NNS distribution or increases in reproductive success, directly to climate change due to a lack of biological and physiological data (Pederson *et al.*, 2011). However, increasing seawater temperatures have been shown to have contributed to the recruitment of certain species, such as the Pacific oyster *Crassostrea gigas* (Syvret *et al.*, 2008; Guy and Roberts, 2010) at more northerly locations in the UK (Kochmann *et al.*, 2012) and Europe (Wrange *et al.*, 2010) and may have contributed to others becoming established outside the warm water areas created by power station outflows, such as the bryozoan *Bugula neritina* (Ryland *et al.*, 2011). Understanding the role that changes in seawater temperature and other indirect consequences of climate change play in the initial establishment of NNS and the range that they may occupy in the introduced environment is critical if their environmental and economic impacts are to be mitigated (Bohn *et al.*, 2012). The aim of this report is to provide regional updates on the evidence for the influence of climate change on marine and brackish water NNS, to discuss what could potentially happen in the future, highlight the knowledge gaps and describe any socio-economic impacts relating to NNS in the UK and Ireland.

1.1 Scotland

In Scotland, 17 marine and brackish water NNS are known to be established (Minchin *et al.*, 2013). A number of these species have spread northwards up the west coast of the UK having been originally recorded on the south coast of England, for example, the Asian club sea squirt *Styela clava* (Ashton *et al.*, 2006) (Figure 2), the Japanese macroalga *Sargassum muticum* (Harries *et al.*, 2007), the Southern Hemisphere ascidian *Corella eumyota* and the Pacific bryozoan *Tricellaria inopinata* (Beveridge *et al.*, 2011). There are a few species whose distribution is likely to be tracking the northwards movement of seawater temperatures in Scotland, for example *S. clava*.

Case Study: *Styela clava*

This species was first recorded in Scottish waters in Loch Ryan (south-west Scotland) in 1988, where populations remained relatively 'stable' for over a decade. In the last 10 years, this species has spread relatively rapidly northwards with the most recent sighting recorded in Loch Carron, on the mainland to the east of the Isle of Skye (Figure 3). *Styela clava* is a large, solitary sea squirt, which is native to the NW Pacific (Davis and Davis, 2009). It was first reported in Plymouth Sound (Devon) in 1953 (Carlisle, 1954) and has slowly spread northwards up the west coast of the UK over the past half century. *Styela clava* can tolerate temperatures from -2 - 23 °C for short periods, yet in a study of 260 European marinas (excluding Denmark), *S. clava* was not reported at sites where the seawater temperatures remained below 16 °C during the summer months (Davis and Davis, 2007). Seawater temperature data however, from sites on the west coast of Scotland indicate that this threshold has been reached in the last decade as far north as Mallaig in the summers of 2003/04 and that temperatures have exceeded

*Figure 2: The Asian clubbed tunicate (*Styela clava*) on mussel longline moorings in Co Cork (courtesy V. Roantree).*

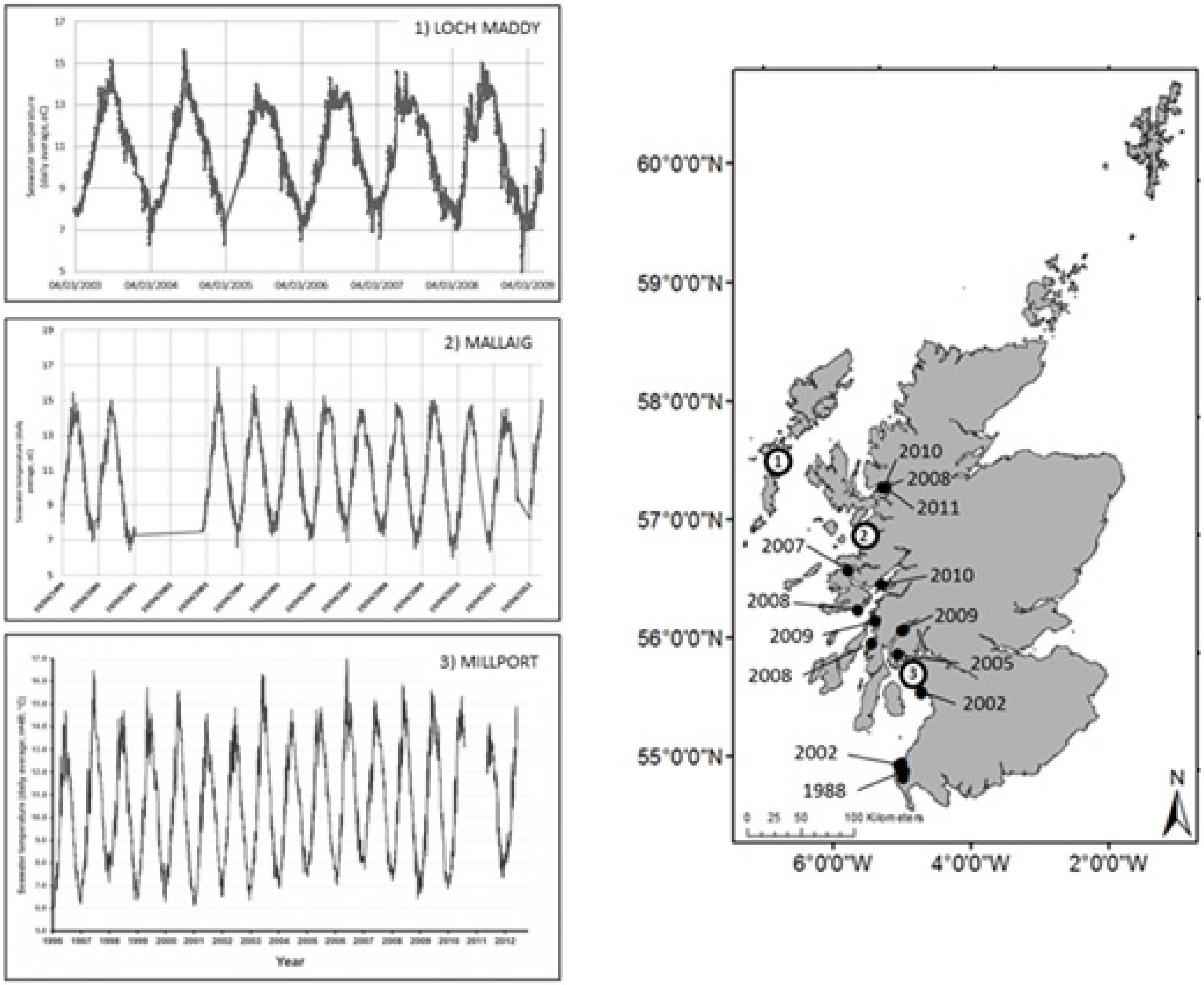


*Figure 3: Upper ocean temperatures (daily averages, °C) at selected locations on the west coast of Scotland (courtesy Marine Scotland (Loch Maddy and Mallaig), M. Sayer, NERC National Facility for Scientific Diving, Scottish Association for Marine Science (Millport)) and distribution of the Asian clubbed tunicate (*Styela clava*) in Scotland. Data retrieved from NBN Gateway, September 2012.*

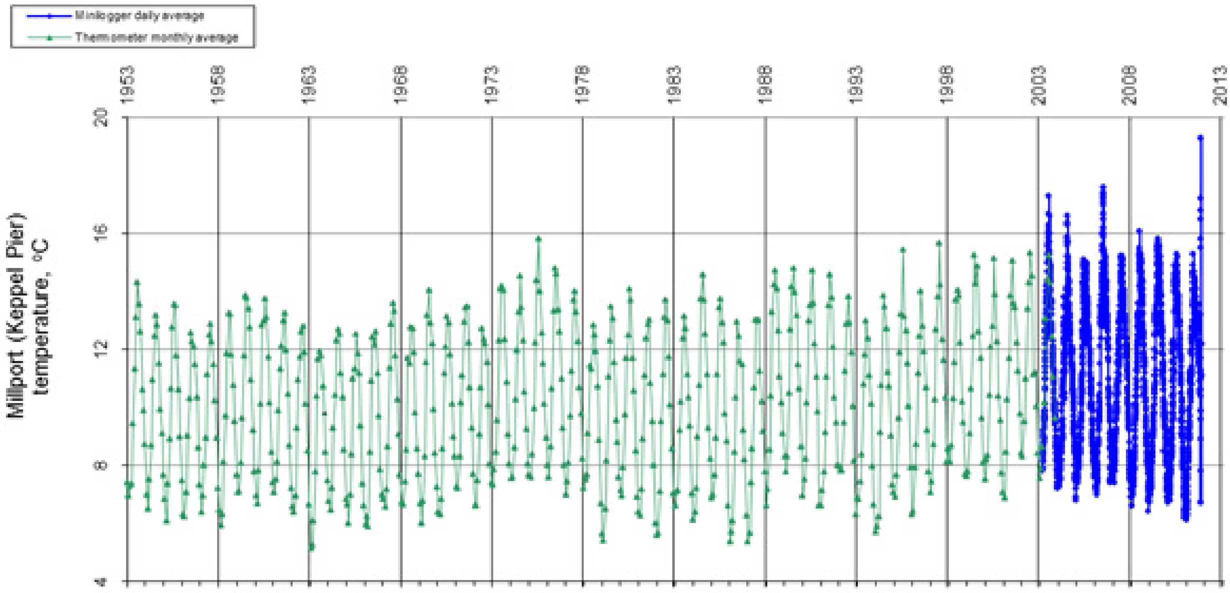


Figure 4: Temperature increase shown to increase from 2003 in Millport.

Figure 5: Japanese macroalga Sargassum muticum *collected at Campbeltown, Mull of Kintyre (courtesy E. Cook, Scottish Association for Marine Science).*

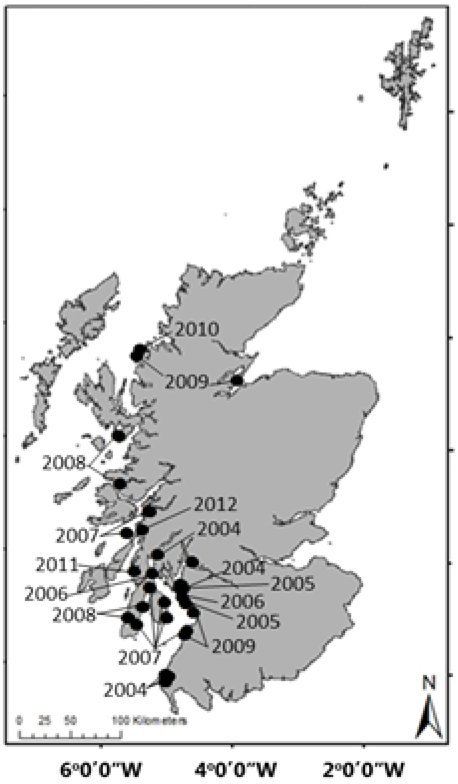


Figure 6: Distribution of the Japanese macroalga Sargassum muticum *in Scotland. Data retrieved from NBN Gateway, September 2012.*

this threshold in the summer months by up to 1.4 °C in the Clyde since 2003 (Figure 4). *Styela clava* is hermaphroditic, producing free-swimming larvae, which can survive in the water column for 12 - 24 hrs prior to attachment (Lützen, 1999). Long distance dispersal (>50 km) though is typically associated with human-mediated movement of the adults (Dupont *et al*., 2009). However, studies on the residual flow northwards along the west coast of Scotland (Economides, 1989) and the occasional 'jet stream' currents (Simpson *et al*., 1979) suggest that passive marine larvae may be transported up to 10 km in one direction by these currents in any 24 hour period (Hiscock *et al*., 2004). A combination of anthropogenic and natural transportation, in conjunction with summer seawater temperatures reaching the 16 °C threshold in more northerly locations in the last decade, may therefore have triggered the recent expansion of *S. clava* northwards up the west coast of Scotland.

Case study: *Sargassum muticum*

It is highly likely that many of the species that have spread northwards in the UK are not restricted in distribution by seawater temperatures, as they are found further north in Norwegian waters (Rueness, 1989; Sjøtun *et al*., 2008) and that other anthropogenic factors, such as vessel activity and natural dispersal, are responsible for their movement. For example, the non-native macroalga *S. muticum* has been spreading northwards in Scotland since it first arrived in Loch Ryan in 2004 (Figure 5 and 6). Seawater temperatures, in this case, are unlikely to be contributing directly to the spread of this species, as germlings have a wide temperature tolerance, will grow at 10 - 30 °C (Hales and Fletcher, 1989) and *S. muticum* is already established in Norway (Rueness, 1989). However, the growth rate of germlings and vegetative branches increases with temperature over the range 5 - 25 °C (Norton, 1977). This suggests that increased seawater temperatures could indirectly increase the abundance of established populations of *S. muticum* in Scotland by the 2050s and as a consequence, negatively affect the abundance of several important indigenous taxa, such as *Laminaria*, *Fucus* and *Codium* (Staehr *et al*., 2000).

1.2 Wales

In Wales, as in the rest of the British Isles, records of marine non-natives have shown a pattern of increasing species number and species abundance over the past decade. Part of this change no doubt reflects increases in monitoring frequency and intensity, particularly in known hotspots such as marinas, but it also seems likely that it is real. Notable arrivals have been the Chinese mitten crab (*Eriocheir sinensis*) in the Dee and Conwy estuaries (Bentley, 2011; E. H. Morgan pers. comm.) and the colonial Carpet sea squirt *Didemnum vexillum* in Holyhead marina (Griffith *et al*., 2009). Neither of these important invasive species can be deemed to have arrived as a consequence of warming or other aspects of climate change, but due to particular vectors to these specific locations. Currently, these species are restricted in their Welsh distribution to these locations. Other records of non-natives have been facilitated through surveys of marinas and rocky shores and reveal an increasing occurrence of species previously restricted to the south coast of England, but now found in many parts of the British Isles including, the sea squirts *C. eumyota* (N. Mieszkowska, pers. comm.) and *Botrylloides violaceus* (GB NNSS, 2012), the bryozoans *T. inopinata* and *Bugula neritina*, and the alga *Grateloupia turuturu* (Minchin *et al*., 2013). There is no available direct evidence, however, that the increasing frequency of such species represents anything other than the consequences of vectors of introduction, including boat traffic and aquaculture movements.

Case Study: *Crepidula fornicata*

Crepidula fornicata, commonly referred to as the slipper limpet, is native to the north-west Atlantic, but has spread rapidly throughout most European waters following its first introduction in the late 19th century (Crouch, 1894). Its non-native range now spans from the Mediterranean Sea in the south to the Irish Sea and Norwegian coastal waters in the north (Pederson *et al.*, 2011). The species first occurred in Welsh waters in the 1950s in Milford Haven Waterway (MHW) (Cole and Baird, 1953), probably as a consequence of the laying up of naval and merchant vessels transported from the English south coast. It spread rapidly within the waterway (Crothers, 1966), where it currently reaches local abundances of >1,000 individual m^{-2} in both the intertidal and subtidal zones (K. Bohn, unpubl.), as well as colonising areas to the south (Mettam, 1979). Recent observations at Skomer Island, outside the waterway, suggest that *C. fornicata* may have established limited breeding populations on the open coast (Newman *et al.*, 2012), but detailed intertidal surveys throughout Cardigan Bay and further north have failed to detect signs of further spread (K. Bohn, pers. comm.). In 2006, *C. fornicata* was accidentally introduced to the Menai Strait in North Wales through movement of mussel spat. A rapid removal and monitoring programme was instigated by the Countryside Council for Wales and no further signs of this species have been found (Menai Strait Fishery Order Management Association, 2011). Thus, despite its obvious success within MHW, *C. fornicata* has failed to make any significant spread northward in Wales in the intervening decades. The MHW and waters immediately adjacent on the open coast still seem to contain the northernmost self-sustaining population of the species along the Welsh coastline.

The factors limiting further northwards spread of *C. fornicata* from the MHW are unclear. Recent work by Bohn *et al.* (2012) has shown that the duration of the reproductive season of populations at their northern limit in Wales is similar to that recorded from more southerly European populations, with spawning and larval release occurring throughout most of the year. Benthic recruitment was, however, observed over a much shorter period and Bohn *et al.* (2012) speculate that predicted rises in seawater temperature could facilitate *C. fornicata*'s spread along the Welsh coast by providing better conditions for successful settlement. However, given the lack of significant northward spread over six decades, the last three of which have shown significant warming, it is also possible that factors such as local and regional hydrodynamic patterns and unsuitable habitat to the north of the MHW are creating a barrier to northward spread. This conclusion is strengthened by the presence of breeding populations of *C. fornicata* in Belfast Lough, Northern Ireland (McNeill *et al.*, 2010) far to the north of the northern limit in Wales.

Case Study: *Ostrea chilensis*

The Chilean oyster, *Ostrea chilensis*, was introduced into the Menai Strait by the Ministry of Agriculture, Food and Fisheries during the early 1960s as a potential commercial replacement for the diminishing native European oyster (*Ostrea edulis*) (see Walne, 1974). 30 years after introduction the oysters which were deemed a commercial failure had expanded their distribution by a modest 400 m (Richardson *et al.*, 1993). However, since the early 1990s, the Chilean oyster has increased its distribution to over 30 km of coastline, occurring at high densities in places (Morgan and Richardson, 2012a). Whilst an increase in the intensity of anthropogenic activities such as bivalve culture and periwinkle harvesting are likely to have facilitated this recent spread (see Morgan and Richardson, 2012b), warmer sea temperatures in recent years may also have played an important role in promoting the range expansion. Despite its narrow breeding season (June-July) and low annual numbers of brooding oysters within the Menai Strait (≤4.6% of all oysters ≥60 mm), high spatfall has been observed over recent years, particularly following periods of high food concentrations during early gametogenesis (E. H. Morgan, pers. comm.). During the first 30 years, following the introduction of *O. chilensis* into the Menai Strait, only 25.8% of the mean annual sea temperatures were ≥11.5°C, coinciding with observations from 1992 of a highly-restricted population distribution with relatively low oyster densities (<12 m^{-2}) (see Richardson *et al.*, 1993). Conversely, 78.9% of the annual mean sea temperatures were ≥11.15°C between 1993 and 2011, coinciding with a geographic range of >30 km of shoreline and densities of up to 232 oysters m^{-2} (see Morgan and Richardson, 2012). A spawning temperature of ~12°C and a high spring phytoplankton bloom concentration are related to the commencement and magnitude of spatfall in this non-native population (E. H. Morgan, pers. comm.). Whilst further increases in seawater temperature are likely to extend the breeding season, it remains unclear whether plankton dynamics will match with the nutritional requirements of adult oysters and whether this will influence the invasion success of this species over the next few years.

1.3 Northern Ireland

In Carlingford Lough, several seaweeds associated with oyster cultivation (including *Polysiphonia morrowii*, originally from Japan and previously introduced into France and the Netherlands) have been recently recorded in Ireland for the first time (Mineur and Maggs, unpublished). A survey of marinas and associated coastline commissioned by the Northern Ireland Environment Agency has also revealed the presence of the sea squirt *D. vexillum* (Strangford Lough and Lecale Partnership, 2012). In most cases, there is no obvious link with warming temperatures or other aspects of climate change, and the introductions have been associated with the presence of suitable vectors. The northwards spread of the Pacific oyster *C. gigas*, however, has been linked to increasing seawater temperatures.

Case study: *Crassostrea gigas*

In our last report (Maggs *et al.*, 2010), we highlighted the impact of warming sea temperatures on the breeding potential of *C. gigas* (Figure 7). This species was shown to have functional gonads in Strangford Lough over several recent years, in association with warmer summer temperatures (Guy and Roberts, 2010), and this had led to successful spatfall and

Figure 7: The Pacific oyster Crassostrea gigas *on marina pilings, Plymouth in July 2007 (courtesy Dan Minchin).*

recruitment at this site. A recent genetic study has now shown that Lough Foyle, which separates Donegal from Northern Ireland in the north-west, has feral populations of *C. gigas* (Kochmann *et al*., 2012). Feral populations have high genetic diversity relative to aquaculture populations and exhibit a large number of private alleles not found in aquaculture stock. The large effective population size (a measure of the number of breeding individuals) also indicates that feral populations are self-sustaining. This study confirms that *C. gigas* has become established in two of the marine inlets on the coast of Northern Ireland and has effectively escaped from aquaculture. It is very likely that it will also be able to breed in Carlingford Lough, which constitutes the eastern border between Northern Ireland and the Republic of Ireland.

1.4 Republic of Ireland

In the Republic of Ireland (hereafter known as 'Ireland'), 28 marine and brackish water NNS have been recorded (Minchin, 2007), but there have been no general surveys since 2005/6 (Minchin, 2007), so this figure is likely to be an underestimate. Accounts of the possible effects of climate change on non-native species in Ireland have been reported (Boelens *et al*., 2005). The clearest indication of impacts of climate change on NNS in Ireland relates to the recent settlements in some shallow bays by the Pacific oyster *Crassostrea gigas* (Pederson *et al*., 2011). Such settlements though are highly dependent upon warm water events, which have occurred locally on all coasts (Boelens *et al*., 2005).

The sea squirt *Styela clava*, has also spread extensively throughout Ireland during the last decade (Minchin *et al*., 2005). Its first known occurrence was in 1972 in Cork Harbour, where it would appear to have remained confined for over 30 years (Minchin and Duggan, 1988), until its more recent spread to the south, east (Minchin *et al*., 2006) and north coasts of Ireland (Nunn and Minchin, 2009). On the south coast, it has formed dense concentrations on floats and moorings used in the hanging culture of mussels in at least one shallow bay (Nunn and Minchin, 2009) (Figure 2). It is unclear, to date, whether its recent expansion has been due to more suitable conditions arising from changes in recent weather events, increased human activity, or both. However, as seawater temperatures continue to increase, this species is expected to spread northwards and to become established on the west coast of Ireland by the 2020s.

Other more recently arrived sea squirts, include *D. vexillum*, first recognised in 2005 at a marina on the east coast of Ireland (Minchin and Sides, 2006) and *C. eumyota* first recorded in 2005 at five sites along the south-west, southern and eastern Irish coasts (Minchin, 2007). Temperature here is unlikely to be the limiting factor for their distribution though, as both species are found further north in the UK and their spread has most probably been related to recreational craft movements and Pacific oyster transfers. In the case of *D. vexillum*, however, temperature is known to be an important factor in controlling the seasonal cycle of growth, reproduction and degeneration of colonies and that increasing temperatures are likely to have a positive influence on asexual and sexual reproduction, the later including gametogenesis, length of the breeding period, larval development and recruitment success (see review in Nimmo *et al*., 2012).

1.5 England

A recent study identified more than 74 established marine and brackish water non-native species in England (Roy *et al*., 2012). The majority of these species were first recorded on the south coast of England and many have since spread northwards. A small number of these species may have spread more rapidly as a result of warming seas.

Case study: *Undaria pinnatifida*

The Japanese kelp, Wakame, *Undaria pinnatifida* grows up to 3 metres long. It has a complex lifecycle involving a large sporophyte (annual) and a microscopic gametophyte stage. In its native habitat, sporophytes grow rapidly in winter and spring when sea surface temperatures are 5 - 13 ^{o}C. Growth is optimal at 10 ^{o}C (Hay and Villouta, 1993). The zoospores are released in late spring or early summer, when temperatures are between 7 and 20 ^{o}C. The zoospores germinate at 20 ^{o}C (Farell and Fletcher, 2000). *Undaria pinnatifida* was first recorded in the River Hamble in 1994 and by 2004 had a distribution between Ramsgate and Torquay, apparently spreading via natural and anthropogenic means (most new arrivals have been documented from marinas and harbours). The species is currently found in and around several ports and marinas in South-west England, including first records for the Fal in 2010 (J. Bishop, pers. comm.) and more recently in 2012, the north-east and west coasts of England, in marinas at Fleetwood and Grimsby (see NBN Gateway) and in Liverpool Docks (C. Frid, pers. comm.). In late 2012, it was also reported for the first time in Ireland in Carrickfergus marina, County Antrim (D. Minchin, pers. comm.). Increasingly, *U. pinnatifida* is being found growing on natural substrate rather than man-made structures and the current rate of spread seems to be high. The temperature requirements for this species suggest that as seas become warmer, *U. pinnatifida* may be able to develop more effectively at the zoospore germination phase and the spread northwards continue. There is evidence, however, that human transportation is playing a major role in the spread around the coast, therefore, confounding any observations that climate change may be responsible for any future changes in distribution.

2. WHAT COULD HAPPEN?

Climate change is likely to play a major role, not only in shaping the distribution of existing marine and brackish water NNS around the British coast (Minchin *et al*., 2013), but also in determining which novel species are successfully introduced to UK and Irish waters in the next few decades.

2.1 Northwards range expansion of INNS already present in UK and European waters

At present, a number of NNS in UK and European waters appear to be restricted in their range due to their requirement for summer seawater temperatures above the threshold for successful gametogenesis and early development. For example, the large, predatory rapa whelk *Rapana venosa* has established populations off the coast of mainland Europe. It is capable of surviving water temperature between 4 -27 °C, however, egg capsules may only be laid when water temperatures exceed 18 °C (Harding *et al*., 2008). This probably explains why, although individuals have been captured in the North Sea (Kerckhof *et al*., 2006), the species does not yet seem to have become established. However as sea temperatures become warmer, particularly in shallow inshore areas, there is a risk that conditions will become suitable for the whelk to become established by the 2020s along the south coast of England and further north by the 2050s. It is highly likely that self-sustaining populations of the molluscs *Crassostrea gigas* and *Crepidula fornicata* will also continue to expand northwards and become established on the west coast of Scotland in the 2020s.

In addition, the Manila clam *Venerupis philippinarum* was intentionally introduced for commercial harvest to the South coast of England in 1980 and evidence suggests that climate changes have resulted in the establishment of wild populations in Poole Harbour (Jensen *et al*., 2004), Southampton Water (Caldow *et al*., 2007) and the Stour-Orwell system in Suffolk (Ashelby *et al*., 2005). To date, further dispersal appears to have been restricted by temperature requirements at stages of early development and reproduction. Temperatures of 14 °C are required for spawning to occur (Drummond *et al*., 2006), and eggs are believed to need one to two days at 13 – 16 °C to hatch followed by optimal temperatures of 23 – 25 °C for larval survival. This species was also introduced to Ireland for cultivation purposes in 1973 and it is highly likely that by the 2050s, seawater temperatures may have increased sufficiently to enable this species to increase in abundance and disperse further northwards.

2.2 Increased extreme climatic events

In addition to steadily increasing seawater temperatures, climatic events, such as an intensification and frequency of storms (Leckebusch *et al*., 2006), extreme wind speeds and wave conditions (Grabemann and Weisse, 2008), heat waves and intense rainfall are all predicted to occur over the next few decades (IPCC, 2007). These events will, in turn influence the distribution of NNS and their impact on ecosystem structure and function in UK and Irish waters by the 2050s and 2080s. For example, the macroalga *Sargassum muticum*, which is monoecious, highly fecund, self-fertilising (Norton, 1977) and is able to float once detached from the main plant (Fletcher and Fletcher, 1975; Norton, 1992), could take advantage of the predicted increase in intensity and frequency of storms to enhance their potential for long-range dispersal. It is likely that colonisation of new locations by *S. muticum* throughout northern Scotland will be observed by the 2050s.

Figure 8: The red alga Gracilaria vermiculophylla *at Dundrum Bay, Co. Down, covering a large area of the intertidal zone in July 2012 (courtesy Charmaine Beer, NIEA).*

In addition, the increasing abundance of *Gracilaria vermiculophylla* (Figure 8) in Northern Ireland (introduced from Japan into northern Europe: Rueness, 2005) may be linked with increased rainfall and the resulting depression in salinity. In Europe, *G. vermiculophylla* occurs from Morocco to SW Sweden and also in the Baltic (Weinberger *et al*., 2008). This species can grow at salinities as low as 5.5, mainly in estuaries and brackish water lagoons (Weinberger *et al*., 2008). Its known distribution in Northern Ireland is in sheltered areas of variable low salinities: in Carlingford Lough and Dundrum Bay (C. Beer, pers. comm.). One of the current features of global warming in Ireland is periods of exceptionally heavy rainfall (IPCC, 2007), which is expected to make intertidal environments temporarily freshwater at low tide. Under these circumstances, *G. vermiculophylla* is likely to become increasingly abundant and widespread by the 2050s, as it recruits both from fragments and spores, can grow by up to 7% per day, and does not require hard substrata (Weinberger *et al*., 2008).

Observation and experimentation on the Carpet sea squirt *Didemnum vexillum* provide contrasting views of the effects of short term salinity changes. *Didemnum vexillum* was lost from floating pontoons in an Irish east coast marina following unseasonal heavy rain (D. Minchin, pers. obs.). However, Gröner *et al*. (2011) showed high tolerance to acute and chronic salinity stress in this species in Wales, above and beyond that of a similar, locally common, cosmopolitan species *Diplosoma listerianum*.

2.3 Declines in native biodiversity

As seawater temperatures increase, it is likely that an indirect consequence will be increases in abundance, reproductive output, extended breeding season, and enhanced survival of NNS. For example, elevated temperatures will tend to favour spat production in *C. gigas* with the potential consequence of its outcompeting native species, such as mussels (Nehls and Büttger, 2007) in more northerly regions of the UK (i.e. Northern Ireland and Scotland) by the 2020s. It is also likely that the abundance of *C. fornicata* will increase in regions where it is already established by the 2020s, resulting in competition for food with other filter-feeders and the smothering of native habitats by faecal accumulation, potentially resulting in a reduction in native biodiversity (Pederson *et al*., 2011). The Manila clam *V. philippinarum* and the bryozoan *Tricellaria inopinata* both have greater ability to colonise than native conspecifics owing to the prolonged reproductive periods (Laruelle *et al*., 1994) and in the case of the latter the absence of any colony die-back over the winter months (E. Cook, pers. obs.). It is highly likely that increasing seawater temperatures will favour these NNS to the detriment of their native conspecifics by the 2020s.

3. KNOWLEDGE GAPS

a. Lack of taxonomic expertise on NNS

For many species recorded in the UK, there has been a dependence on the taxonomic skills of national and international experts. Their abilities have been essential in understanding current NIS distributions. A significant decline in the number of these experts over the last few years, particularly in marine taxa that are typically small and taxonomically difficult to identify (Pederson *et al*., 2011), will no doubt have led to an under-reporting of invasions in the UK. In addition, taxonomists have concentrated on near shore marine and brackish water NNS, particularly benthic species due to the ease of sampling marinas, ports and vessels, with the result that offshore benthic and pelagic communities have received comparably less attention (Pederson *et al*., 2011). With the rapid development of offshore sites for marine renewable energy development around the UK, this is an area which requires urgent attention.

b. Lack of baseline distribution and biological information and long-term, regional scale data on NNS

Until recently, there was a distinct paucity of baseline information for marine and brackish water NNS, in northern Scotland and on the north-east coast of England. Two groups (ERI/SAMS and NAFC) are currently addressing the former area including the Northern Highlands, Orkney and Shetland. Monitoring programmes for NNS are also intermittent, for example the last general survey in Ireland took place in 2006/7 and in the UK the last detailed survey was in 2008, as part of the Marine Aliens programme (Cook *et al*., 2011). In England, the surveys have been more regular along the south coast of England. Significant improvements in biological data have been produced for a small number of NNS since the last report card and a full list of species in British marine and brackish waters has recently been published (Minchin *et al*., 2013). The lack of long-term data collection for NNS and in-depth biological information, however, will continue to mean that the influence of climate change on NNS will be difficult to elucidate and future predictions will be based on often conflicting and confounded data.

c. Lack of information on other aspects of climate change and increased atmospheric CO_2 on the invasion success of NNS

Very little information is available on the influence of other aspects of climate change and increased atmospheric CO_2, such as increased rainfall, heat waves, frequency of storm events and ocean acidification on the invasion success of NNS. Research has shown that ocean acidification can have deleterious effects on physiological processes in calcareous species (Ries *et al*., 2009). Preliminary investigations on the Japanese caprellid amphipod *Caprella mutica* showed that increased acidification levels (pH 7.35-7.84; predicted 2100 levels) had no significant impact on survival, growth or moult cycle durations compared with ambient pH conditions when rearing young individuals from hatch (Cook and Boos, 2009). This suggests that certain NNS may have a greater tolerance than native species to increasing acidification, thus facilitating invasion events (Hulme, 2005), however, no field evidence exists in the North Atlantic to support this theory (Pederson *et al*., 2011).

4. SOCIO-ECONOMIC IMPACTS

Non-native species can have a variety of socio-economic impacts on maritime industries including; fouling of nets, cages, buoys, intake pipes, moorings, boat hulls and cultured species, such as mussels and oysters (Williams *et al*., 2010). In the UK, a small number of marine NNS have been reported as causing negative impacts, for example:

Pacific oyster - *Crassostrea gigas*

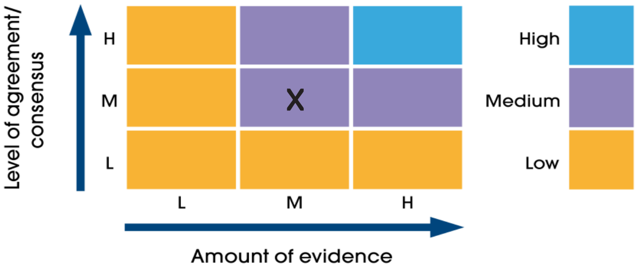
The formation of extensive reefs of sharp shells on the south coast of England has the potential to lead to a reduction in amenity of public beaches (Miossec *et al*., 2009) by the 2020s. Natural spatfall has also provided a source of seed for growers in south-east England (Syvret *et al*., 2008) and supported fisheries in the Netherlands and France (Maggs *et al*., 2010). However, this natural supply of juvenile *C. gigas* has had deleterious effects on growth rates in cultured oysters in France and has led to the modification of oyster-farming practices and the removal of wild oyster stocks in cultivation areas (Cognie *et al*., 2006).

Carpet sea squirt - *Didemnum vexillum*

This species was first reported in Ireland in 2005 (Minchin and Sides, 2006) and it has since been reported in Wales (Griffith *et al*., 2009), south coast of England (Bishop *et al*., 2010) and south-west Scotland (Nimmo *et al*., 2012). Heavy fouling of artificial structures; including fin- and shellfish equipment and support structures by *D. vexillum* has been seen in other countries including, the US and New Zealand, which has led to increased husbandry costs and modification of farming practices (Nimmo *et al*., 2012). To date, this species has only been observed at particularly high densities in north Kent. With increasing seawater temperatures, providing more optimal conditions for both asexual and sexual reproduction (Nimmo *et al.*, 2012), and continued movements via anthropogenic activity, it is likely that this species will have an impact on the major UK fin- and shellfish farming region on the west coast of Scotland by the 2020s.

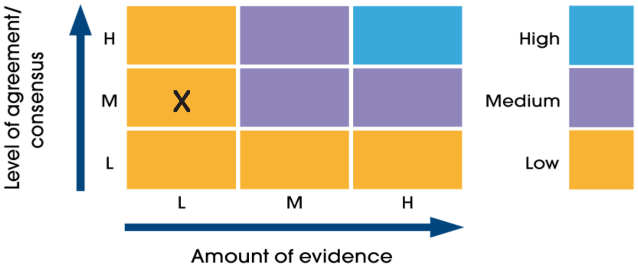
5. CONFIDENCE ASSESSMENT

What is already happening?



The level of confidence in the science has remained the same since the 2010-11 MCCIP ARC report on marine non-natives (Maggs *et al.*, 2010).

What could happen?



The level of confidence has remained the same since the last report (Maggs *et al.*, 2010), although the level of agreement/ consensus has increased from low to medium, since it is now more widely accepted that climate change will result in changes to NNS distribution patterns and an increased frequency of invasion events in the North Atlantic (Walther *et al.*, 2009; Pederson *et al.*, 2011). It must be highlighted, however, that this consensus is based on a relatively limited number of species and therefore, the overall level of confidence in the science remains low.

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REFERENCES

Ashelby, C. W. (2005) The occurrence and distribution of non-native fauna in Harwich Harbour and the Stour and Orwell estuaries, including new records of *Caprella mutica* Schurin 1935 and Bugula stolonifera Ryland 1960. *Essex Naturalist*, **22**, 103-116.

Ashton, G. V., Boos, K., Shucksmith, R. and Cook, E. J. (2006) Rapid assessment of the distribution of marine non-native species in marinas in Scotland, *Aquatic Invasions*, **1**(4), 209-213.

Bentley, M. G. (2011) Eriocheir sinensis *H. Milne-Edwards (Chinese Mitten Crab)*, Oxford: Routledge.

Beveridge, C., Cook, E. J., Brunner, L., MacLeod, A., Black, K., Brown, C. and Manson, F. J. (2011) *Initial response to the invasive carpet sea squirt,* Didemnum vexillum, *in Scotland.* Scottish Natural Heritage, 24.

Bishop, J.D.D., Wood, C.A. and Yunnie, L.E. (2010) *Surveys of marinas and harbours on the south and east coasts of England for the invasive ascidian* Didemnum vexillum *(October to December 2009), Internal report.* DEFRA, 20.

Boelens, R., Minchin, D. and O'Sullivan, G. (2005) *Climate Change: Implications for Ireland's marine environment and Resources, Marine Foresight Series*. County Galway, Marine Institute. 2, 40.

Bohn, K., Richardson, C. and Jenkins, S. (2012) The invasive gastropod Crepidula fornicata: reproduction and recruitment in the intertidal at its northernmost range in Wales, UK, and implications for its secondary spread. *Mar. Biol.*, **159**, 2091-2103.

Carlisle, D.B. (1954) *Styela mammiculata n.sp.*, a new species of ascidian from the Plymouth area, *J. Mar. Biol. Assoc. UK*, **33**, 329-334.

Caldow, R.W.G., Stillman, R.A., le V. dit Durell, S.E.A., West, A.D., McGrorty, S., Goss-Custard, J.D., Wood, P.J. and Humphreys, J. (2007) Benefits to shorebirds from invasion of a non-native shellfish. *Proc. R. Soc. B*, **274**(1616), 1449-1455.

Carlton, J. T. and Geller, J. B. (1993) Ecological roulette: the global transport of nonindigenous marine organisms, *Science*, **261**, 78-82.

CBD (2012) *Glossary of Terms*. http://www.cbd.int/invasive/terms.shtml : date of access (26 10 2012)

Chapman, J. W. (2000) *Climate effects on the geoography of nonindigenous peracaridan crustacean introductions in estuaries.* Marine Bioinvasions Conference, 1999, MIT Sea Grant College Program, Cambridge, MA. 66–80.

Cognie, B., Haure, J. and Barille, L. (2006) Spatial distribution in a temperate coastal ecosystem of the wild stock of the farmed oyster *Crassostrea gigas* (Thunberg). *Aquaculture*, **259**, 249-259.

Colautti, R.I. and MacIsaac, H.J. (2004) A neutral terminology to define 'invasive' species. *Diversity and Distributions*, **10**(2), 135-141.

Cole, H.A. and Baird, R.H. (1953) The American slipper limpet (*Crepidula fomicata*) in Milford Haven. *Nature*, **172**, 687.

Cook, E.J., Baker, G., Beveridge, C.M., Bishop, J.D.D., Brown, L., Clark, P.F., Huys, R., Jenkins, S., Maggs, C., McCollin, T. *et al.* (2011) *Marine Aliens II - Controlling marine invasive species by targeting vectors of dispersal*, Scottish Association for Marine Science, Oban, Report No. 274, 34pp.

Cook, E.J. and Boos, K. (2009) *Effect of ocean acidification on life history traits in the caprellid amphipod* Caprella mutica *Schurin, 1935*, British Ecological Society. Report No. 2585/3162, 11pp.

Crothers, J. H. (1966) *Dale Fort Marine Fauna*, Field Studies 2.

Crouch, W. (1894) On the occurrence of *Crepidula fornicata (L.)* off the coast of Essex. *Essex Naturalist*, **8**, 36-38.

Davis, M.H. and Davis, M.E. (2007) The distribution of *Styela clava (Tunicata, Ascidiacea)* in European waters. *J. Exp. Mar. Biol. Ecol.*, **342**, 182-184.

Davis, M. and Davis, M. (2009) *Styela clava (Tunicata, Ascidiacea)* - a new threat to the Mediterranean shellfish industry? *Aquatic Invasions*, **4**, 283-289.

Drummond, L., Mulcahy, M. and Culloty, S. (2006) The reproductive biology of the Manila clam, *Ruditapes philippinarum*, from the North-West of Ireland. *Aquaculture*, **254**, 326-340.

Dupont, L., Viard, F., Dowell, M.J., Wood, C. and Bishop, J. D.D. (2009) Pathways of spread of the introduced ascidian *Styela clava (Tunicata)* in Northern Europe, as revealied by microsatellite markers. *Biological Invasions*, **12**, 2707-2721.

Economides, B. (1989) *Tracer applications of Sellafield radioactivity in British west coastal waters*, University of Glasgow. Ph.D. Thesis.

Farell, P. and Fletcher, R. (2000) *The biology and distribution of the kelp,* Undaria pinnatifida (Harvey) Suringar. In: Solent Science - A Review. Collins, M. and Ansell, K. (eds.) Amsterdam, Elsevier Science B.V.

Fletcher, R.L. and Fletcher, S.M. (1975) Studies on the recently introduced brown alga *Sargassum muticum* (Yendo) Fensholt. I. Ecology and reproduction. *Botanica Marina*, **18**, 149-156.

GB NNSS (2012). *Botrylloides violaceus*. Great Britain Non Native Species Secretariat, https://secure.fera.defra.gov.uk/nonnativespecies/factsheet/factsheet.cfm?speciesId=514 : date of access (24 09 2012).

Grabemann, I. and Weisse, R. (2008) Climate change impact on extreme wave conditions in the North Sea: an ensemble study. *Ocean Dyn.*, **58**, 199-212.

Griffith, K., Mowat, S., Holt, R., Ramsay, K., Bishop, J.D. D., Lambert, G. and Jenkins, S. R. (2009) First records in Great Britain of the invasive colonial ascidian *Didemnum vexillum* Kott, 2002, *Aquatic Invasions*, **4**, 581-590.

Gröner, F., Lenz, M., Wahl, M. and Jenkins, S.R. (2011) Stress resistance in two colonial ascidians from the Irish Sea: the recent invader *Didemnum vexillum* is more tolerant to hypo-salinity than the cosmopolitan *Diplosoma listerianum. J. Exp. Mar. Biol. Ecol.,* **409**, 48–52.

Guy, C. and Roberts, D. (2010) Can the spread of non-native oysters (Crassostrea gigas) at the early stages of population expansion be managed?, Marine Pollution Bulletin 60(7), 1059-1064.

Hales, J. M. and Fletcher, R. L. (1989) Studies on the Recently Introduced Brown Alga *Sargassum muticum* (Yendo) Fensholt 4. The Effect of Temperature, Irradiance and Salinity on Germling Growth. *Botanica Marina*, **32**(2), 167-176.

Harding, J.M., Mann, R. and Kilduff, C.W. (2008) Influence of environmental factors and female size on reproductive output in an invasive temperate marine gastropod *Rapana venosa (Muricidae). Mar. Biol.*, **155**(6), 571-581.

Harries, D.B., Cook, E.J., Harrow, S., Wilson, J.R., Mair, H. and Donnan, D.W. (2007) The establishment of the invasive alga *Sargassum muticum* on the west coast of Scotland: Rapid northwards spread and identification of potential new areas for colonisation. *Aquatic Invasions*, **2**(4), 367-377.

Hay, C. H. and Villouta, E. (1993) Seasonality of the adventive Asian kelp *Undaria pinnatifida* in New Zealand. *Botanica Marina*, **36**, 461-476.

Hiscock, K., Southward, A. J., Tittley, I. and Hawkins, S. J. (2004) Effects of changing temperature on benthic marine life in Britain and Ireland. *Aquatic Conserv. Mar. Freshw. Ecosyst.*, **14**, 333-362.

Holmes, J.M.C. and Minchin, D. (1995) Two exotic copepods imported into Ireland with the Pacific oyster *Crassostrea gigas* (Thunberg). *Irish Naturalists' Journal*, **25**, 17-20.

Hulme, P. E. (2005) Adapting to climate change: is there scope for ecological management in the face of a global threat? *J. Appl. Ecol.*, **45**, 784.

Hulme, P. E. (2009) Trade, transport and trouble: managing invasive species pathways in an era of globalisation. *J. Appl. Ecol.*, **46**, 10-18.

IPCC (2007) *Climate change 2007: the physical science basis*, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmenal Panel on Climate Change. Cambridge, Cambridge University Press.

Jensen, A.C., Humphreys, J., Caldow, R.W.G., Grisley, C. and Dyrynda, P.E.J. (2004) Naturalization of the Manila clam (*Tapes philippinarum*), an alien species, and establishment of a clam fishery within Poole harbour, Dorset. *J. Mar. Biol. Assoc. UK*, **84**, 1069-1073.

Kerckhof, F., Vink, R.J., Nieweg, D.C. and Post, J.J.N. (2006) The veined whelk *Rapana venosa* has reached the North Sea. *Aquatic Invasions*, **1**, 35-37.

Kochmann, J., Carlsson, J., Crowe, T. P. and Mariani, S. (2012) Genetic evidence for the uncoupling of local aquaculture activities and a population of an invasive species-a case study of Pacific oysters (*Crassostrea gigas*). *J. Heredity*, doi: 10.1093/jhered/ess042

Laruelle, F., Guillou, J. and Paulet, Y. M. (1994) Reproductive pattern of the clams Ruditapes decussatus and R. philippinarum on intertidal flats in Brittany. *J. Mar. Biol. Assoc. UK*, **74**, 351–366.

Leckebusch, G.C., Koffi, B., Ulbrich, U., Pinto, J.G., Spangehl, T. and Zacharias, S. (2006) Analysis of frequency and intensity of European winter storm events from a multi-model perspective, at synoptic and regional scales. *Clim. Res.*, **31**(1), 59-74.

Lützen, J. (1999) Styela clava Herdman (*Urochordata, Ascidiacea*), a successful immigrant to North West Europe: ecology, propagation and chronology of spread. *Helgoland Meeresunters*, **52**, 383-391.

Maggs, C.A., Mineur, F., Bishop, J.D.D. and McCollin, T. (2010) *Non-natives in MCCIP Annual Report Card 2010-11*, MCCIP Science Review, 11pp. www.mccip,org.uk/arc

McNeill, G., Nunn, J. and Minchin, D. (2010) The slipper limpet Crepidula fornicata Linnaeus, 1758 becomes established in Ireland. *Aquatic Invasions*, **5**(1), S21-25.

Menai Strait Fishery Order Management Association (2011) *Fishery Activity Report*, http://www.msfoma.org/wp-content/uploads/2011/10/Menai-Management-Association-Papers-Oct-2011.pdf : date of access (01 11 2012)

Mettam, C. (1979) Faunal changes in the Severn Estuary over several decades. *Mar. Pollution Bull.*, **10**, 133-136.

Minchin, D. (2007) A checklist of alien and cryptogenic aquatic species in Ireland, *Aquatic Invasions*, **2**, 341-366.

Minchin, D. (2007) Rapid coastal survey for targeted alien species associated with floating pontoons in Ireland, *Aquatic Invasions*, **2**(1), 63-70.

Minchin, D., Cook, E.J. and Clark, P.F. (2013) A list of alien brackish and marine British species. *Aquatic Invasions*, **8** (1), 1-17

Minchin, D., Davis, M.H. and Davis, M.E. (2006) Spread of the Asian tunicate *Styela clava* Herdman, 1882 to the east and south-west coasts of Ireland. *Aquatic Invasions*, **1**(2), 91-96.

Minchin, D. and Duggan, C.B. (1988) The distribution of the exotic ascidian, *Styela clava* Herdman, in Cork Harbour, *Irish Naturalists' Journal*, **22**(9), 388-392.

Minchin, D., Gollasch, S. and Wallentinus, I. (2005) *Vector pathways and the spread of exotic species in the sea,* Co-operative Research Report 271. ICES, Copenhagen, 29pp.

Minchin, D. and Sides, E. (2006) Appearance of a cryptogenic tunicate, a *Didemnum sp.* fouling marina pontoons and leisure craft in Ireland. *Aquatic Invasions*, **1**(3), 143-147.

Miossec, L., Le Deuff, R. and Goulletquer, P. (2009) *Alien Species Alert:* Crassostrea gigas *(Pacific Oyster)*, Cooperative Report 299. ICES, Copenhagen.

Molnar, J.L., Gamboa, R.L., Revenga, C. and Spalding, M.D. (2008) Assessing the global threat of invasive species to marine biodiversity. *Frontiers Ecol. Env.*, **6**, 485-492.

Morgan, E.H. and Richardson, C.A. (2012a) Capricious bioinvasions versus uncoordinated management strategies: how the most unlikely invaders can prosper under the current UK legislation framework. *Aquatic Conserv. Mar. Freshw. Ecosyst.*, **22**(1), 87-103.

Morgan, E. H. and Richardson, C. A. (2012b) The potential role of an unregulated coastal anthropogenic activity in facilitating the spread of a non-indigenous biofoulan, *Biofouling*, **28**, 743-753.

Nehls, G. and Büttger, H. (2007) *Spread of the Pacific Oyster* Crassostrea gigas *in the Wadden Sea: causes and consequences of a successful invasion*, Bioconsult SH, The Common Wadden Sea Secretariat, Wilhelmshaven, 55pp.

Newman, P., Lock, K., Burton, M. and Jones, J. (2012) *Skomer Marine Nature Reserve Annual Report 2011*, CCW Regional Report CCW/WW/11/3, 59pp.

Nimmo, F., Cook, E. J., Moxey, A. P., Hambrey, J. and Black, K. (2012) *Cost-benefit analysis of management options for* Didemnum vexillum *(Carpet sea squirt) in Scotland*, Hambrey Consulting in association with the Scottish Association for Marine Science and Poseidon Aquatic Resource Management. Scottish Government, Edinburgh, 69pp.

Norton, T.A. (1977) Ecological experiments with *Sargassum muticum. J. Mar. Biol. Assoc. UK*, **57**, 33-43.

Norton, T.A. (1992) Dispersal by macroalgae. *British Phycological J.*, **27**, 293-301.

Nunn, J.D. and Minchin, D. (2009) Further expansions of the Asian tunicate *Styela clava* Herdman 1882 in Ireland, *Aquatic Invasions*, **4**(4), 591-596.

Pederson, J., Mieszkowska, N., Carlton, J. T., Gollasch, S., Jelmert, A., Minchin, D., Occhipinti-Ambrogi, A. and Wallentinus, I. (2011) *Climate change and non-native species in the North Atlantic.* ICES Status Report on Climate Change in the North Atlantic, Reid, P. C. and Valdés, L. (eds.), 174-190.

Pimentel, D., Zuniga, R. and Morrison, D. (2005) Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecol. Econ.*, **52**(3), 273-288.

Reid, P.C., Cook, E.J., Edwards, M., McQuatters-Gollop, A., Minchin, D. and McCollin, T. (2009) *Marine non-native species, Marine Climate Change Ecosystem Linkages Report Card*. Baxter, J. M., Buckley, P. G. and Frost, M. T. (eds.), Online Science Reviews, 29.

Richardson, C.A., Seed, R., Alroumaihi, E.M.H. and McDonald, L. (1993) Distribution, Shell Growth and Predation of the New-Zealand Oyster, *Tiostrea (=Ostrea)* lutaria Hutton, in the Menai Strait, North Wales. *J. Shell. Res.*, **12**(2), 207-214.

Ries, J. B., Cohen, A. L. and McCorkle, D. C. (2009) Marine calcifiers exhibit mixed responses to CO_2-induced ocean acidification, *Geology,* **37**, 1131-1134.

Roy, H.E., Bacon, J., Beckmann, B., Harrower, C.A., Hill, M.O., Isaac, N.J.B., Preston, C.D., Rathod, B., Rorke, S.L., Marchant, J.H. *et al.* (2012) *Non-Native Species in Great Britain: establishment, detection and reporting to inform effective decision making*, DEFRA, 110pp.

Rueness, J.A.N. (1989) *Sargassum muticum* and Other Introduced Japanese Macroalgae: Biological Pollution of European Coasts. *Mar. Pollution Bull.*, **20**, 173-176.

Rueness, J. (2005) Life history and molecular sequences of *Gracilaria vermiculophylla* (Gracilariales, Rhodophyta), a new introduction to European waters. *Phycologia*, **44**, 120–128.

Ryland, J.S., Bishop, J.D.D., De Blauwe, H., El Nagar, A., Minchin, D., Wood, C. and Yunnie, L.E. (2011) Alien species of *Bugula* (Bryozoa) along the Atlantic coasts of Europe. *Aquatic Invasions*, **6**, 17-31.

Simpson, J.H., Edelsten, D.J., Edwards, A., Morris, N.C.G. and Tett, P.B. (1979) The Islay front: physical structures and phytoplankton distribution. *Estuarine Coastal Shelf Sci.*, **9**, 713-726.

Sjøtun, K., Husa, V. and Peña, V. (2008) Present distribution and possible vectors of introductions of the alga *Heterosiphonia japonica* (Ceramiales, Rhodophyta) in Europe. *Aquatic Invasions*, **3**, 377-394.

Staehr, P.A., Pederson, M.F., Thomsen, M.S., Wernberg, T. and Krause-Jensen, D. (2000) Invasion of *Sargassum muticum* in Limfjorden (Denmark) and its possible impact on the indigenous macroalgal community. *Mar. Ecol. Prog. Ser.*, **207**, 79-88.

Strangford Lough and Lecale Partnership (2012) *First Report of* Didemnum vexillum *in Strangford Lough*. http://www.strangfordlough.org/Projects-and-Issues/First-Report-of-Didemnum-vexillum-in-Strangford-Lo.aspx : date of access (25 10 2012)

Syvret, M., Fitzgerald, A. and Hoare, P. (2008) *Development of a Pacific oyster aquaculture protocol for the UK - Technical Report*, 195pp.

Vitousek, P.M., D'Antonio, C.M., Loope, L.L., Rejmanek, M. and Westbrooks, R. (1997) Introduced species: a significant component of human-caused global change. *NZ J. Ecol.*, **21**(1), 1-16.

Walne, P. R. (1974) *Culture of bivalve mollusks. 50 years' experience at Conwy*. London, Fishing News (Books) Ltd, 173pp.

Walther, G.R., Roques, A., Hulme, P.E., Sykes, M.T., Pyšek, P., Kühn, I., Zobel, M., Bacher, S., Botta-Dukán, Z., Bugmann, H. *et al.* (2009) Alien species in a warmer world: risks and opportunities. *Trends Ecol. Evol.*, **25**(3), 686- 693.

Weinberger, F., Buchholz, B., Karez, R. and Wahl, M. (2008) The invasive red alga *Gracilaria vermiculophylla* in the Baltic Sea: adaptation to brackish water may compensate for light limitation. *Aquatic Biology*, **3**, 251-264.

Wilcove, D.S., Rothstein, D., Dubow, J., Phillips, A. and Losos, E. (1998) Quantifying Threats to Imperiled Species in the United States. *Bioscience*, **48**(8), 607-615.

Williams, F., Eschen, R., Harris, A., Djeddour, D., Pratt, C., Shaw, R.S., Varia, S., Lamontagne-Godwin, J., Thomas, S.E. and Murphy, S. . (2010) *The economic cost of invasive non-native species on Great Britain*, CABI. Wallingford, CABI, 198pp.

Wrange, A. L., Valero, J., Harkestad, L. S., Strand, O., Lindegarth, S., Christensen, H.T., Dolmer, P., Kristensen, P.S. and Mortensen, S. (2010) Massive settlements of the Pacific oyster, *Crassostrea gigas*, in Scandinavia. *Biological Invasions*, **12**(6), 1453-1458.