4 Assessing and Reducing Impacts of Aquaculture on Marine Biodiversity

4.1 Context

Since the 1980s, the global expansion of capture fisheries has virtually stopped, while demand for fish has continued to increase rapidly. In response, world aquaculture production has increased by an average of 7% per annum and now produces half of the fish and shellfish consumed by humans (Food and Agriculture Organization of the United Nations [FAO] 2009). The Irish aquaculture industry began in the 1970s. In 2007, the total production of shellfish and finfish in Ireland was 48,350 tonnes – 37,112 tonnes of shellfish (mainly oysters and mussels) and 11,238 tonnes of finfish (mainly salmon). The value of the sector was €105.7 million and it employed 2000 people. The economic and social value of aquaculture is heightened by the fact that it is one of the few industries with a strong presence in Ireland's remote coastal communities. While the production of shellfish is increasing steadily, salmon production has shown a decrease from a maximum output of 23,312 tonnes in 2001 to 9,923 tonnes in 2008. Industry output in Ireland is focused on high-quality, low-volume niche markets. An increasing proportion (almost 50% in 2003) of Irish salmon is produced to Organic or Eco-Standards and sells at a premium (Browne et al. 2008). In 2008, 90% of Irish salmon production was independently accredited to either Organic or Eco-Standards and this pattern will continue into the future. The salmon-growing sites on the west coast of Ireland occur in naturally higher-energy, more exposed environments than the sea-lochs utilised by Scottish and Norwegian operators. Consequently, typical impacts associated with salmon farming, such as seabed anoxia and nutrient enrichment, are not as much of an issue in Ireland when compared with other jurisdictions.

Nevertheless, aquaculture can influence biodiversity and ecosystem functioning and services in a number of ways. The influences considered most important in Ireland are interactions with wild fisheries resources, physical damage to or replacement of habitat, organic and nutrient enrichment, as a vector for invasive species, and through interactions with seals and birds (Callier et al. 2011).

To ensure the sustainability of this industry, it is essential to better understand the interactions between aquaculture, biodiversity, ecosystem services and society. Changes to biodiversity, for example in terms of the numbers and identities of species present in an area, can affect the functioning of ecosystems, altering rates of production, nutrient cycling, etc., which in turn can influence the benefits to society that ecosystems provide. A key challenge is to find the balance between the benefits of aquaculture and maintaining conservation status in coastal Natura 2000 sites.

4.2 Summary of Findings

4.2.1 Direct Impacts of Caged Salmon Farms on Biodiversity and Ecosystem Functioning

The extent of salmon farming's influence on the environment and the uptake of particulate and dissolved effluents by benthic organisms were assessed using community structure and stable isotope analyses (Callier et al. 2013). Sediment cores were collected along transects in two directions (perpendicular to [T1] and in the direction of [T2] the main residual current) at 0m, 25m and 200m from two salmon farms (Millstone and Cranford) located in Mulroy Bay, Republic of Ireland (Fig. 4.1). In addition, fouling communities were collected on artificial substrates, which were placed for 2 months at 1m depth at the same distances. The extent of measurable change in benthic communities depended on residual current direction. At both farms, communities living below the cages had low diversity (Fig. 4.1), and were dominated by opportunistic species. Variation in isotopic signatures of the food sources was sufficient to identify variation in the organisms' diet. Intra-specific variation in isotopic value in benthic invertebrates was mostly explained by distance from cages. Organisms collected beneath the cages were depleted in δ13C compared to individuals collected at 200m. A shift in δ13C was observed in species present at more than one distance, including the bristleworm

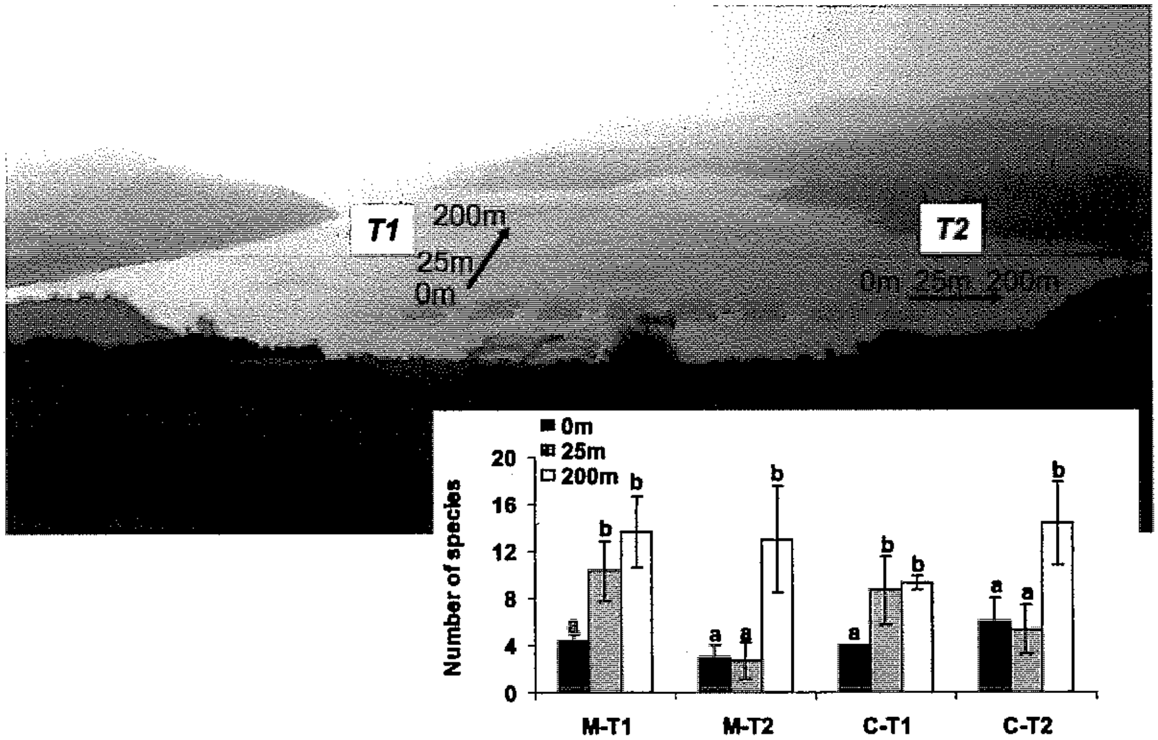

Figure 4.1. Millstone farm, Mulroy Bay showing Marine Harvest salmon farm and arrangement of sampling stations along transects T1, perpendicular to residual current and T2, downstream from farm. Inset is a graph showing average number of species (species richness) per core (*n* = 3) sampled at stations along transects T1 at Millstone farm (M) and Cranford farm (C) – located elsewhere in Mulroy Bay. Bars representing means that are not statistically different from each other are denoted by the letters a or b; bars with different letters above them are statistically different from each other. Compared to control sites 200m from the cages, species richness is significantly reduced immediately under the cages (0m) in all transects. Along T2, reduced species richness is also apparent 25m downstream from the cages. Along T1, species richness at stations 25m from the cages is not different from that at control stations 200m from the cages. Multivariate analysis of community structure revealed comparable spatial patterns of difference.

(*Malacoceros fuliginosus*), the catworm (*Nephtys hombergii*), nematode worms and the Red speckled anemone (*Anthopteura balii*). Fouling communities collected on artificial structures – mainly composed of tunicates (*Ascidiella aspersa*) – showed higher δ15N values at fish-cage sites compared to 200m sites. The study demonstrated that fish effluents were assimilated and became a food source for native organisms with repercussions for trophic structure. Sedimentary and fouling organisms, potential sinks for fish effluents, may play an important role in the carrying capacity of ecosystems for aquaculture.

4.2.2 *Indirect Effects of Aquaculture*

This body of work focused on the Pacific oyster, *Crassostrea gigas*. Native to Japan, the Pacific oyster has been introduced for aquaculture to many parts of the world and has become one of the world's main aquaculture species (FAO 2012). In many intertidal habitats outside aquaculture areas it has established permanent, self-sustaining and also invasive populations worldwide (Reise 1998; Ruesink et al. 2005; Troost 2010). In Europe, there are invasive populations along the Atlantic and North Sea coasts, for example in Germany (Reise 1998; Diederich et al.

2005), the Netherlands (Fey et al. 2010) and France (Cognie et al. 2006). Recent studies indicate that the northern boundaries of distributions of this species are expanding; they have been found in England and Wales (Couzens 2006), Northern Ireland (Guy & Roberts 2010) and Scandinavia (Wrange et al. 2010).

Pacific oysters are habitat generalists. Their colonisation process generally starts with settlement onto pieces of hard substratum, for example shell fragments, stones, mussel beds, aquaculture racks or harbour walls. They can be found in a wide range of habitat types, from coastal sheltered soft-sediment environments to exposed rocky shores (Ruesink et al. 2005; Cognie et al. 2006; Troost 2010) and they are tolerant of a wide range of environmental conditions (Enríquez-Díaz et al. 2008). Growth of oysters occurs between 3 and 35°C, but temperatures for spawning range between 16 and 34°C (Mann et al. 1991; Ruiz et al. 1992) and increasing summer temperatures have been associated with the spread of Pacific oysters in Europe (Diederich et al. 2005; Fey et al. 2010).

In locations around the world, wild Pacific oyster populations have established soon after their farming had commenced (Brandt et al. 2008; Troost 2010). Pacific oysters were introduced to Ireland in 1973 for aquaculture and they are now extensively farmed around the north, the west and south coast (Browne et al. 2008). Recently, there have been reports of individuals being found in the wild, but the extent and distribution of these populations was hitherto known. Given their potential rate of spread, there is an urgent need to characterise its pattern of establishment at an early stage and determine which factors are associated with its presence or absence.

Invasive oyster populations can have substantial impacts, including saturation of the carrying capacity of estuaries, change in phytoplankton composition and food webs, spatial competition with other species and alteration of habitat heterogeneity (Ruesink et al. 2005; Cognie et al. 2006; Troost 2010). Before the current study, the potential impacts of Pacific oysters on biodiversity in Ireland had not yet been characterised and indeed there had been little experimental research in other parts of their invaded range. Their impacts on ecosystem functioning and the mechanisms underlying those impacts had not previously been studied anywhere.

4.2.2.1 Oyster Escape, Establishment and Future Spread

Documenting the establishment and spread of invasive species requires extensive coordinated sampling programmes. Identifying the factors promoting or inhibiting local establishment of an invasive species can improve capacity to predict further spread and underpin strategies to limit spread. Here, a structured sampling programme was used to assess the current distribution of feral populations of Pacific oysters in Ireland (Kochmann, 2012; Kochmann et al. 2013). In a direct collaboration between UCD, the Loughs Agency, the Marine Institute, Queen's University Belfast (QUB) and Bord Iascaigh Mhara (BIM), 69 sites were sampled in 2009 using a standardised protocol combining semi-quantitative and quantitative approaches. Sites were chosen to represent a variation in proximity to aquaculture and a range of environmental variables. Oyster populations were found at 18 locations (Fig. 4.2). Highest densities occurred in Lough Swilly and Lough Foyle with up to 9 individuals/m^2 and lower densities were found in the Shannon Estuary and Galway Bay. Analysis of size frequency distributions revealed that several recruitment events had occurred, probably within the previous 6–10 years. Logistic regression indicated that feral oysters were positively associated with the presence of hard substrata or biogenic reef, long residence times of embayments and large intertidal areas. There was also a tendency for oysters to occur disproportionately in bays with aquaculture, but >500m from it. Small-scale analysis within sites showed that oysters were almost exclusively attached to hard substrata and mussels. The approach taken here provides a rigorous repeatable methodology for future monitoring and a detailed basis for the prediction of further spread.

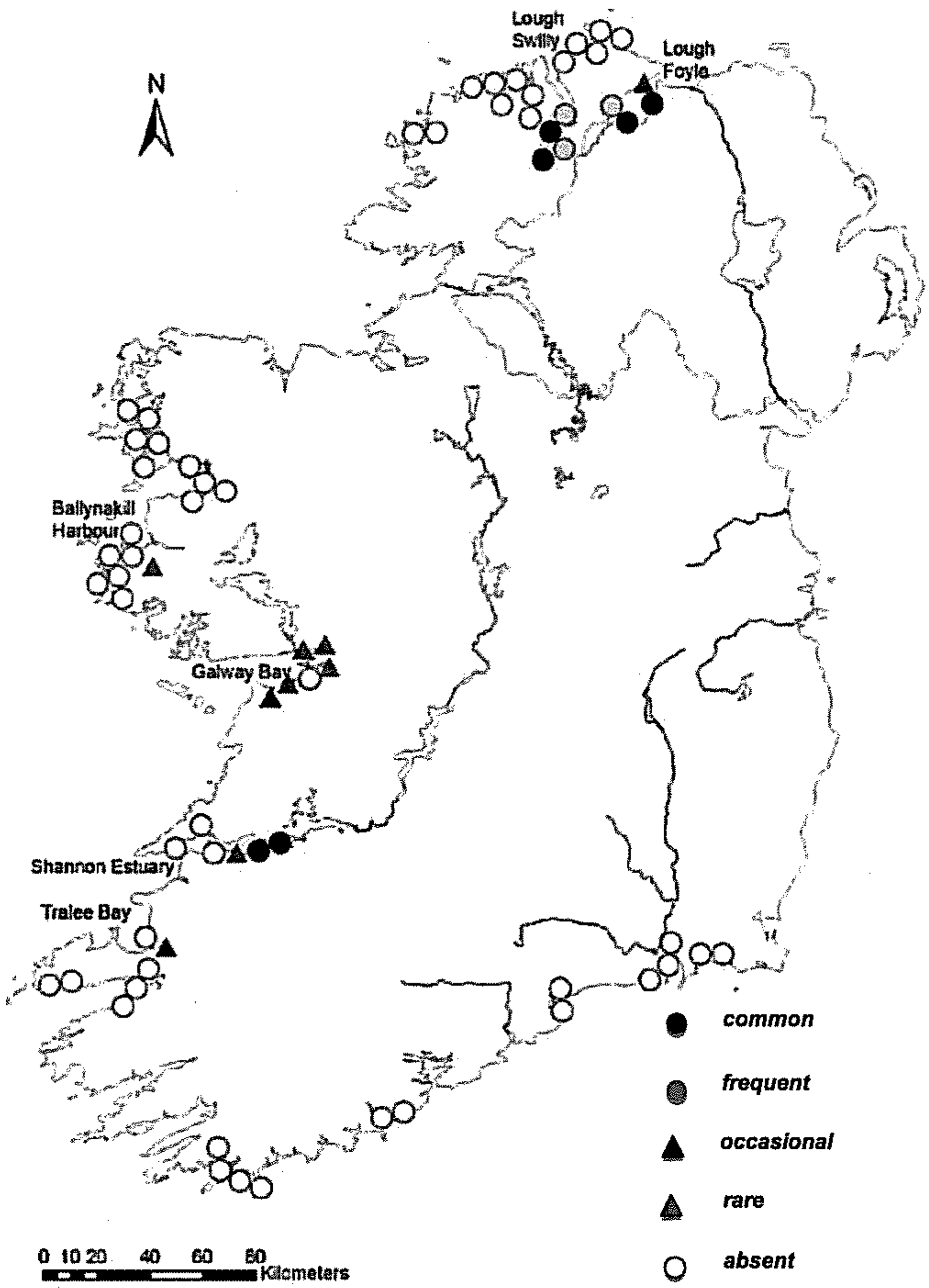

Figure 4.2. Sampling sites and abundances of feral Pacific oysters in Ireland in 2009. Sites are categorised on the semi-quantitative SACFOR scale on the basis of timed searches. Names of the embayments where oysters were found are given.

Biotic interactions can play a key role in promoting or inhibiting the spread of invasive species. Here, we tested the influence of predation and macroalgae on growth and survival of juvenile Pacific oysters. A field experiment was set up in July 2011 at two intertidal macroalgae-dominated boulder shores where only single individuals of oysters occur. After 10 months, the condition of oysters was not significantly decreased in the presence of macroalgal canopy; however, shell growth was significantly reduced by at least 3mm in less than 4 months, but only at one site. Although predation had a strong negative effect on oyster survival (mean oyster size 16mm) in a pilot experiment conducted in July 2010, no effect of predators was detected in the present study (mean oyster size 36mm). Trapping of shore crabs (*Carcinus maenas*), which are considered one of the main potential predators of Pacific oysters in their introduced range, revealed the presence of significantly larger crabs at sites where oysters were not found. More crabs (>35mm carapace width) were found at shores where oysters are rare but numbers were not significantly different from other shores. Our results suggest that pre-settlement and recruitment processes might better explain abundance patterns of Pacific oysters in intertidal habitats than post-recruitment growth and survival.

Human-mediated introduction of non-native species into coastal areas via aquaculture is one of the main pathways that can lead to biological invasions. To develop strategies to counteract invasions it is critical to determine whether populations establishing in the wild are self-sustaining or based on repeated introductions. In this study, temporal genetic variability of farmed and wild oysters from the largest enclosed bay in Ireland was assessed to reconstruct the recent biological history of the feral populations using seven anonymous and seven expressed sequence tag (EST)-linked microsatellites (Kochmann et al. 2012). There was no evidence of EST-linked markers showing footprints of selection. Allelic richness was higher in feral samples than in aquaculture samples (p=0.003, paired t-test). Significant deviations from Hardy-Weinberg (HWE) due to heterozyote deficiencies were detected for almost all loci and samples, most likely explained by the presence of null-alleles. High genetic differentiation was found between aquaculture and feral oysters (largest pairwise multilocus FST 0.074, p<0.01) and between year classes of oysters from aquaculture (largest pairwise multilocus FST 0.073, p<0.01), which was also confirmed by the strong separation of aquaculture and wild samples using Bayesian clustering approaches. A ten-fold higher effective population size (Ne) – and a high number of private alleles – in wild oysters suggest an established self-sustaining feral population. The wild oyster population studied appears demographically independent from the current aquaculture activities in the estuary and alternative pathways of introduction and establishment are discussed.

4.2.2.2 *Effects of Oysters in Wild on Biodiversity and Ecosystem Services*

An experiment was used to separate the effects of cover, physical structure and biological activities of Pacific oysters on the development of assemblages (Green 2012; Green & Crowe 2013). Increasing cover of living (biologically active) and dead (physical structure only) oysters were added to the tops of new boulders and deployed within an intertidal boulder field. After 14 months, diversity, evenness and assemblage structure were affected by Pacific oysters, with patterns differing depending on the cover and state of oysters. Boulders with Pacific oysters, regardless of their cover or state, supported assemblages with more species, greater Shannon-Wiener diversity and evenness, but boulders with the least cover of living oysters had the greatest diversity and evenness. Assemblage structure also differed depending on the cover and state of oysters with differences driven by changes to the establishment of several key species. These included the honeycomb worm, *Sabellaria alveolata*, which constructs reefs protected by the EU Habitats Directive and which mainly established on the underside of boulders, and was nonetheless greatly reduced by increasing cover of oysters on their upper surfaces, regardless of their state.

To test the impacts of Pacific oysters on biodiversity and ecosystem functioning in different habitats, experimental plots with increasing cover of oysters were set up in mussel-beds and mud-flats within two estuaries, Lough Foyle and Lough Swilly and were sampled after 4 and 15 months (Green 2012; Green & Crowe 2013). At both times and within each estuary, species richness, diversity (calculated using the Shannon-Wiener index) and total number of individuals increased, with increasing cover of oysters within mud-flat habitats. In mussel-bed habitats, however, species richness, Shannon-Wiener diversity and total number of individuals peaked with medium cover of oysters at one estuary and significantly decreased with the greatest cover of oysters at the other estuary. At both estuaries at each time, assemblage structure differed between habitats and among covers of oysters with a reduction in β-diversity as assemblages became more homogenous with the increasing cover of oysters in mud-flat habitats. These responses were primarily underpinned by increases in the density or cover of several taxa, including a grazing gastropod (*Littorina littorea*), a non-indigenous barnacle (*Elminius modestus*) and a primary producer (*Fucus vesiculosus*) with increasing cover of oysters. The response of many species differed between locations and over time, suggesting that some effects are context dependent.

Measurements of ecosystem functioning were made only in Lough Swilly (Green 2012; Green & Crowe 2013). Pacific oysters significantly altered several biogeochemical properties and processes, and some of its effects differed between habitats. Sediment-water fluxes of NH_4^+ and $Si(OH)_4$ and benthic turnover rates increased with increasing cover of oysters in mud-flats but decreased at the greatest cover of oysters in mussel-beds. Community respiration (CO_2 flux) increased with the greatest cover of oysters in both habitats. Biodiversity increased with increasing cover of oysters in mud-flats but decreased with the greatest cover of oysters in mussel-beds. The relationship between assemblage structure and functional variables was assessed using distance-based linear models (DISTLM). A total of 28.8% of the total variation in assemblage structure was accounted for by 9 variables in distance-based redundancy analysis, and 18% of this variation was explained by variation in NH_4^+. Pacific oysters can alter biodiversity and benthic turnover rates of important limiting nutrients, and therefore may affect ecosystem services provided by estuarine ecosystems.

The effects of different percentage covers of invasive Pacific oysters on ecosystem processes and associated microbial assemblages in mud-flats were tested experimentally in the field at Lough Swilly (Green 2012; Green et al. in review). Pore-water nutrients (NH_4^+, NO_2^- and NO_3^-), sediment chlorophyll content, microbial activity, total carbon and nitrogen and community respiration (CO_2 and CH_4) were measured to assess changes in ecosystem functioning. Assemblages of bacteria in general as well as functional groups including methanogens, methanotrophs and ammonia-oxidisers were assessed in the oxic and anoxic layers of sediment using terminal restriction length polymorphism on the 16S, mcr*A*, mxa*F* and amo*A* genes respectively. Effects of Pacific oysters differed with cover. At the highest cover, there was significantly greater total microbial activity, chlorophyll content and CO_2 (13 fold greater) and CH_4 (6 fold greater) emission from the sediment compared to mud-flats without any Pacific oysters. At the lowest cover, Pacific oysters increased the concentration of total oxidised nitrogen and altered the assemblage structure of ammonia oxidisers and methanogens. At any cover of Pacific oysters, concentrations of pore-water NH_4^+ were greater than in areas of mud-flat without Pacific oysters. Invasive oysters may alter ecosystem functioning not only directly, but also indirectly by affecting microbial communities vital for the maintenance of ecosystem processes.

4.3 Conclusion

Aquaculture is an important industry for Ireland, particularly in the context of remote rural communities, where it brings considerable economic and social benefits. Irish aquaculture has a number of features that make its impacts on the environment generally less than in some other jurisdictions. Nevertheless, it has the potential to influence native biodiversity and ecosystem processes in important ways. Such impacts can affect not only the conservation status of coastal marine habitats, but can also reduce the capacity of marine ecosystems to deliver vital ecosystem services, including provisioning services such as aquaculture itself. The significance of its impacts varies considerably with environmental context and must also be considered in the context of social and economic imperatives, as well as policy and legislative frameworks, particularly those derived from EU directives, such as the Habitats Directive, the Marine Strategy Framework Directive and the Water Framework Directive.

Effective management of aquaculture is needed to reduce its environmental impacts and safeguard its long-term sustainability. Some statutory measures are in place and there are also some effective voluntary programmes, such as ECOPACT and CLAMS, which enjoy a high level of support from industry. Effective management must also be underpinned by good scientific understanding. A range of recommendations is made above, based on the research completed during the SIMBIOSYS project. A number of key research gaps are also identified. These should be filled with a nationally coordinated programme of integrated research developed and executed in cooperation with the full range of relevant stakeholders.

4.4 Recommendations for Decision-makers

1 In environmental decision-making and spatial planning for bays involving aquaculture, it should be noted that the extent of influence of salmon cages on benthic assemblages is very narrow (<25m) perpendicular to the main direction of current flow in comparatively high-energy areas such as Mulroy Bay, but greater (25–200m) downstream from the cage.

2 Stable isotopes were an effective tracer of salmon farm wastes into biota and enabled us to reveal assimilation of salmon waste by benthic species, which underwent a shift in their diet. Further use of this approach could yield additional insights into changes in trophic structure and may help inform decisions about the compatibility of aquaculture with other activities in Natura 2000 sites.

3 Increased biomass of suspension feeders (e.g. tunicates) as part of 'fouling communities' could decrease levels of particulate and dissolved material in the surrounding environment. This could potentially be used as a mitigation strategy, in which substrata could be deployed in highly sensitive environments, where small reductions in nutrient loading could be critical. Further research would be required to assess the effectiveness of this approach on a larger scale.

4 Further consideration should also be given to using Integrated Multi-Trophic Aquaculture in Ireland. This is an approach with potential to both diminish environmental impacts and increase profitability. Benthic polychaetes could potentially be used to consume waste under fish cages, for example, and in turn be harvestable themselves.

5 Pacific oysters can pose a considerable threat to native biodiversity and ecosystem functioning. The current study showed that they may negatively impact the establishment of a protected biogenic habitat (*Sabellaria* reefs). At their highest cover, Pacific oysters can decrease biodiversity, increase the homogenisation of habitats, increase the emission of gaseous carbon and decrease the turnover rate of important limiting nutrients, possibly leading to a reduction in provisioning services, such as aquaculture production. Experience in other countries has also included negative effects on bird populations and on recreation and tourism.

6 Action should be taken at an early stage to restrict (or eliminate where possible) the spread of Pacific oysters in Ireland before dense reefs are formed. The task would already be very challenging, but if large populations become established, the challenge would be far greater.

7 In developing management strategies, surveillance should be focused on areas with hard substrata or biogenic reef, long residence times of embayments and large intertidal areas. Pacific oysters also tend to occur disproportionately in bays with aquaculture, but >500m from it. Management efforts should also be targeted towards areas of particular conservation or economic value, for example areas designated for *Sabellaria* reefs, areas important for aquaculture.

8 Risk of spread of Pacific oysters from aquaculture could be greatly reduced by the use of triploid oysters. This approach has already been adopted by many farmers and presents a win-win solution as triploid oysters also grow faster than diploids.

9 Genetic evidence indicates that feral Pacific oysters are likely to be spawning, such that their populations are self-sustaining. Management measures must therefore focus on feral populations as well as aquaculture operations.

10 At present in some areas, feral populations of Pacific oysters are being harvested in some habitats (F. O'Beirn, pers. comm.), which will contribute considerably to their control and should be encouraged. However, this would cease if populations become too dense: once they have formed dense reefs, they are not harvested commercially because individuals with distorted shells have limited commercial value.

11 Pacific oysters can impact biodiversity even when dead, albeit to a lesser extent, so management action should include the removal of oyster shell material where feasible. It should be noted, however, that shell material can be important for the promotion of native oyster production.

12 A coordinated sampling programme should be established to monitor the spread of Pacific oysters and test effectiveness of any control measures adopted. The methodology developed in the current project is rigorous, repeatable and cost effective.

13 Statutory measures and existing voluntary programmes such as CLAMS and ECOPACT provide a good framework for the development and implementation of further improvements to the management of aquaculture activities with the broader view of reducing and managing environmental impacts.

14 The understanding of impacts of aquaculture in Ireland could be improved by the development of a coordinated monitoring programme and research to understand: (i) changes to communities and ecosystem processes in the water column (which have been less well studied than those on the sea bed); (ii) the extent of influence of individual aquaculture installations and how their influence combines and interacts with other local and global pressures; (iii) the resistance and resilience of coastal ecosystems and the carrying capacity of Irish embayments, and (iv) how ecological changes induced by aquaculture translate into changes in the provision of ecosystem services.

5 Impacts of Wind Energy on Biodiversity: a Review[1]

In response to climate change, the EU has set a target to achieve 20% of energy from renewable sources by 2020. Consequently, Ireland has set targets of 40, 10 and 12% of energy coming from renewable sources for electricity, transport and heat, respectively. Wind energy is expected to contribute to over 90% of these targets given Ireland's large onshore and offshore wind potential, with over 2000MW of installed capacity to date. However, the potential impacts of these wind farm developments on Ireland's biodiversity remain largely unquantified.

In this assessment we used a review of the literature to identify the potential positive and negative impacts of wind farms on Ireland's marine and terrestrial biodiversity. We also combined spatial analysis techniques with national datasets to reveal the extent to which wind resources and current and future wind farm developments overlap with habitats and species of conservation value.

To maximise effectiveness, wind farms should ideally be sited in open, exposed areas where mean wind speeds are high, with developments therefore most suited to upland, coastal and offshore areas. To date wind farms in Ireland have mostly been developed at onshore locations, but offshore developments may significantly increase in the future. This means that a wide range of species and habitats of high conservation value are or will be potentially influenced by wind energy developments.

Results of the literature review highlight little published information on the impacts of wind developments on Ireland's biodiversity and ecosystem services. Accessibility to existing monitoring datasets and grey literature proved challenging.

The international literature suggests that birds (onshore and offshore), bats (onshore), and marine mammals (offshore) are the groups most vulnerable to the direct impacts of wind turbines. The four principal impacts on birds are: (i) collision; (ii) displacement due to disturbance; (iii) barrier effects; and (iv) habitat loss, with consequences for direct mortality, or changes to behaviour, condition and breeding success. The effects of a wind farm on birds are highly variable and depend on a wide range of factors, including the specification of the development, the topography of the surrounding land, the habitats affected and the number and species of birds present.

Less research on the impacts of wind-farm construction, operation and decommissioning has focused on bats. The principal impacts on bats are (i) collision, (ii) barotrauma, (iii) habitat loss (avoidance), and (iv) barriers to migration/commuting, with consequences for direct mortality, or changes to behaviour, condition and breeding success.

For marine species, including marine mammals, fish and invertebrates, positive impacts include habitat creation, with turbines functioning as artificial reefs benefiting epibenthic invertebrate and algae and fish assemblages. Wind farms also act as no-take zones for fish and fish-aggregation devices. Negative impacts on marine species include habitat change and loss, construction- and operation-induced noise, artificial structures providing habitats for non-indigenous species, electromagnetic fields affecting fish orientation, and construction (pile diving) impacts on the foraging, orientation and communication of harbour porpoises and bottlenose dolphin.

Some key areas for future research in Ireland include: (i) the development of bird/bat sensitivity maps; (ii) studies focused on population-level impacts to disentangle wind farm impacts from other threats and pressures; (iii) species-specific studies concerning the behavioural responses of different species based on lifecycle characteristics, population dynamics, ecology and abundance in response to construction, operational and removal phases of wind farms. This will establish species-specific sensitivities to several types of large-scale wind farms; (iv) identify migration routes/corridors and stepping stones of bats in Ireland; (v) cumulative effects on onshore and offshore wind farms on birds and bats; and (vi) preliminary research into impacts on Ireland's marine species and

1 Full review available from: http://www.tcd.ie/research/simbiosys/images/SIMBIOSYS%20Wind%20Energy%20Sectoral%20Review.pdf