SCALLOP LARVAL DISPERSAL BACKGROUND STUDY

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Further information

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Executive Summary

The King scallop, *Pecten maximus*, is a long lived scallop which can commonly grow to 150mm in length or more. In Northern Ireland fishing for scallops has been established since the 1930s. In 2015 over 1,300 tonnes of scallops were landed into NI with a first sale value of £2.7 million. Whilst historically the NI scallop fishery consisted of a small number of vessels, the fishery has now greatly expanded. In 2015 76 vessels, ranging in size from 9m to over 30m in length, reported landings of scallops into NI ports.

With increasing exploitation of scallop stocks around the Northern Irish coast, the NI Scallop Association has expressed a wish to be proactive in working with industry to enhance long-term sustainability of stocks. Following on from the partial success of a reseeding project trialled in 1999, the Scallop Association approached AFBI to discuss the potential of carrying out an enhanced scallop reseeding programme which examines the suitability of reseeding sites for scallop retention and provides an indication of potential larval dispersal from the reseeding sites (such that reseeded sites, which will be unfished, act as “breeding” grounds).

Initially a literature review was carried out to examine the key life history stages of *P. maximus* with a focus on the key aspects of dispersal and settlement.

Scallops become sexually mature at 2-3 years old with spawning across the UK generally taking place between April and September. Fertilisation produces planktonic larvae which live in the water column for approximately 15-40 days. The larvae have some control over their movement (primarily vertical movement) but their dispersal is greatly influenced by the hydrodynamics in the area. Initially the larvae accumulate near the surface before moving down the water column and crawling along the seabed to find a suitable settlement substrate. In addition, thermoclines have been found to influence the distribution of the larvae with young larvae appearing to be unable to cross the area of thermal stratification into the surface water layers, where there is greater food availability, or from the surface layers to the deeper water to find a suitable settlement substrate.

At the end of their planktonic period the larvae metamorphoses and settles onto substrates such as bryozoans, hydroid turf, algae, bedrock, boulders, stable cobbles, pebbles or shell. Once scallops have grown to the size were they can recess into the sediment they move very little from their settlement area, with movements primarily being limited to disturbance. As such, the habitat must be must be conductive to filter-feeding with non-silt areas being preferential.

Sites selected through industry engagement as proposed reseeding sites were examined to ensure that they met the characteristics required for successful settlement of scallops. Seabed habitat maps were combined to provide information for the full sea area under consideration. Scallop catches from the annual AFBI scallop survey were mapped with the full habitat map to determine the areas where scallops were present and identify the underlying habitat type. This allowed a map to be created which showed the suitable habitat for adult scallops within NI waters (the majority of scallops caught during the scallop survey are age 3+, very little scallop under age 2 are recorded). All of the proposed reseeding sites fell within areas of suitable habitat.

To examine further characteristics of the proposed sites, a combination of measured and modelled data was used. The majority of the measured data used was collected as part of the 2016 winter and summer Water Framework Directive sampling schedule, either using set stations were profiles are recorded, or via the flow-through system onboard the RV *Corystes* which collects continuous georeferenced data.

Salinity was determined not to be an issue at any of the proposed sites, with the entire NI coast being of an optimal salinity for scallops. However, when temperature was examined, a potentially limiting aspect was reported for the proposed reseeding sites at Killough, Roaring Rock/ Russell's Point, Cranfield Point (inshore) and Cranfield Point (offshore), with the presence of thermoclines at these sites during months when scallops may be spawning. The presence of the thermocline could impede dispersal of larvae produced by scallops reseeded in these areas.

Food availability at each of the proposed sites was examined using modelled data for Chlorophyll a concentration. Measured flurometer data was used to corroborate the modelled data. The proposed reseeding site at Red Bay had the lowest food availability whilst the County Down sites had the highest levels of Chlorophyll a. This was supported by presenting size-at-age data collected during the AFBI scallop survey which shows scallops along the County Down coast to be larger than those along the Antrim coast.

Bed stress, which reflects the natural physical disturbance at the seabed from wave action and/or tidal currents, has been noted by previous studies to affect both the settlement and retention of scallops. In this report the bed stress data were provided by Proudman Oceanographic Laboratory, based upon the Proudman Oceanographic Laboratory Coastal Modelling System (POLCOMS). Based on literature, a nominal combined (wind and tide) bed stress threshold of 2 Nm^{-2} was applied, with sites exceeding this value considered potentially unsuitable due to increased probability of re-laid seed being washed away.

The literature review indicated that the levels of suspended particulate inorganic matter can reduce the efficiency of scallop feeding affecting scope for growth and fecundity of adult scallops. Modelled non-algal suspended particulate matter (SPM) was examined. The data showed a wide variation throughout the year, with peaks in winter months (related to suspension of non-algal particulate matter through increased wave action/mixing, or from increased river flow). This was corroborated by measured data from Belfast and Strangford Loughs. The proposed reseedings sites at Donaghadee Sound and Ballyhalbert Bay showed levels of SPM higher than the average at the other sites.

Using bycatch data collected as part of the annual AFBI scallop survey, abundances of predators (starfish and crab) were examined at five of the proposed sites (no data was available for the other eight sites). The common starfish, a primary predator of scallops, was found at all the sites examined except for Donaghadee Sound. The proposed reseeding site at Ballyhalbert Bay had the highest total abundance of predators. As the presence of predators can be one of the main determining factors in the success of a reseeding area, areas with high predator abundance should be avoided. Removal of predators at a reseeding site should be actively carried out.

As site characteristics fluctuate throughout the year it is important to know when scallops are likely to spawn to ensure that at the time of spawning the characteristics are optimal. The time of spawning is also required to examine the movement of the larvae using the correct current direction and strength information. Data collected during the AFBI scallop survey was used as an indicator of the time of spawning for local scallops. During the earlier years the primary peak in spawning is indicated as being in spring. However, in 1996 the width of the first band is much more varied, with no main peak at any size class. Following 1996 there is a shift in the peak in band width which appears to indicate a shift in the main spawning season from spring to autumn. As re-laid seed scallops may be from non-local stocks, the variation in potential spawning season should be considered for any future larval dispersal modelling.

To determine the potential movement of larvae produced by scallops at the proposed reseeding sites, published relevant larval dispersal and hydrodynamic models were examined. These models showed a similar trend for the bivalve species used (unfortunately there is no current larval dispersal model for scallops in Northern Ireland waters). POLPRED tidal prediction software was accessed to determine tidal currents in the areas of the proposed reseeding sites. From this and published literature it is clear that there is a notable split between current directions north of Belfast Lough and that south of the Lough. In general there appears to be a net movement north inshore along the County Antrim coast whilst there is a net movement south along the County Down coast. Dispersal distances are affected by the timing of spawning events; where spawning coincides with the establishment of the western Irish Sea gyre and sites are proximal to the gyre, dispersal distances increase.

The above information was presented to the project steering group to select the most suitable sites for reseeding out of the 13 proposed sites. In order for this to be effectively enforced it was suggested that the selected sites are located inshore with a land boundary. Other established boundaries such as those for Strangford Lough Marine Conservation Zone (MCZ) were also examined as this could aid the simplicity of closing areas for reseeding.

The steering group decided that initially three reseeding sites would be put forward with a fourth, Roaring Rock, having potential for any future reseeding plans. The three selected sites are;

1. Whitehead (3.26km^2)
2. Drumfad Bay (1.46km^2)
3. Ballyquintin Point (3.22km^2)

The location of these sites is shown in Figure A. The "Ballyquintin Point" reseeding area has been positioned to partially fall within the MCZ boundary.

Figure A: Sites selected for reseeding taking in to account the characteristics of the sites and feedback from the scallop fishing sector. Those outlined in red were drawn by the steering group and are ready for progression. The site outlined in purple (Roaring Rock) was a provisional extra site, with the boundary being an indication of a possible site.

Recommendations

1. Reseeding has been used worldwide and provides an effective way of creating a broodstock which enhances the population. This study included a full environmental parameter appraisal and stakeholder engagement with the Northern Ireland Scallop Association prior to selecting recommended sites. The recommended sites are;
   - Whitehead (3.26km^2)
   - Drumfad Bay (1.46km^2)
   - Ballyquintin Point (3.22km^2)

2. Whilst the previous Northern Ireland reseeding trial showed mixed results, this study has provided information which should be applied to increase the effectiveness of future reseeding work.

3. If funding is available, a full larval dispersal model should be produced to determine the exact location of settlement of the larvae produced by the reseeded scallops.

4. The scallops used to reseed the area must be selected carefully to ensure they do not impact the local scallops in terms of genetics (see section 4.2).

5. To give the scallops to be reseeded the best chance of survival they should be transported in the correct manor (see section 4.1).

6. Reseeding a site with scallops will only be successful if the selected sites are closed to mobile fishing gear, allowing the reseeding site to act as a source of larval production. This will require a ban to be introduced and enforced to prevent mobile gear fishing in reseeded areas. Static gear fishing in the reseeding area should be allowed to continue.

7. Monitoring of the site is required to determine the overall effectiveness of reseeding in that area. This should include initial examination of retention of scallops at the site as well as longer-term survival, growth and spawning of the reseeded scallops.

Contents

1. Study Background

With increasing exploitation of scallop stocks around the Northern Irish coast, the Northern Ireland Scallop Association has expressed a wish to be proactive in working with industry to enhance long-term sustainability of stocks. In 1999 the Northern Ireland Scallop Association carried out a reseeding project with the Centre for Marine Resources and Mariculture (C-Mar) (Centre for Marine Resource and Mariculture, 2000). The success of the reseeding was highly variable between sites. Issues indentified for further work during the initial project were; the survival of scallop seed during transport to the reseeding site, lack of predator control, continued fishing of the reseeded sites and lack of suitable post reseeding monitoring. Furthermore, it is observed that a significant proportion of the scallop seed which was re-laid onto the reseeding sites could not be detected. This was thought to be due to seed being washed away by strong currents in the area rather than high mortality.

However, the project was regarded as having partial success in some of the areas in terms of survival of re-laid scallops. For example, in Strangford Lough reseeded scallops had a 100% survival rate but with below average growth. In 2016 the Scallop Association approached AFBI to discuss the potential of carrying out an enhanced scallop reseeding programme which would take into account aspects of reseeding success identified in the previous project by addressing the suitability of reseeding sites for scallop retention, as well as providing an indication of the larval dispersal from the reseeding sites to ensure that the larvae from the seeded scallops settle in an area that can be exploited by the scallop fleet.

The objectives of this study are to answer two key questions to allow informed decisions to be made when selecting the most viable sites in order for successful reseeding.

Questions to be addressed

1. Which sites are the most suitable to reseed with scallop spat?
2. Where will the larvae from the reseeding sites settle and is this available for fishing by the Northern Ireland fleet?

This work will inform the Scallop Association proposed reseeding work.

2. The Northern Ireland Scallop Fishery

Scallops are fished using dredges with metal teeth set vertically along the front edge of the dredge. The teeth rake scallops which are caught by a bag positioned behind the tooth bar. Groups of dredges are hung from a tow bar which has wheels on either end so it can move over the seabed. In Northern Ireland a number of gear restrictions apply to the fishery. These included

- Ø a limit of 6 dredges to be allowed on each side of the vessel;
- Ø a maximum of 9 teeth per dredge;
- Ø minimum tooth spacing of 75mm;
- Ø Use a scallop dredge or system of scallop dredges with a width, or in the case of a system of scallop dredges, an aggregate width, of more than 915 cm;
- Ø Use a tow bar which exceeds 5.5m in length
- Ø a minimum diameter of belly ring of 75mm
- Ø a minimum mesh size of 100mm in the netting cover
- Ø The prohibition of French dredges

In Northern Ireland water fishing for scallops (including that by diving) is only allowed to take place from Monday to Friday and between the hours of 0600-2000. In addition, the Minimum Landing Size (MLS) for scallops is set at 110mm, including from areas on the North Coast (VIa) where under EU regulations the MLS is set at 100mm.

Fishing for scallops has been established in Northern Ireland since 1935 (Briggs, 1992). In 2015 over 1,300 tonnes of scallops were landed into Northern Ireland ports with a first sale value of £2.7 million. Figure 1 shows the landings of scallops into Northern Ireland between 1973 and 2015.

Whilst in the 1970's the Northern Ireland scallop fishery was generally less than ten vessels, based mainly at Portavogie (Briggs, 1975), in 2015 76 vessels reported landings of scallops into Northern Ireland, sixty of which were registered to Northern Ireland. These vessels ranged in size from 8.6m to over 30m in length. Of these vessels 45% were less than 12m in length, compared to 21% in 2007 – these vessels are not required to have a Vessel Monitoring System (VMS) in place. A further 18% of vessels were between 12m and 15m in length compared to 32% in 2007 and (Figure 2) and 37% were greater than 15m in length compared to 50% in 2007. All vessels greater than 20m landing scallops into Northern Ireland, were registered to a Scottish port (Figure 3).

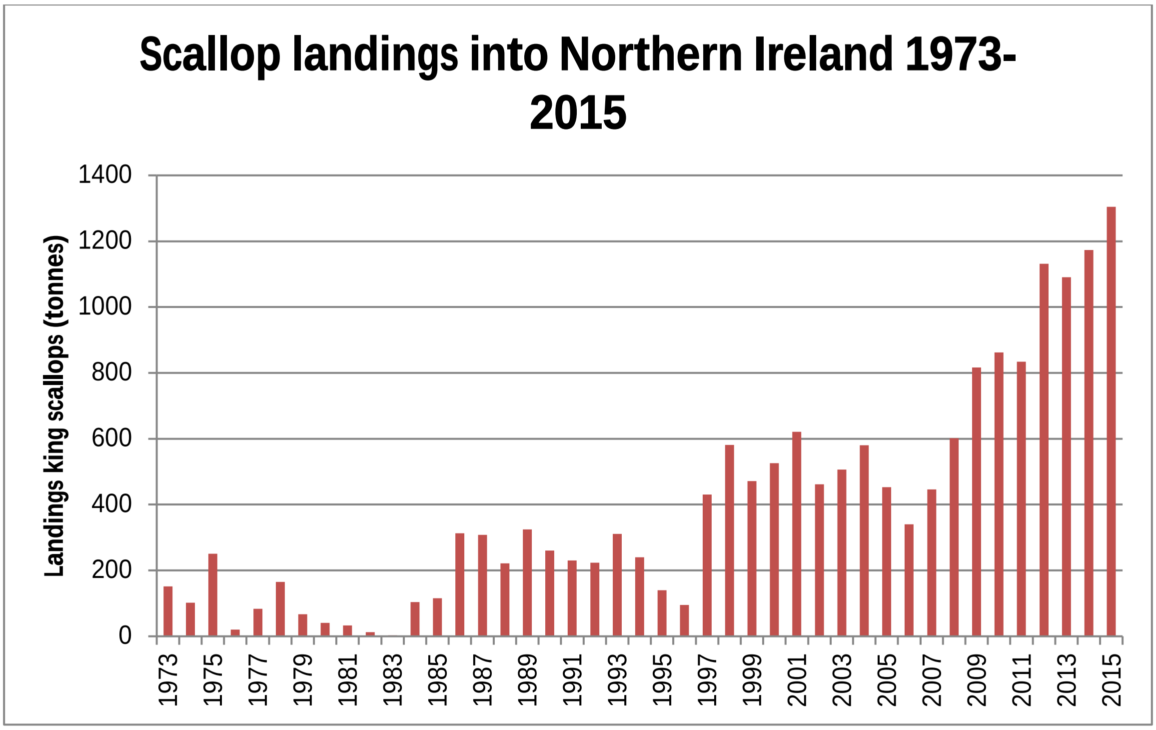

Figure 1: Landings of scallops (*P. maximus*) into Northern Ireland between 1973 and 2015 (Source: DARD official landings and MMO)

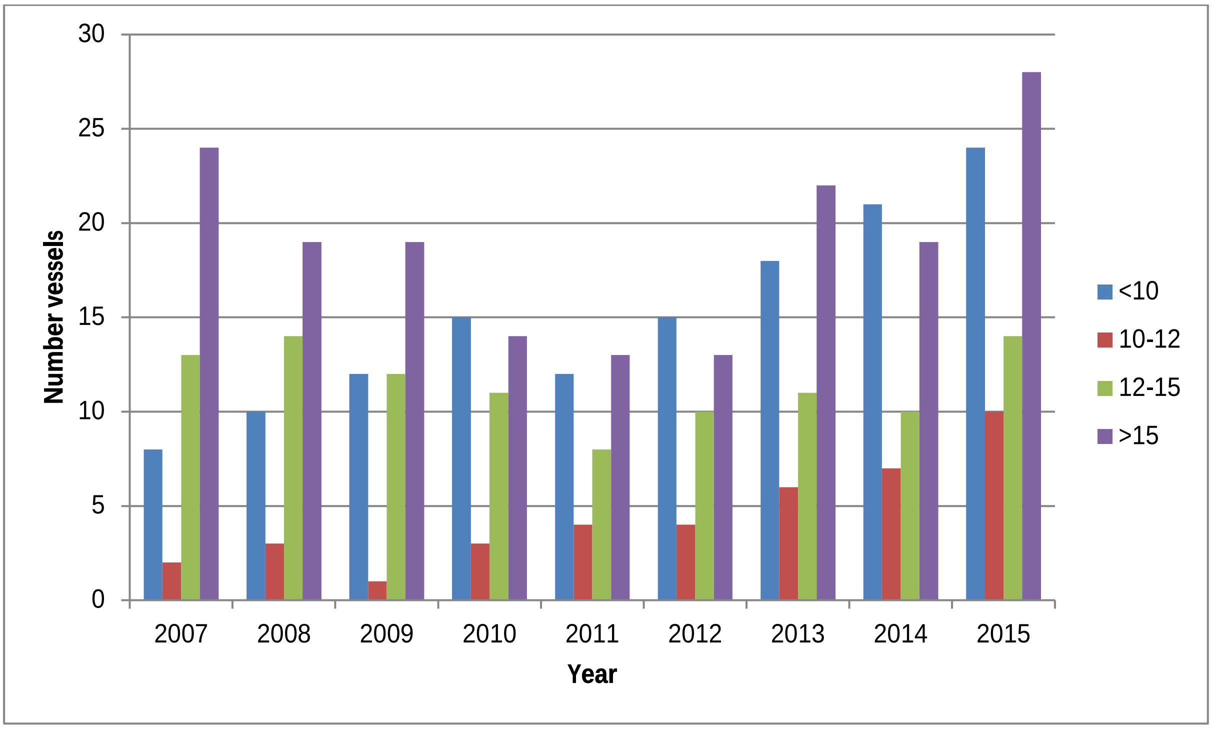

Figure 2: Number of vessels, by length, which reported landings of scallops into Northern Ireland between 2007 and 2015

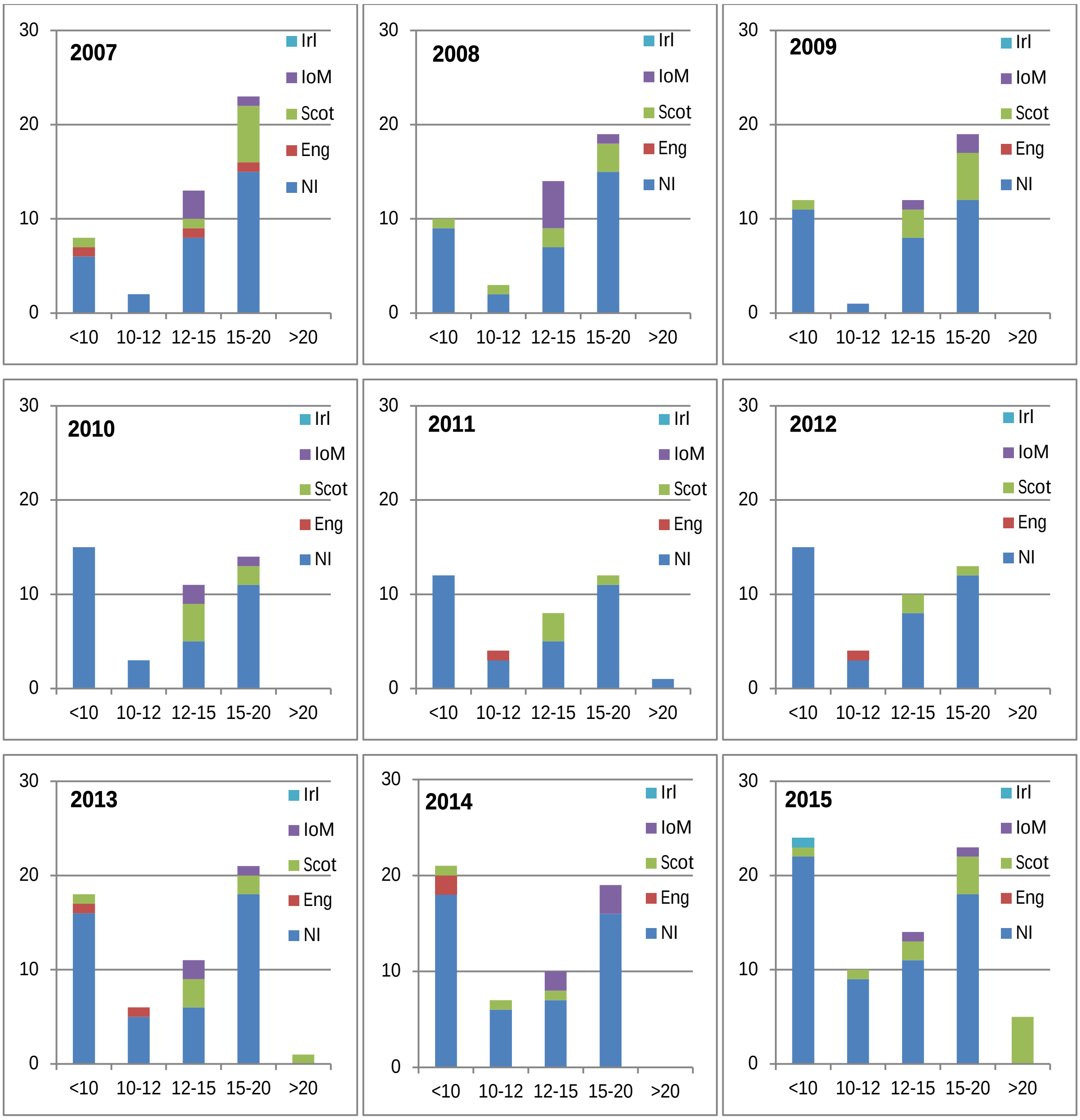

Figure 3: Nationality of vessels landing scallops into NI between 2007 and 2015

Between 2007 and 2015 scallops have been landed into Northern Ireland from 28 different ICES rectangles. ICES rectangle 37E4 consistently had the largest number of vessels (of all nationalities) reporting landings into Northern Ireland from that area (Figure 4). Averaging at 40, the number of boats landings scallops into Northern Ireland from 37E4 ranged from 26 in 2011 to 61 in 2015. ICES rectangle 37E5 has seen the largest increase in effort in terms of the number of vessels landing into Northern Ireland from that area. 37E5 has seen a fourfold increase in the number of vessels from 12 in 2007 to 48 in 2015. In terms of Northern Ireland only vessels, the effort in terms of number of vessels fishing in 37E5 has increased almost six-fold from 2007 to 2015.

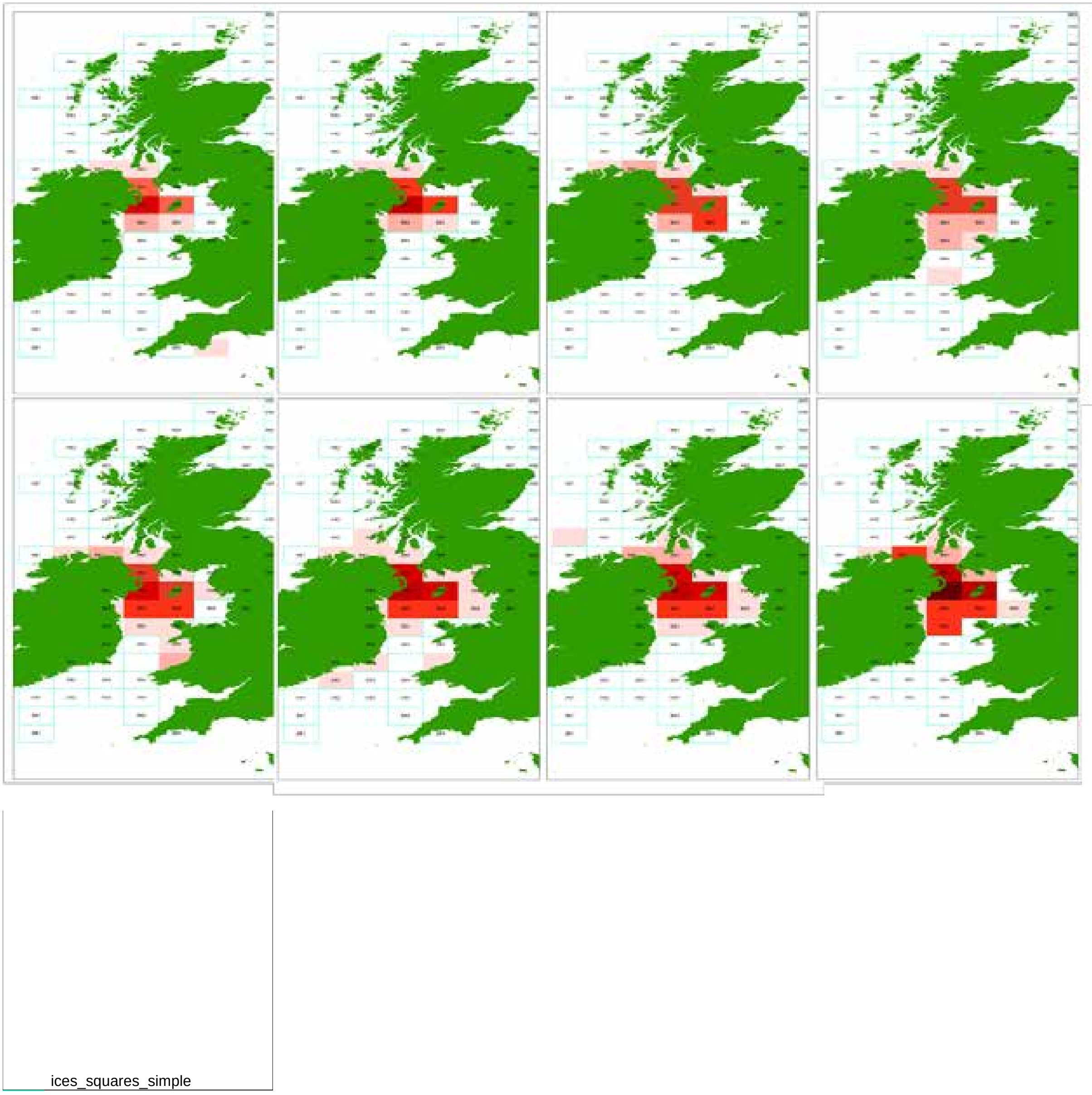

Figure 4: Number vessels fishing for scallops by ICES rectangle which landed into Northern Ireland (all Nationalities)

ICES rectangles 37E4, 37E5 and 38E4 are fished by the greatest number of Northern Ireland vessels which are less than 12m in length, landing into Northern Ireland. However, effort by these vessels is distributed over sixteen ICES rectangles. As these vessels have no VMS the spatial intensity of fishing within these rectangles is not available. Indeed, prior to 2013 VMS data will only be available for vessels of 15m or greater.

The peak in scallop fishing occurs annually in November after the reopening of the Irish Sea. Fishing continues at moderate levels between December and May. Due to the Irish Sea closures, scallop landings taken from the Northern Ireland coast during the summer months are from the North coast which has no closed season. Figure 5 shows the total monthly landings of scallops into Northern Ireland, averaged from 2013 to 2015.

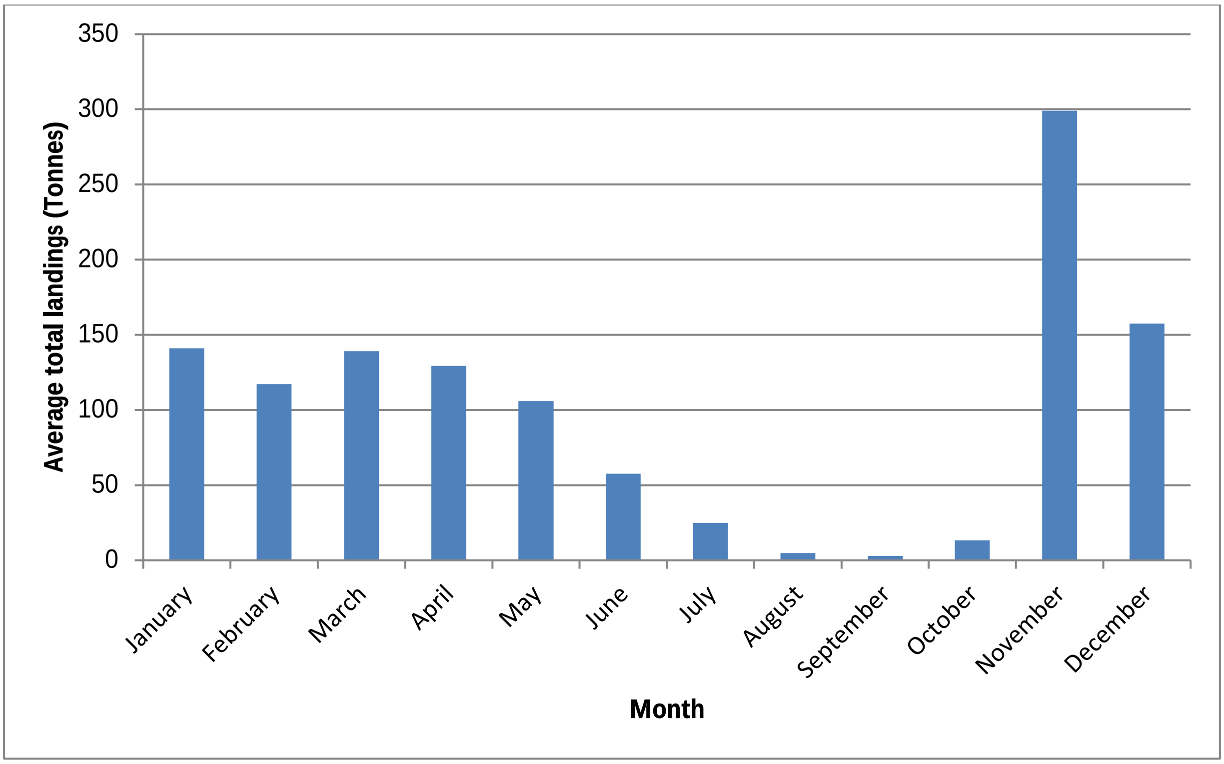

Figure 5: The average total catch of scallops landed into Northern Ireland between 2013-2016, by month.

3. Literature Review

3.1 General Biology

The King scallop, *Pecten maximus,* is a large long lived bivalve which can commonly grow to 150mm or more (Ansell *et al.,* 1991). The shell is unequivalve with the right valve being convex whilst the left is flat. Both shells are externally ridged with up to 17 thick rounded ribs. Scallops are entirely sublittoral. They are a meroplanktonic hermaphrodite species spending a small part of its development in the water column (as larvae) and the major part of its life on the sea floor (Le Goff *et al.*, 2017). Whilst they can live to depths of 180m, they are more abundant in depths of 18-46m. Scallops recess into the substrate with the upper flat valve level with the seabed. This recessing behaviour may help to reduce predation on the adult scallops by camouflaging the scallop from predators such as crabs, whilst the layer of sediment on the top of the upper valve may reduce starfish predation by restricting the contact of the tube feet to the shell (Brand, 2006).

3. 2 Life History

Below we review the key life history stages of *P. maximus.* The life cycle of *P. maximus* is shown in Figure 6. We shall address each of these in turn with a focus on the key aspects of dispersal and settlement.

3.2.1 Spawning

Scallops become sexually mature at 2-3 years old. Cycles in gametogenesis vary from empty, filling, full, partially spent and spent (Barber and Blake, 1991). The environmental triggers of spawning include temperature, salinity, lunar phase, light, dissolved oxygen, pH, mechanical shock and various chemicals (Barber and Blake, 1991). Spawning time may also be linked to genetic differences between stocks (Salomonsen *et al*., 2015). Spawning across the UK generally occurs between the months of April and September. Spawning in *P. maximus* in spring is thought to be triggered by increasing water temperatures whilst autumn spawning is believed to occur when water temperatures are decreasing (Naidu, 1970 cited in Barber and Blake 2006). Barber and Blake, 1991, reviewed the peak spawning time of scallops (Table 1). Whilst this shows the general trend in spawning of scallops from these areas there are differences between years in both the timing and duration of spawning. In Strangford Lough a single protracted spawning in July and August was reported in 1995 whilst 1996 showed a bimodal pattern with highest levels in August (McDonough, 1998). In Manx waters scallops first spawn in the autumn when most of them are just 2 years old, the following year they have one main spawning in autumn and after that they have two spawning, one in spring and 1 in autumn (Mason, 1958). Two main spawning peaks are usual for most Irish Sea scallop populations (Duncan *et al*., 2016).

Table 1: Peak spawning periods reported for *Pecten maximus* across the UK and Ireland (compiled by Barber and Blake, 1991).

Location	Spawning period	Source
Isle of Man	April-August	Dakin, 1909
Isle of Man	June	Tang, 1941
Bantry Bay	April-May, September	Gibson, 1956
Isle of Man	August-September, April-May	Mason, 1958
Wales	Spring, Fall	Baird, 1966
Northern Ireland	May-June, August	Stanley, 1967
Clyde	June-July	Comely, 1974
Galway Bay	April-May, July-August	Wilson, 1987

Scallops are hermaphrodite having both female (orange or red part) and male (creamy white part) organs which together form the roe. As they are hermaphrodite they have the potential to self-fertilise. However, if this occurs the progeny may be less viable than if the eggs had been fertilised by a different scallop. The chance of self-fertilisation is reduced by releasing sperm and eggs separately as well as the dispersal of the gametes in the water column, with eggs settling downwards whilst the sperm disperse out into the water column (Salomonsen *et al.,* 2015).

When one individual spawns, some of the eggs which are released are filter fed from the water column by its neighbour. The pheromones contained in the eggs then cause the neighbour to release its eggs and so on. Therefore in low density populations it is possible that there is a spawning stock but no reproduction due to a phenomenon known as the Allee effect i.e. there are too few individuals present to come in to contact for fertilisation.

Fertilisation produces trochophore larvae which live in the plankton (Figure 6 outlines the life cycle of *P. maximus*). Through the observation of hatchery reared larvae, the larval stage (D Larvae to pediveliger) of *P. maximus* lasts 15-32 days (Pennec *et al*., 2003). In situ the pelagic stage from gamete emission to spat fall has been found to be variable (Table 2). It is estimated that the survival rate of scallops during the larval stage is only 0.1%.

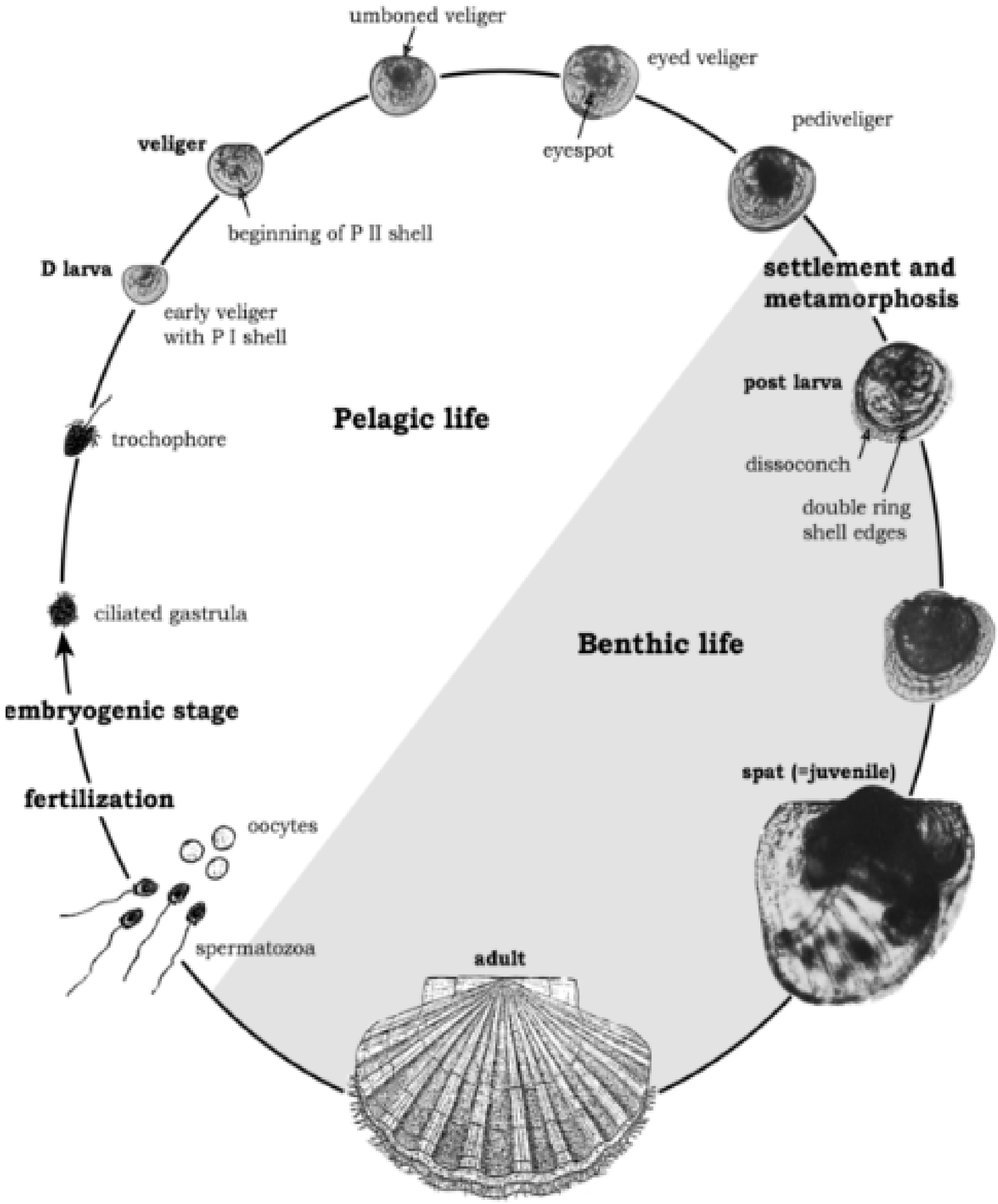

Figure 6: Life cycle of *Pecten maximus* taken from Le Pennec *et al*., 2003

Table 2: Duration of the pelagic phase of *Pecten maximus* from published literature.

Number days	Reference
18-42	Pennec *et al.,* 2003
23-41	Cragg, 1980
21-28	Brand *et al.*, 1980
30	Darby and Durance, 1989
33-38	Galley, 2014
21-56	Duncan *et al.*, 2016
21-28 (in lab)	Dao *et al.*, 1996

3.2.3 Dispersal

The distribution of benthic marine species is driven by abiotic (hydrodynamics, sediment type etc.) and biotic (individual physiology characteristics, ecological interactions) factors (Le Goff *et al*., 2017). Orensanz *et al*., (1991) addressed the question of the spatial distribution of scallop beds. Their review suggested that along with differential survival and individual movements, settlement and early distribution based on passive larval accumulations (via hydrodynamics) and availability of a primary settlement substrate explain the spatial patterns in the distribution of scallops. Whilst Le Pennec *et al.*, (2003) reported the role of hydrodynamic conditions in larval displacement they found that the larvae are not inert particles, with a ciliated velum which allows for locomotion via helicoid swimming. Cragg (1980) showed that the larvae may have some control over their vertical distribution, with the trochophore stage tending to swim upwards in vertical spirals and accumulate at the surface. As the larvae get older they accumulate in the lower water column until the pediveliger stage when they tend to accumulate near the substratum due to a reduction in swimming effort, as they crawl along the bottom looking for a settlement substrate. Horizontal dispersal of larvae is determined by water currents. Larvae which are distributed close to the surface are influenced by wind, modified by the physical oceanographic features in the area; larvae deeper in the water column are carried by currents and other wind independent flows (Hartnett *et al.*, 2007). Knights *et al.,* (2006) reported that in the Irish Sea maximum densities of larvae of the mussel *Mytilus edulis* were reported during flood tides of both spring and neap tides.

Hartnett *et al*., (2007) used a numerical model to investigate the migration-transport pathways of scallop larvae produced in the Irish Sea. They also wanted to examine the impact of thermoclines on the behaviour of larvae. In the study they attempted to mimic larvae behaviour in seeking favourable conditions to feed during initial growth. The rules they used to simulate this were,

1. Day 0-2 the larvae remain at, or near, the seabed;
2. Days 3-20 the larvae swim to within 5m of the surface at a rate of 0.75mm s^{-1};
3. Days 21-30+ larvae swim to seabed at a rate of 1.4mm s^{-1}.

From the simulation they found,

1. At or near the surface the particles are transported due to tidal advection and random diffusion;
2. Without a vertical swimming ability particles cannot get above the thermocline, therefore they cannot reach the surface to feed and will never become viable;
3. When larvae are given the ability to swim they can penetrate the thermocline to reach the surface (in well mixed water the larvae are dispersed throughout the water column);
4. Larvae outside of the horizontal thermocline cannot cross it but are forced along the edge of the thermal front, following a fixed pathway. This pathway can be altered with different meteorological conditions.

Gallagher *et al.*, (1996) also found that thermoclines have an impact on the vertical movement of scallop larvae, but this behaviour is dependent on the size of the larvae; smaller veligers migrate vertically between the water surface and the temperature boundary whereas veligers > 175 µm begin to penetrate the thermocline and are found throughout the water column. Pearce *et al*., (1998) presented results which examined the effect of thermoclines on the giant scallop *Placopecten magellanicus*. From their study they determined that a critical level of stratification must be reached before larvae behaviour changes i.e. before larvae settle at or above the vertical thermocline. This critical threshold may be lower in deeper waters. Examining the response of the giant scallop to a weak thermocline in 9m mesocosms Manuel *et al*., (2000) also found peaks in veliger density just above the thermocline but only when temperature differences were greater than 1°C. Their research showed that it was the thermal stratification, rather than changes in other parameters which vary with depth, that altered the distribution of the veligers. Older veligers were found to migrate through the thermocline in both directions. They related the altered distribution to behavioural changes rather than physical changes of the temperature directly affecting the swimming (which they believed would lead to a peak in veligers below the thermocline). By staying above the thermocline the larvae are in the most productive area. Secondly, the higher temperature above the thermocline can increase the rate of development and growth, leading to earlier settlement and thus lower mortality due to predation, loss by advection etc. Thirdly, this behaviour keeps the larvae in the region of the pycnocline (which has the greatest shear after the near-bottom changes in velocity) which is not only associated with peaks in chlorophyll density but which enhances opportunities for vertical transport (Manuel *et al*., 2000).

Scallops tend to be most abundant just inside or just away from areas of strong current and Dare *et al.*, 1994, found, that in the English Channel, there is a clear inverse relationship between *P. maximus* distribution and the magnitude of frictional bottom stress with virtually all commercial scallop grounds restricted to areas where bottom stress is low, in this case less than 10 dynes cm^{-2} (Brand, 2006).

3.2.4 Settlement

After approximately 15-40 days the larvae metamorphoses and settles onto other sessile organisms, such as bryozoans, using byssus threads produced by the byssus gland on the foot, before developing in to a small scallop. At the time of settlement the larvae are around 250µm in size (Dao, 1990). After a while the byssus threads break down and the scallop can join the adult scallop population (Briggs, 2000). In colder years, the growth of the larvae is much slower and so they remain in the plankton for longer. The longer the larvae remain in the plankton the further they are carried away from the broodstock and suitable attachment substrates. This may mean that after colder periods recruitment is reduced as the larvae are lost out of the system.

Once scallops have settled and recessed into the substrate they move very little from the scallop bed. During the 1950’s Gibson (1956) tagged and released scallops into the Bere Island fishery (South West Ireland). They reported no movement of scallops between beds. Further tagging studies reviewed by Barber and Blake (1991) also show very little movement with nearly all returns coming from the same bed or within 1-2km of the release site. More significant movements of scallops tend to be through current transport. This lack of significant movement is apparent by looking at the shell of the scallop which generally matches the colour of the environment where it is living. However, if disturbed, scallops can jump or swim, but these movements are localised with no great distance being travelled. Minchin and Mathers

(1982) estimated that, during one swimming burst, *P. maximus* can move around 3m reaching a height of 0.46m from the seabed. Scallops in high density beds may also stimulate each other to move. Howell and Fraser (1984) reported that during the relaying of tagged scallops onto a natural scallop bed swimming behaviour by one scallop was enough to cause a similar response in others. This increased level of swimming continued until the scallops were at a sufficient distance from each other. Also, high densities of transplanted scallops may increase predator aggregates in the area, increasing swimming response and thus dispersal (Brand, 2006). Studies on *P. maximus* have shown that whilst they show minimal movement when in sand, when placed on hard substrates they swim frequently and disperse widely (Wilkens, 2006).

The natural density of scallops is variable. Howell and Fraser (1984) reported natural densities between 0.1 and 0.41 scallops per m^2 on the sandy-gravel and mud habitat of Loch Creran, West Scotland. Franklin *et al.,* (1980a) found from underwater television and divers that scallops can be present at densities of 5-6 per m^2 but a more normal density is 0.2 per m^2. Dao *et al.,* (1999) reported that a good recruitment will reach 0.5 to 1 scallop per m^2. Brand (2006) provided a summary of natural densities reported for *P. maximus* which varied from 0.01 scallops m^2 to 0.67 per m^2 (Table 3).

Table 3: Natural densities of *Pecten maximus* (Source: Brand 2006).

Location	Density (number m^2)	Reference
Strangford Lough	0.67	Hartnoll, 1967
Claonaig Bay, Scotland	Before fishing – 0.12	Mason *et al*., 1979
	After fishing – 0.03	
English Channel	Mean – 0.16; Max – 2.33	Franklin *et al.,* 1980
Isle of Man	0.04-0.13	Murphy, 1986
	0.01-0.04	Wilson and Brand, 1995

Laing (2002) investigated the effect of salinity on the growth and survival of hatchery reared scallop spat. They reported that a salinity of 30-35 psu had no apparent effect on the performance of king scallop spat. However, sites where salinity regularly fell to 26psu or below showed lower growth. Whilst the growth rates of spat surviving short-term exposure to low salinity recovered to normal levels they concluded that low salinity sites should be avoided for cultivation.

3.3 Habitat

The spat of *P. maximus* are usually seen attached to algae in shallow water, with the algae attached to bedrock, boulders, cobbles or pebbles. Spat can also be found on other filamentous erect taxa such as bryozoans and hydroid turf, which in turn are attached to hard substrata or found on embedded cobbles, pebbles or dead shell. Erect bryozoans and hydroids are especially important as depth increases and suitable algal settlement sites are not available (Brand, 2006). Settling on to growing organisms provides clean surfaces for attachment and these may be important in areas of heavy siltation. Surfaces covered by older bacterial films and diatom biofilms also appear to promote settlement (Eckman, 1987).
Eckman (1987) reported that higher current velocities near the seabed promote scallop spat settlement, and spat are seldom found attached to surfaces covered with silt, which has been reported as detrimental to attachment in some scallop species (Brand *et al*., 1980). In hatcheries, turbulence has been demonstrated to have a beneficial and reproducible effect on settlement and metamorphosis of *P. maximus* larvae (Nicolas, 1998). However, near-bed currents above 1ms^{-1} are considered prohibitive to settlement (due perhaps to difficulties in byssal attachment at such speeds) (Le Goff *et al.,* 2017).

Free spat are found on sediment immediately surrounding hard substrata (bedrock, boulders, cobbles or pebbles), with scallops from 4mm total shell height noted detached (Minchin, 1992). Recessing in the sediment appears to occur from 6mm and greater shell height. ‘Free’ spat on sediment were often observed to be attached by byssal threads to small particles of shell or coarse sediment until they were large enough to fully recess into the sediment (Minchin, 1992). It is clear therefore that although hard substrata is required for spat to attach to as they settle out of the water column following metamorphosis, it is equally important for there to be an availability of nearby surrounding sediment for the young scallops to recess into once 4-6mm in shell height. As such, heterogeneous habitats are optimal, where there is a matrix of hard substrata (or stable embedded pebbles, shell and/or cobbles) and softer sediments (e.g. sands).

Once spat have grown to the stage where they can recess into the sediment, there is minimal further dispersal (see section 3.4). As such, the habitat must be conducive to filter-feeding, and it has been shown that high sediment silt content may have negative effects on feeding (Gruffydd and Beaumont, 1972, cited in Le Pennec *et al*., 2003). As such non-depositional areas are preferential, where near-bed currents reduce the silt content of the sediments.

However, excessive near-bed turbulence may cause juvenile mortality due to dispersal of small scallops or spat to unsuitable areas, or preventing spat attachment (Le Pennec *et al*, 2003). Commercial fishery areas for *P. maximus* in the English Channel have seabed temperature ranges from 10-12°C, and exhibit tidal bed shear stress ranges from 0.24 - 1.7 N m2 (Szostek, 2015). It has been demonstrated that the growth rate and maximum size of scallops in such areas is influenced by chlorophyll a concentration (i.e. food availability), temperature and bed shear stress (Smith *et al*., 2007). In an English Channel scallop model developed by Le Goff *et al*., (2017), it was found that the spatial variability in food availability was an important determinant in scallop fecundity and abundance of eggs released. Where depth typically exceeds 100 m, food availability is low, and scallops rely exclusively on sinking organic particles (McCave, 1975; Bienfang, 1981; Smetacek, 1985, cited in Le Goff *et al*., 2017), resulting in a relatively low amount of energetic reserves compared to enriched coastal areas. Many studies have shown that high suspended particulate inorganic matter (SPIM) concentrations can affect the food assimilation efficiency of filter-feeders, largely due to food dilution by re-suspended inorganic particles (Barillé *et al*., 1997, cited in Le Goff *et al*., 2017). As such, to identify the most suitable scallop habitat for optimal growth and reproduction, food availability as well as SPIM concentrations should be considered, in addition to seabed substrata, near-bed current speeds/bed stress and temperature.

4. Scallop stock enhancement

Over half the world's reported bivalve production relies on culture or enhancement programme (Bourne, 1984). Natural restocking of scallop beds has been carried out for over a century; in 1906 scallops were transplanted to areas of Buzzards Bay, USA, from where they had virtually disappeared. The following years strong settlement was attributed to the translocated stock (Belding, 1910).

However Japan were the first country to carry out routine stocking of natural beds from the 1930's. This practice evolved from using translocated seed from other beds, to the use of seed collected on spat collectors, to suspended culture of scallops (Orensanz *et al.,* 1991). These practices have greatly increased the settlement of *Patinopecten yessoensis* in Mutsu Bay, Japan, where average settlement onto collectors has increased from a few hundred in the 1970's to more than 10,000 spat per collector (Orensanz *et al.*, 2006).

In terms of restocking, scallop seed generally comes from hatchery production or by collecting wild spat using artificial substrates. This spat can then be intermediately cultured using pearl nets, trays or small lantern nets before the final grow out stage which is either via suspended cages or bottom culture (Parsons and Robinson, 2006). Whilst bottom culture is relatively inexpensive there are several disadvantages. The growth rates of bottom cultured scallops are slower in comparison to those in suspended culture and predation rates are higher, particularly after reseeding. Scallops may leave the site through swimming or be carried away in strong currents. There also needs to be management of the site to ensure limited access is permitted. This area may need to be extensive. For example, Parsons and Robinson (2006) reported that if 1,000,000 scallops are to be seeded annually at a density of 5 m^{-2} then 20 hectares a year would be required.

Since 1989, in the Bay of Brest, sea ranching, combined with management measures to reduce effort on the fishery have been successful at re-establishing the King scallop fishery and is being tested at other sites. Hatchery reared scallops as small as 15-30mm are re-seeded at a density of one to three individuals per m^2 on fished grounds and 4 per m^2 on areas closed to fishing (Dao *et al.*, 1999). It is believed that by 2003 two thirds of the marketable sized scallops in the fishery have come from the ranched stock with the remaining third from natural recruitment. To reseed the areas 10 million seed are raised in the hatchery per year although more could be used. (Laing and Palmer, 2003).

In the Isle of Man there are five areas designated as Fisheries closed or Restricted areas for the enhancement of scallops. Of these five areas, Niarbyl Bay and Laxey Bay (a combined area of 950 hectares) were closed in 2009 and were reseeded with over 200,000 juvenile scallops in a ranching project carried out by Department of Agriculture, Fisheries and Forestry in partnership with the Manx Fish Producers Organisation. In 2010, Ramsey Bay was reseeded with juvenile scallops which had been tagged to allow their survival and movement to be monitored.

In 2010 Scot-Hatch was set up to produce young scallops in a hatchery which are grown on ropes before being grown to market size on the seabed, taking 4-5 years to produce a 125 to 140mm scallop. ScotHatch believe that these ranched scallops are "... good for the wild scallop fishery because they add to the breeding stock, whilst careful site selection and attention to stocking density leads to increased yields. We have found that the meat content of our ranched scallops is far superior to those taken from the wild fishery" (www.seafoodsource.com). ScotHatch have also sent Scottish scallops to Norway where they were spawned and reared to 15mm before being imported back to Scotland. In 2013 one million scallops were returned successfully. However, in 2014 two million scallops being imported suffered mass mortality of around 80% (Barr and McLeod, 2014). Scallops are distributed at 5-10 individuals per m^2 with each hectare sustaining 50-100,000 scallops (studylib.net).

4.1 Reseeding site selection

Laing (2002a) provided a guide to site selection for scallop cultivation. An optimal cultivation procedure should include;

- Continuous submerging of scallops during transport to minimise stress, or as a minimum a method to keep the scallops moist such as misting or packaging in seawater soaked sponge;
- A sediment type of clean firm sand, fine gravel or sandy gravel, the preferred natural habitat of scallops;
- A depth of 15-30m;
- A salinity of 30-35psu;
- A temperature of 10-17^{o}C;
- Predator control

Laing (2002a) stated, the transport of juvenile scallops for reseeding should be carried out carefully to reduce mortality of the scallop seed through desiccation. Additionally, Bremec *et al.*, (2004) found that the stress of transporting scallops has impacts on their escape response to predators. Aerial exposure for 20 minutes showed negative impacts on escape response of the scallop *P. maximus*, which was still evident after 24 hours.

In Norway high predation by crabs on ranched scallops has seen the development of a crab-proof fence which has given 90% survival of reseeded stock compared to 0% survival when no fence is used. The fence requires regular maintenance especially to remove seaweed which crabs can use to get over the fence (Laing and Palmer, 2003).

4.2 Genetic effects of reseeding

Morvezen *et al*., (2016) warned that enhancing wild populations with hatchery-born individuals can induce a reduction of their effective population size, a phenomenon known as the Ryman-Laikre effect. In their study of the Bay of Brest which has been reseeded since the 1980's using seed from another area in France, no trend was observed over time in the stability of the allelic richness of the sampled population as would be expected if significant genetic erosion was occurring. In spite of the relative alteration of the genetic diversity the genetic variability appears relatively stable over the study period in populations supplemented with hatchery seed. However, Bell *et al*., (2008, cited in Morvezen *et al*., 2016) recommend that a population enhancement programme should take into account the maintenance of genetic diversity by using the largest possible broodstock, renewing it regularly, releasing families in equal quantity and carrying out genetic monitoring. *Hold et al*., (2013) reported that scallops have evolved in response to the conditions where they live; therefore, transferring scallops to different environments could affect their survival to maturity and success of their offspring. They do however state that there is a history of movement of *P. maximus*, and this, along with the possible transfer of larvae in ballast water, could mean that contamination of the genetic composition may have already occurred (Hold *et al*., 2013). For example in 1999 a reseeding trial in Northern Ireland used seed collected from Mulroy Bay. Scallops from Mulroy Bay are genetically distinct from those around the Northern Ireland coast (Vendrami *et al*., 2017).

Whilst seeding an area can increase the stock, closing areas to fishing without additional stock enhancement has been shown as an effective management option. For example, on Georges Bank, following a 4 year closure to gear, *Placopecten magellanicus* showed a 14 fold increase (Brand, 2016b).

Beukers-Stewart *et al*., (2005) reported on the impacts of a protected area in the Isle of Man. They found that scallops within a protected area showed increases in the density and mean age and size of scallops, with recovery of the population increasing as the duration of the closure increased. They suggested that the build up of high densities of scallops within the protected area enhances local reproductive potential and the likelihood of larval export to surrounding fishing grounds. Indeed, commercial CPUE increased significantly on all fishing grounds off the West coast of the Isle of Man – those nearest to the closed area. Recruitment into the closed area may also be enhanced due to increased settlement material such as hydroids which increase due to lack of disturbance by fishing gear. Twist *et al*., (2016) suggest that while fecundity and larval export will increase after providing a refuge, due to the limited mobility of scallops, the "spillover" of adult scallops from protected areas will be minimal. Contrary to this, fishermen from the Isle of Man perceived improved fishing catches around the boundary of the protected area within the Bradda inshore fishing ground, off Port Erin (Duncan *et al.,* 2016).

5. *Data used to predict viability of sites*

5.1 Proposed site selection

An initial meeting was held with Northern Ireland scallop fishermen, during which potential areas were identified as suitable for reseeding using their knowledge from fishing the areas as well as from the previous scallop reseeding trial. The areas suggested by the industry engagement are shown in Figure 7. In addition to these areas the suitability of existing protected sites was assessed (Figure 7). Table 4 provides a summary of all the sites which will be examined.

Table 4: Summary of potential reseeding sites. These selected sites have been related to the sites used in the 1999 reseeding trial.

Area	Location	Close to area used in previous trial	Result from previous trial
1	Muck Island, Moyle Interconnector route		
2	Black Head/Cloghan Point	Cloghan Jetty	All scallops lost within 3 weeks of seeding
3	Donaghadee Sound		
4	Ballyhalbert Bay	Ballyhalbert	Initial survival in April 1999 was over 75% but by August 1999 had dropped to 5%.
5	Ballyquintin Point		
6	Killard Point/Guns Island		
7	St John's Point, Ardglass		
8	Killough		
9	Roaring Rock/Russell's Point, Annalong	Bloody Bridge, Newcastle	Survival of 47% nine months after re-seeding – **considered successful.**
10	Cranfield Point, inshore		
11	Cranfield Point, offshore		
12	Scott's Hole, Strangford Lough	Scott's Hole, Strangford Lough	Showed a high survival of 100% - **considered successful.**
13	Red Bay SAC		

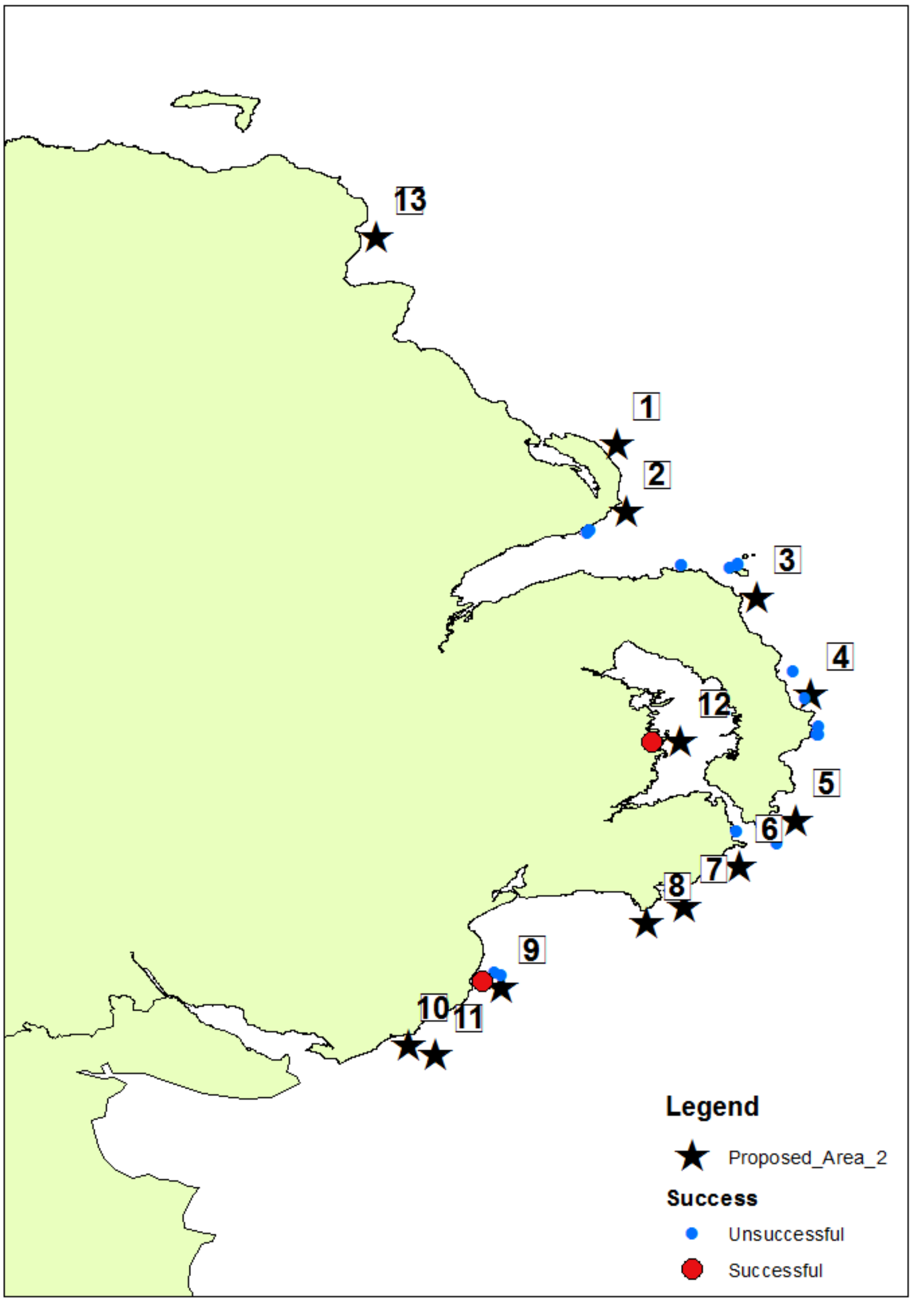

Figure 7: Location of potential sites for reseeding (black stars). The coloured circles represent sites which were surveyed during the 1999 C-Mar trial (blue areas which were surveyed but not reseeded due to unsuitability or reseeding was unsuccessful; red areas were deemed as having been reseeded successfully). Details of these sites are given in Table 4.

5.2 Literature Review

A literature review (Section 3) was carried out initially to ascertain the key factors in scallop spawning, dispersal and settlement.

5.3 Examination of habitats

A number of seabed habitat maps were combined to provide information for the full sea area under consideration. The following data sources were used:

1. Northern Ireland nearshore habitat maps (Mitchell and Service, 2004) based upon RoxAnn acoustic ground discrimination system (AGDS – operated through a single-beam echosounder) ground-truthed with underwater video and grab samples.
2. Murlough/Dundrum Bay habitat map (AFBI, 2015a) based upon multibeam sonar bathymetry and backscatter ground-truthed with underwater video, diver surveys and grab samples.
3. Strangford Lough habitat map (AFBI, 2015b) based upon multibeam sonar bathymetry and backscatter ground-truthed with underwater video, diver surveys and grab samples.
4. Fairhead Tidal Development site and cable route site habitat maps (AFBI, 2014) based upon multibeam sonar bathymetry and backscatter ground-truthed with underwater video and grab samples.
5. Joint Nature Conservation Committee (JNCC) EUNIS habitat map combining maps from surveys and from broad-scale habitat models (covers all UK waters) v 8.3.

These source datasets were standardised into the EUNIS habitat classification scheme, which details seabed substrata, energy and depth zones. The maps were set in a common projection and all converted to a 50m resolution cell size (Figure 8).

AFBI annual scallop dredge catch data from 1992-2016 as standardised to number of scallops caught per 100m^2 (calculated from dredge tow area) were mapped with the combined habitat map in ArcGIS 10.3 Geographic Information System (GIS). Kernel density analysis was used with a search radius of 1km to calculate the density of adult scallops per 100m^2 across the surveyed areas, using the full AFBI tow dataset (1992-2016) plotted at a resolution of 50m^2 (Figure 9).

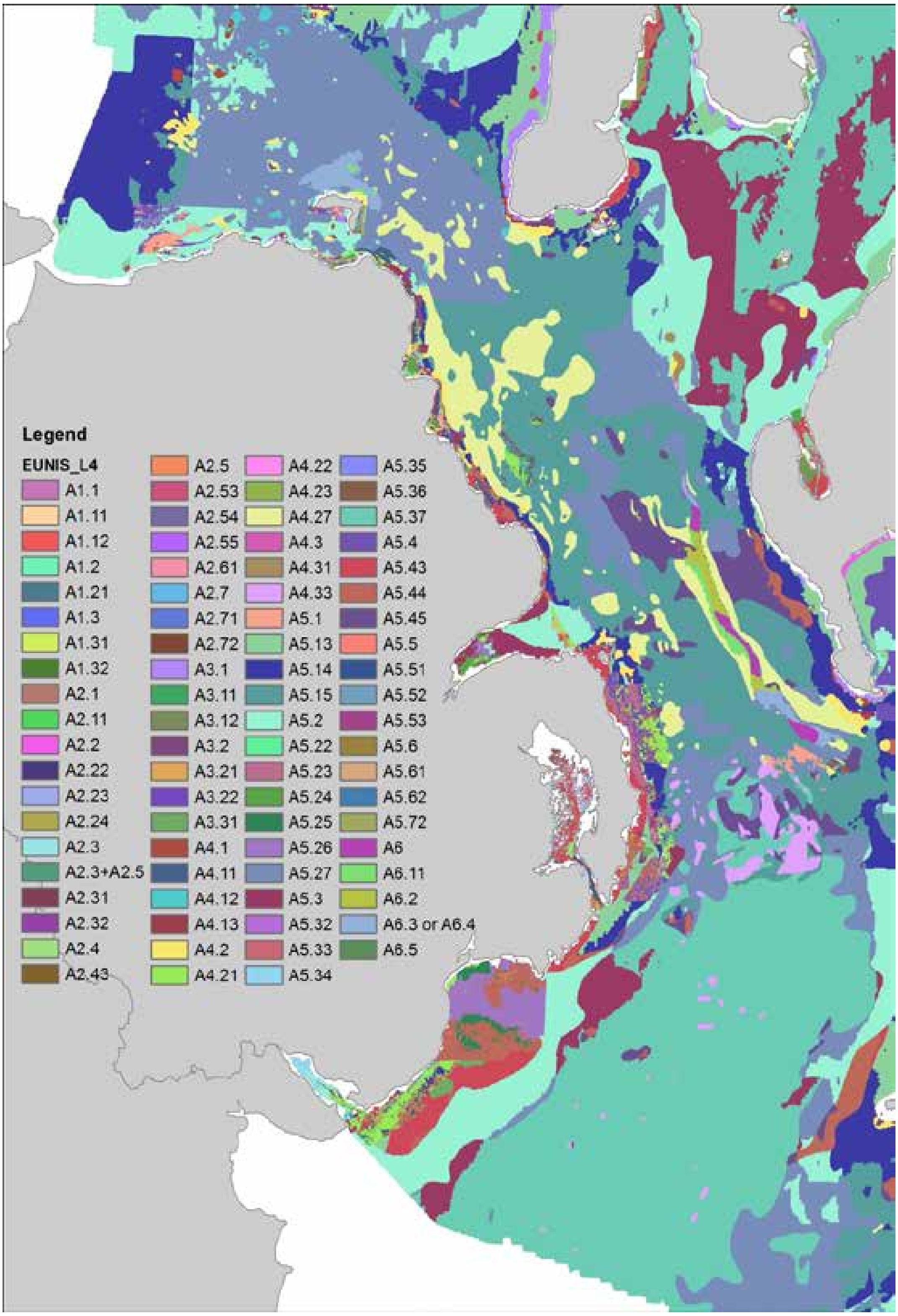

Figure 8: Combined habitat maps for the Northern Ireland sea area – integrated survey maps and modelled habitat maps, classified to the EUNIS habitat classification system (level 4 where possible, otherwise level 3).

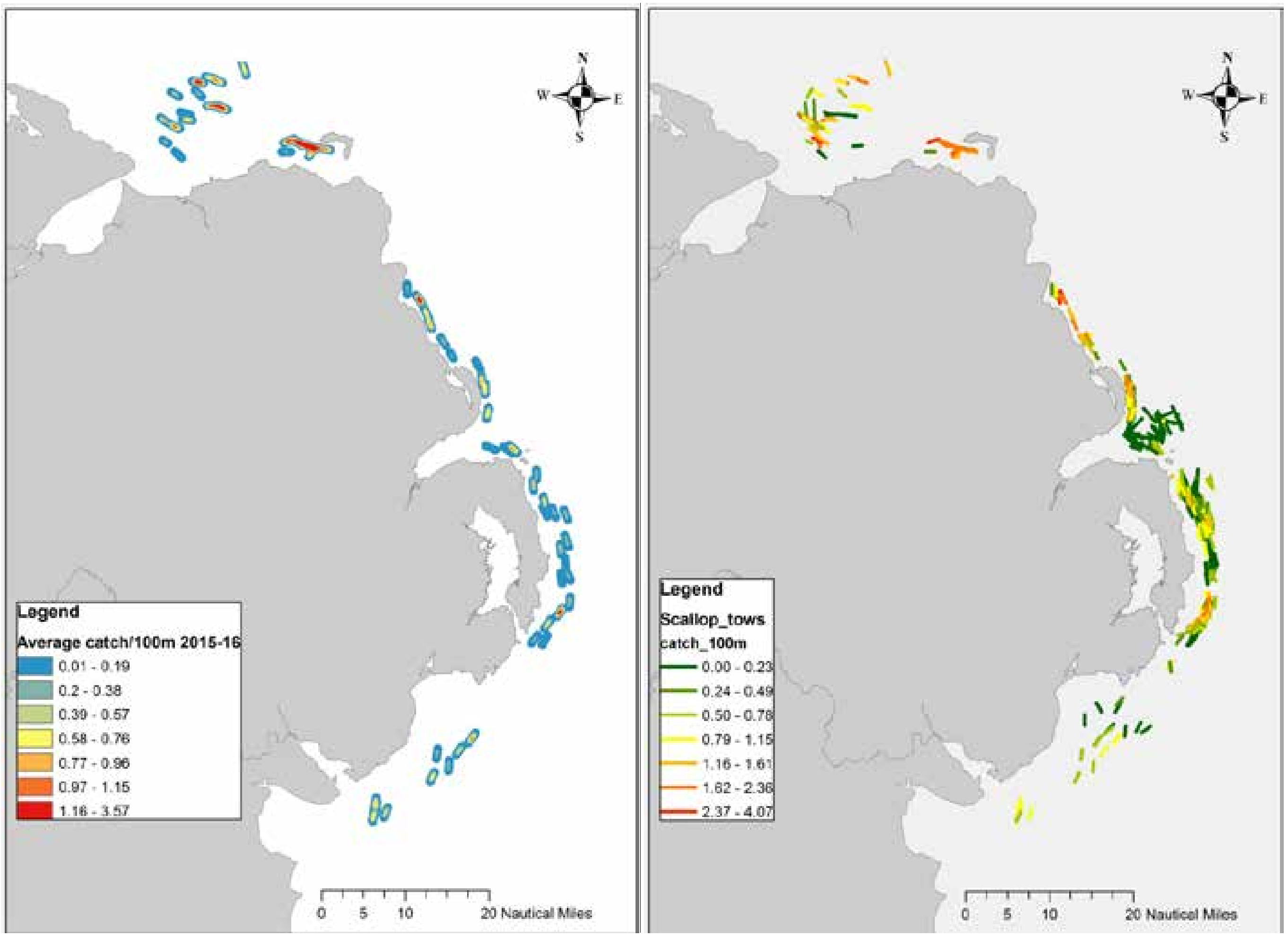

Figure 9: Adult scallop catch per 100m^2 (at a 50m resolution) from AFBI scallop tows. Left, average count per 100m2 from 2015 and 2016 surveys (with a search radius of 1000m); categories have been split by ½ standard deviation intervals. Right, scallop tow count per 100m2 data from 1992-2016.

GIS tools were used to extract the habitat beneath the adult scallop density data, which allowed identification of suitable habitat in harvestable areas. This was then used to identify all the areas with the same habitat throughout the Northern Ireland sea area, and finally a depth filter was added whereby areas shallower than 10m or deeper than 150m were excluded, as scallops are unlikely to be found at such depths in harvestable densities. Together, this created a “scallop habitat suitability” layer, identifying suitable habitat for adult scallops throughout the NI sea area (Figure 10). As expected, the seabed habitats deemed suitable consisted primarily of sand, coarse sediment and mixed sediment areas, although some rock habitats were also included – these areas are predominantly boulders and cobbles or small bedrock outcrops interspersed/adjacent to sediment substrata, and were found in mostly the shallower regions. No ‘pure’ mud habitat was included, although there was one modelled EUNIS level 3 habitat area “Sublittoral sands and muddy sands” that was deemed suitable, in spite of the inclusion of finer sediment fractions. Figure 10 has also overlaid existing Marine Protected Area designations which incorporate seabed features.

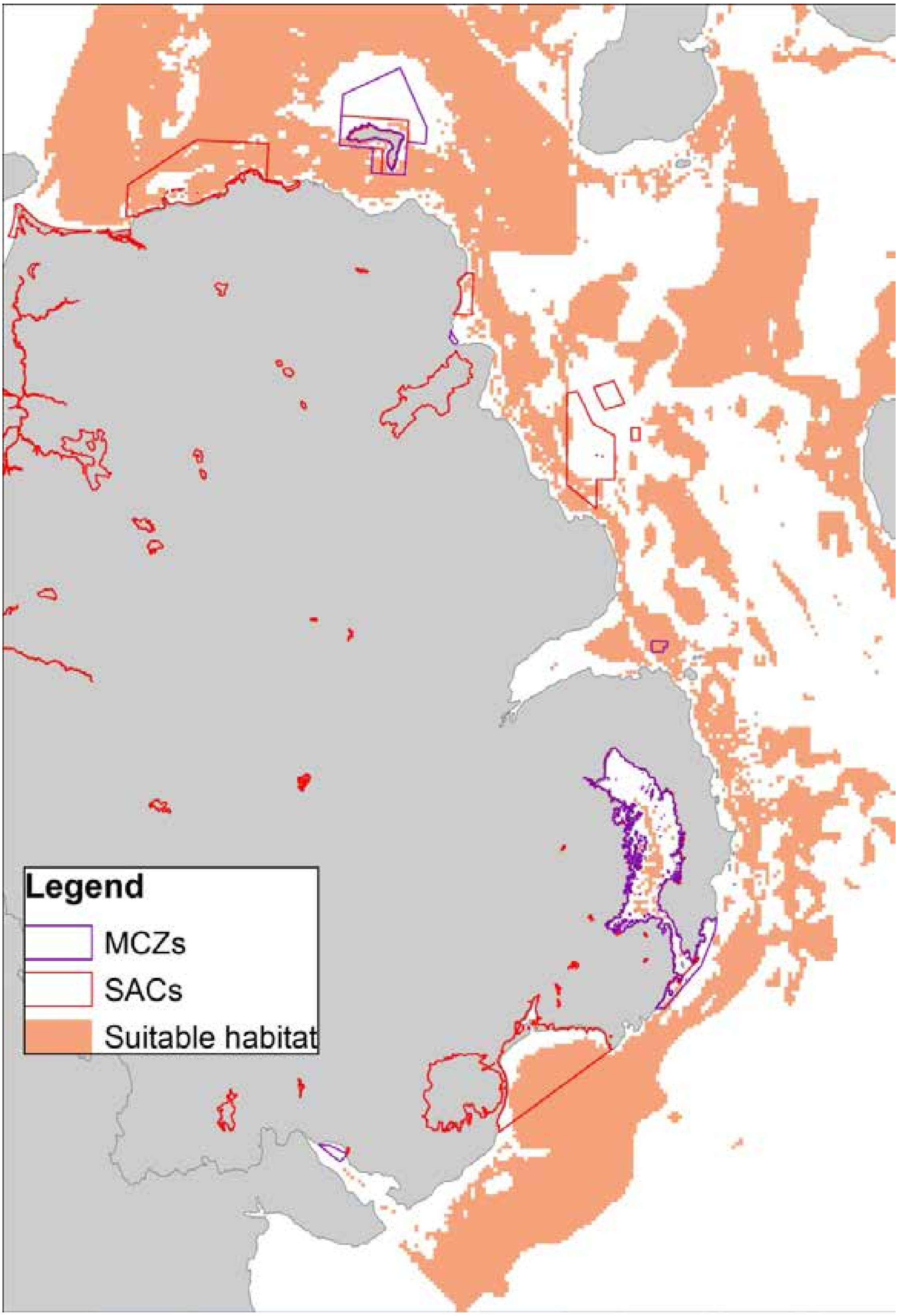

Figure 10: Predicted suitable habitat with NI waters for adult scallops based upon seabed habitat type, with Marine Protected Areas (inshore Marine Conservation Zones (MCZs) and Special Areas of Conservation (SACs)) that contain seabed features in their designations overlaid.

5.4 Characteristics of sites

A number of datasets were utilised to understand the characteristics of each potential reseeding site, and assist in the assessment of their suitability. These datasets have been split into “Measured & instrument datasets”, where actual samples or measurements have been taken at a specific location at a point in time, and “Modelled & remotely-sensed datasets”, where oceanographic-meteorological models covering a wide regional area (and validated by actual measurements) provide data across the entire sea area.

The Copernicus Marine Environment Monitoring Service (CMEMS – http://marine.copernicus.eu/) contains archived datasets which cover the entirety of the NI sea area for a range of parameters and time periods. This service was accessed to complement the *in-situ* data recorded by AFBI and provide data across all seasons, and is summarised for each of the potential reseeding sites at the end of this section. In addition, Proudman Oceanographic Laboratory (POL) data used in the first UK SeaMap project were accessed to provide data on bed stress from wave action, tidal currents and in combination. Finally, POLPRED tidal prediction modelling software was utilised to provide tidal current speeds and directions for near the seabed. Details on the regional datasets accessed and used within this project are provided in Table 5. The parameters in Table 5 were selected based upon the literature review (section 3).

Table 5: Modelled & remotely-sensed parameters accessed across seasons throughout the full study region (NI sea area).

Parameter	Units	Data source
Bed stress (wave action, tidal (currents), combined)	Newtons/ m2	Data was provided from a 1.8 km tidal application of POLCOMS (Proudman Oceanographic Lab Coastal Modelling System) on the northwest European shelf forced by 15 tidal constituents and the residual, and a ~12 km application of the proWAM (WAM cycle-4 with PROMISE modifications for shallow water) wave model forced by Met. Office mesoscale model winds for the period 2000-2004. The maximum tidal current data and, as biological communities tend to reflect the maximum water movement rather than an average. Mean wave stress was used due to the inter-annual variation in extremes of wave stress.
Tidal currents near seabed	m/s, direction in degrees	Tidal current maximum speed & direction near seabed calculated from inspecting 12 months' data (2014) from POLPRED using the CS20 model (1.8km2 resolution)
Mixed layer depth - by season	m	Mixed Layer Depth [m] calculated as an average over 2010-2014 by season, generated from the NORTHWESTSHELF_REANALYSIS_PHYS_004_009 dataset (CMEMS), which uses UK Met Office's Forecasting Ocean Assimilation Model 7km Atlantic Margin Model (FOAM AMM7) validated by satellite sensors and observations
Chlorophyll a concentration - by season	mg/m3	Chlorophyll a concentration [mgC m-3day-1] calculated as an average over 2010-2014 by season, generated from the NORTHWESTSHELF_REANALYSIS_BIO_004_011 dataset (CMEMS), which uses UK Met Office's Forecasting Ocean Assimilation Model 7km Atlantic Margin Model (FOAM AMM7) (surface layer) validated by satellite sensors and observations, with the ecosystem model using World Ocean Atlas (2009) at boundaries
Temperature at the seabed - by season	°C	Sea Water Potential Temperature [K], converted to °C, at the seabed calculated as an average over 2010-2014 by season, generated from the NORTHWESTSHELF_REANALYSIS_PHYS_004_009 dataset (CMEMS), which uses UK Met Office's Forecasting Ocean Assimilation Model 7km Atlantic Margin Model (FOAM AMM7) validated by satellite sensors and observations
Suspended particulate matter (SPM) - averaged by month	g/m3	Satellite observations - Ocean Colour Optics (L4) - using an OC5 algorithm at a 1.2km resolution, made available via CMEMS for 2013-2014, validated by in-situ SPM data

5.4.1 Salinity

Modelled & remotely-sensed datasets

Salinity data were not accessed as all the sites are in salinities known to be well above critical biological thresholds for scallops (Laing (2002a)).

Measured & Instrument datasets

AFBI carry out biannual nutrient sampling around the Northern Ireland coastline to collect data for the Water Framework Directive (WFD). Data collected includes temperature, salinity, fluorescence, oxygen and turbidity. A flow through salinometer runs throughout the survey and collects continuous georeferenced data on temperature and salinity at a fixed depth (5m). [1]

Salinity data collected from the salinometer run on the RV Corystes during January and July 2016 was plotted using Arc GIS. This data is presented in Figure 11. Laing (2002a) stated that an optimal cultivation site should have salinity between 30-35 psu. The entire coast falls in to the optimal salinity category. Whilst the salinometer data is only available during January and July, other months were checked using the CMEMS modelled data set NORTHWESTSHELF_REANALYSIS_PHYS_004_009 for 2010-2014.

Key Message 1:

All the sites to be investigated by this study have a salinity which would allow scallop cultivation to be viable.

[1] Full analysis of the measured environmental data is outside the remit of this report but is currently being progressed.

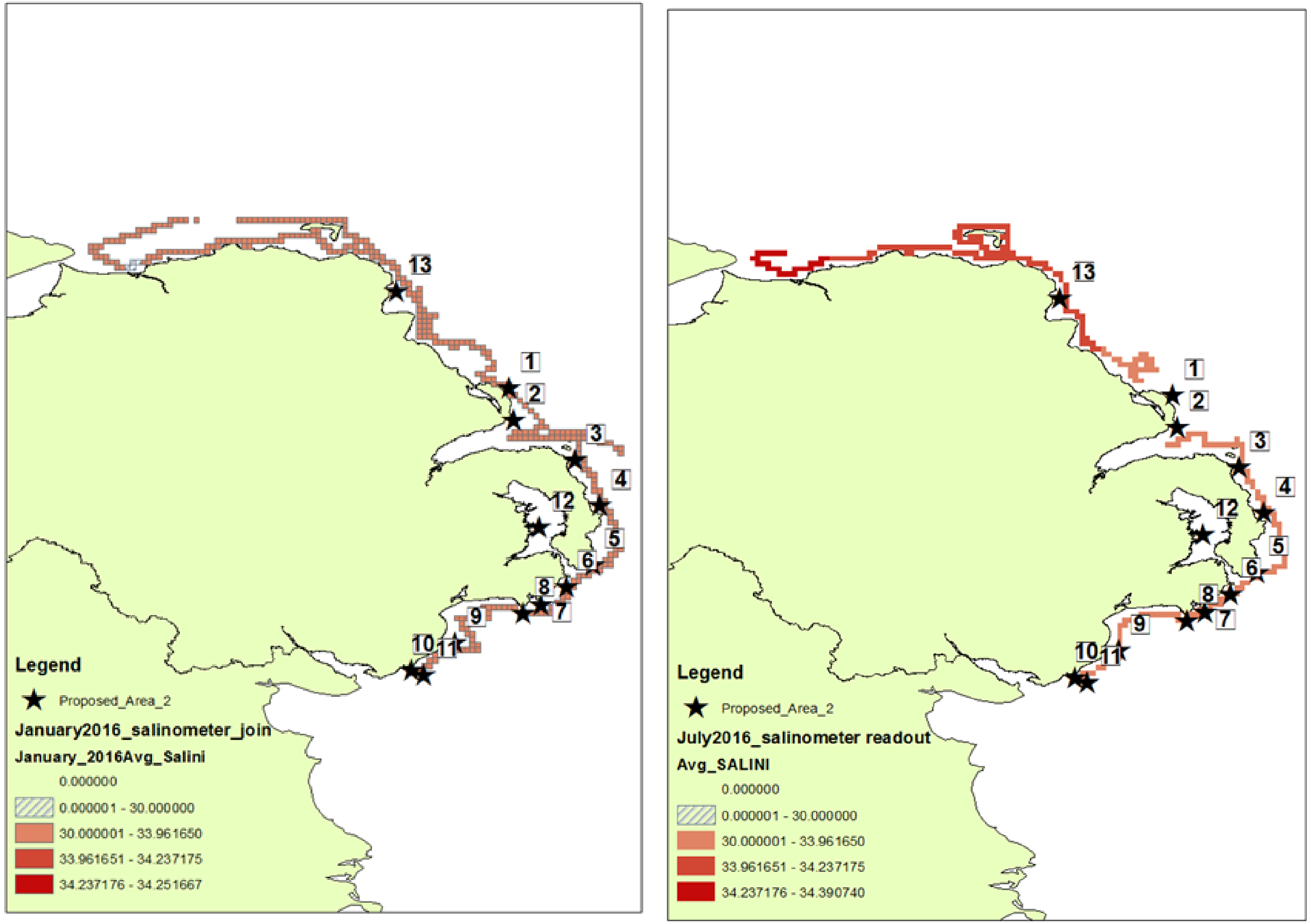

Figure 11: Salinity at 5m depth in January 2016 (left) and July 2016 (right) as collected by a salinometer during the AFBI coastal WFD winter and summer nutrient surveys.

5.4.2 Temperature

Modelled & remotely-sensed datasets

Temperature data were accessed (Table 6) as these may be informative for potential pelagic larval duration lengths, should the seed grow on to become reproductive adults. Of more critical importance to the selection of sites, the mixed layer depth is an indication of water column stratification. The definition of mixed layer depth is the depth where there is a 0.2°C or more difference between the layer of water at that depth and the surface water temperature. Gallagher *et al*., (1996) noted that thermoclines have an impact on the vertical movement of scallop larvae, which is notably most critical in the earlier stages of larval development. Manuel *et al*., (2000) noted from mesocosm studies that peaks in veliger density were notable just above the thermocline- but only when thermal differences were greater than 1ºC. It is postulated for this study that a thermocline in waters above a reseeded site could potentially act to reduce success of larval development/growth should the seed scallops become reproductively active. It is therefore recommended that where there is even weak evidence of a thermocline (i.e. from the mixed layer depth threshold of 0.2°C) during typical spawning months, such a site should be avoided for reseeding. Naturally, many other processes may interact to mitigate the effect of the thermocline (such a near-bed currents sweeping larvae to areas where water is well mixed, enabling vertical transport into mid water-surface), but to optimise chances of success the existence of a mixed layer depth in spring, summer or autumn immediately above (i.e. shallower than) the reseeding site will be used to preclude that site.

Measured & Instrument datasets

The stations which were sampled in 2016 as part of the Water Framework Directive (WFD) winter and summer nutrient surveys were plotted against the proposed reseeding sites (Figure 12). Some of the sampling stations are within the areas proposed for reseeding.

The measured temperature data, which is summarised in Table 7 and Figures 13 and 14, agrees with previous studies that there appears to be good vertical mixing in the water column during winter months (Slinn, 1974). However during the summer months there may be increased stratification. Temperature profiles taken at sites 8, 9, 10 and 11 show thermoclines present in the water column. This corroborates findings by Slinn (1974) reported that in summer reduced temperature gradients indicative of tidal mixing were apparent off the County Down coast.

Table 6: Modelled & remotely-sensed temperature data at the 13 proposed reseeding sites.

Site:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Seabed temperature (Winter) °C	8.95	8.86	8.81	8.81	8.27	8.11	8.00	7.95	7.71	7.40	7.51	8.36	9.08
Seabed temperature (Spring) °C	7.91	7.94	7.99	8.06	8.17	8.17	8.14	8.11	8.20	8.34	8.25	8.10	7.88
Seabed temperature (Summer) °C	11.41	11.57	11.55	11.95	12.27	12.43	12.34	12.24	12.92	13.61	13.06	12.22	11.35
Seabed temperature (Autumn) °C	12.68	12.63	12.59	12.65	12.55	12.43	12.36	12.33	12.24	12.15	12.20	12.47	12.79
Mixed layer depth - summer (m)	44.84	24.68	20.12	17.93	15.02	12.20	11.42	10.78	10.54	9.54	10.13	12.48	55.51
Mixed layer depth - autumn (m)	50.78	26.25	20.80	23.49	20.95	18.02	19.72	21.93	15.90	13.54	17.41	15.18	57.62
Depth (m)	11.02	22.82	9.44	15.31	20.15	15.30	16.70	27.20	15.50	11.17	20.66	14.43	21.94
MLD less than Depth? (summer)	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N
MLD less than Depth (autumn)	N	N	N	N	N	N	N	Y	N	N	Y	Y	N

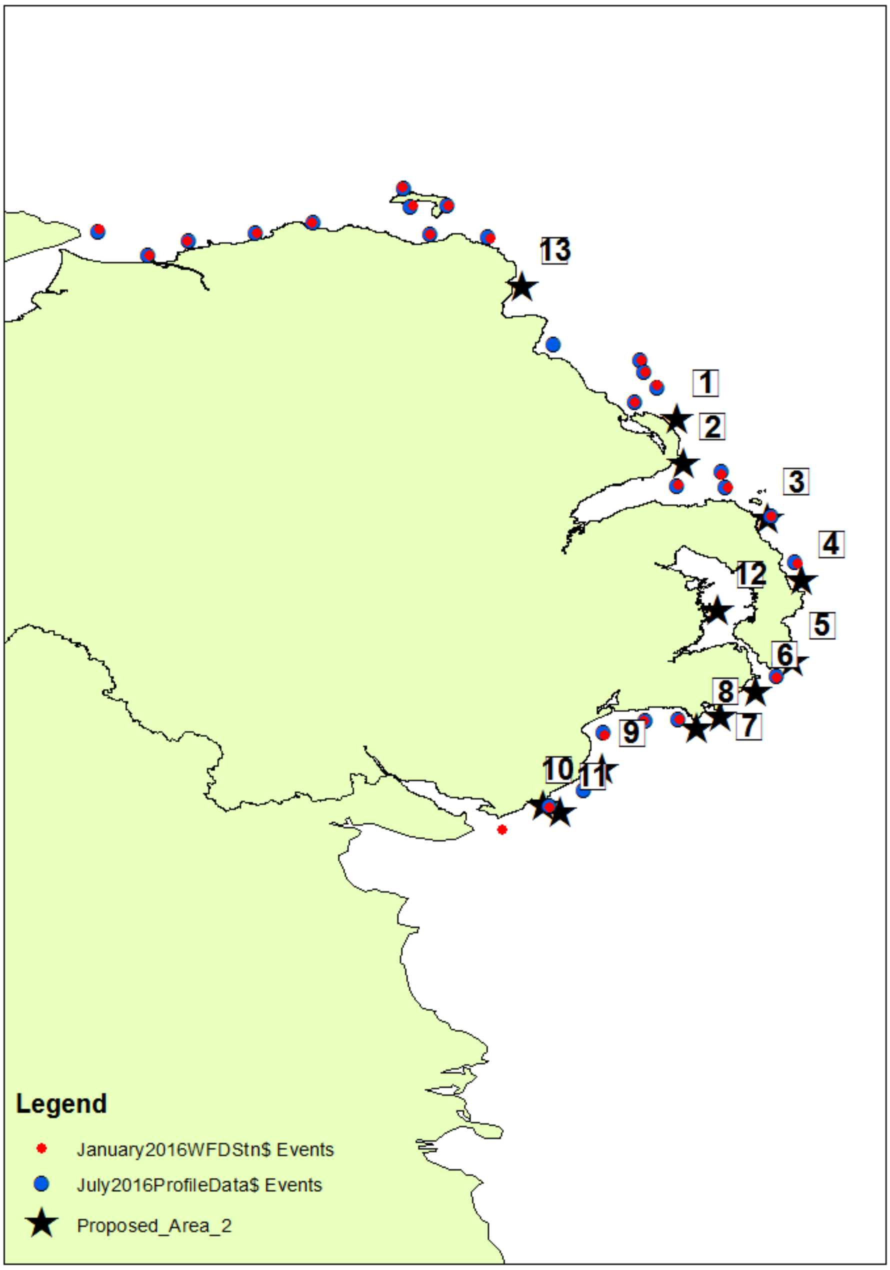

Figure 12: Location of sampling points in January 2016 (red dots) and July 2016 (blue dots) in relation to the proposed reseeding sites (black stars)

Comparing the measured and modelled data for seabed temperature shows that there is good agreement between the two datasets during the summer months, for example at site 10 the measured temperature at the deepest recording (13.38m) is 13.87°C whilst the modelled seabed temperature is 13.61°C (average for summer months between 2010 and 2014). However, during the winter months there was a consistent discrepancy between the two data sets with the modelled data being cooler. As it is unlikely that any spawning occurs during the winter months, the modelled data is deemed to be appropriate for assessment of the potential reseeding sites.

Both the measured and modelled temperature data sets show thermal stratification at depths shallower than the seabed at a subset of the reseeding sites. These thermoclines can act as a barrier to larval migration to the more productive surface water layers (see section 3.3).

Key Message 2:

Whilst all sites are within the optimal temperature range for *P. maximus*, due to the presence of thermoclines at sites 8, 9, 10 and 11 over the summer and autumn months when scallops are spawning, caution is advised due to potential limits in scallop productivity in these areas.

Table 7: Summary of the measured temperature data collected during January and July 2016 by AFBI. Data for sites 1, 2, 7, 12 and 13 is not available as the nearest WFD sampling station was deemed too far away for the data to be representative.

Proposed reseeding site	3	4	5	6	8	9	10	11
WFD site closest to	65	67	70	70	83	87	89	89
January 2016								
Depth range	1.49-27.75	1.49-21.31	1.98-18.33	1.98-18.33	0.99-13.88	0.99-14.87	1.98-18.34	1.98-18.34
Temperature range (shallowest-deepest)	9.74-9.75	9.17-9.27	9.81-9.89	9.81-9.89	9.10-9.11	8.80-8.90	8.91-9.30	8.91-9.30
Thermocline	No	No	No	No	No	No	No	No
July 2016								
Depth range	1.98-28.74	1.98-16.35	2.97-21.31	2.97-21.31	1.98-12.39	1.98-10.90	1.98-13.38	1.98-13.38
Temperature range (shallowest-deepest)	13.73-13.71	13.93-13.75	13.56-13.49	13.56-13.49	14.74-14.35	14.67-14.55	14.81-13.87	14.81-13.87
Thermocline	No	No	No	No	Yes	Yes	Yes	Yes

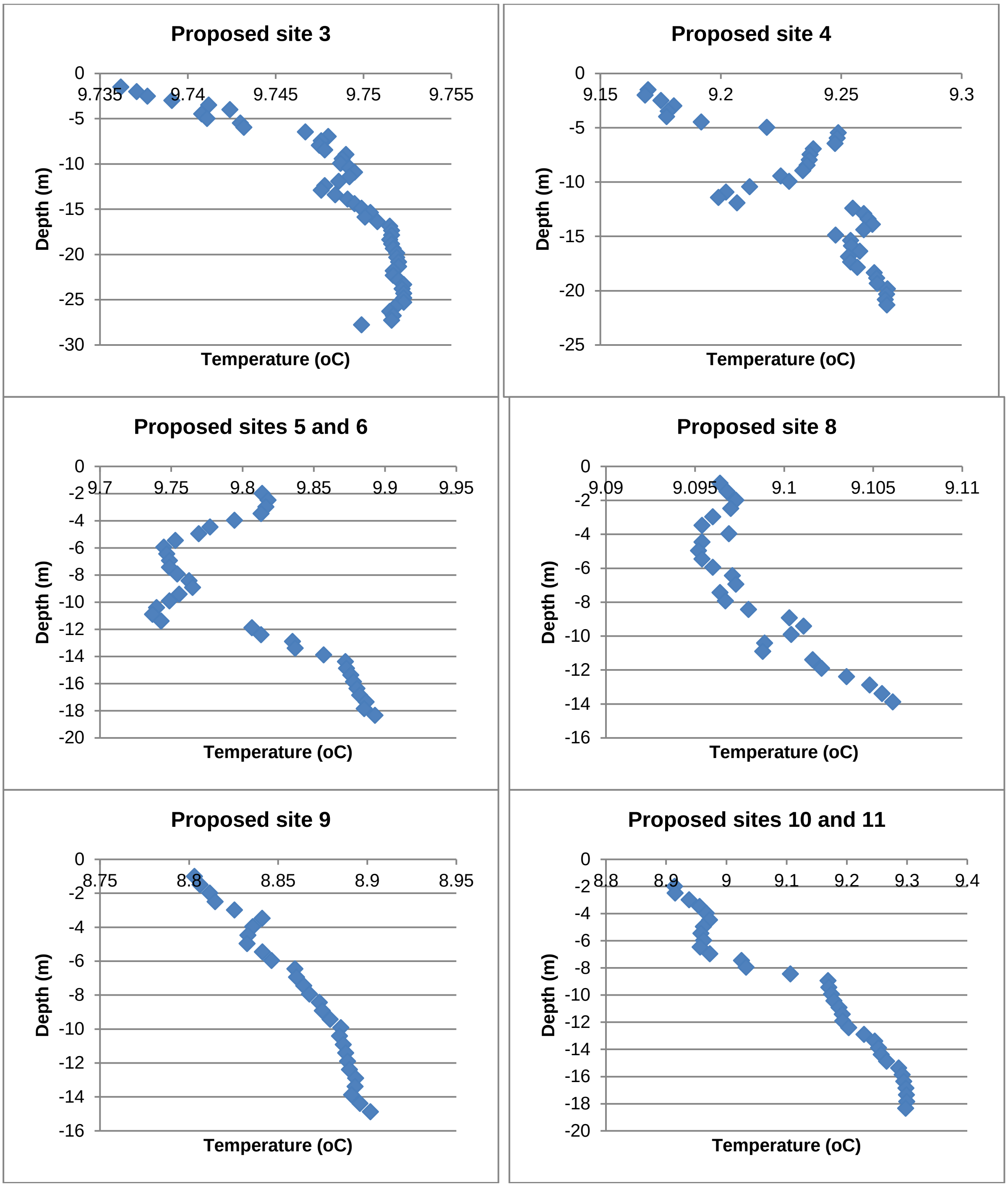

Figure 13: Temperature profiles from stations sampled during the January 2016 winter nutrient survey, which are within the proximity of the proposed scallop reseeding sites.

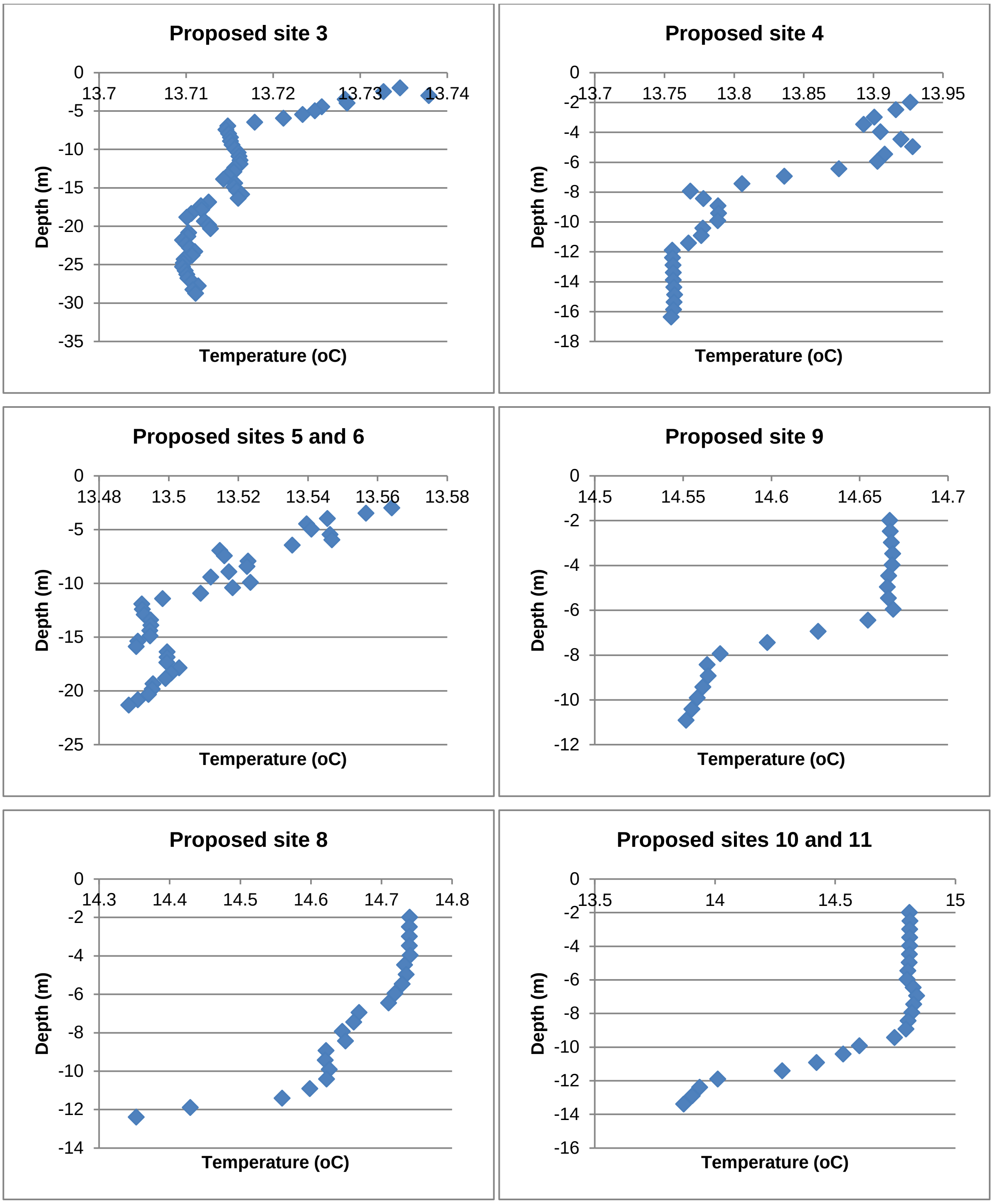

Figure 14: temperature profiles from stations sampled during the July 2016 nutrient survey, which are within the proximity of the proposed scallop reseeding sites.

5.4.3 Food Availability

Modelled & remotely-sensed datasets

Chlorophyll a concentration may be considered a proxy for scallop food availability. There is a notable spatial and temporal trend of food availability throughout the NI sea area (Table 8), which may have a bearing on the success of reseeding sites, so such information should be considered.

Table 8: Modelled & remotely-sensed food availability at the 13 proposed reseeding sites

Site:	1	2	3	4	5	6	7	8	9	10	11	12	13
Chl a concentration (Spring) mg/m3	1.31	1.61	1.47	1.73	1.52	0.34	1.64	1.86	1.29	1.78	1.65	No Data	1.41
Chl a concentration (Summer) mg/m3	0.98	1.44	1.67	2.13	1.36	1.05	1.79	1.67	1.26	1.62	1.54	No Data	1.09
Chl a concentration (Autumn) mg/m3	0.65	1.53	3.84	2.14	1.18	1.03	1.54	1.98	1.63	1.93	1.96	No Data	0.31

As part of the SMILE Shellfish Management modelling project (Ferreira et al.,2007), shellfish growth models were developed for the NI sea loughs. This information may be useful should the larvae from reseeding sites settle within these areas, to determine the length of time it will take for the juvenile scallops to become harvestable.

Measured & Instrument datasets

Data collected by the flow through system onboard the RV Corystes also includes fluorescence which is indicative of the amount of photosynthetic material in the water. Whilst the fluorescence and chl a relationship has not been calculated for this report it is indicative[2] of production around the coast (Figure 15). The levels are higher from Belfast Lough south. Laing (2002a) reported that up to 85% of the differences in growth between scallops from different areas can be related to water temperature and primary productivity and that the growth of scallop spat is positively correlated to the concentration of chlorophyll in the water. However, at high concentrations of food, the veligers are less efficient at filtering (Cragg, 2006).

[2] Full analysis of the measured environmental data is outside the remit of this report but is currently being progressed.

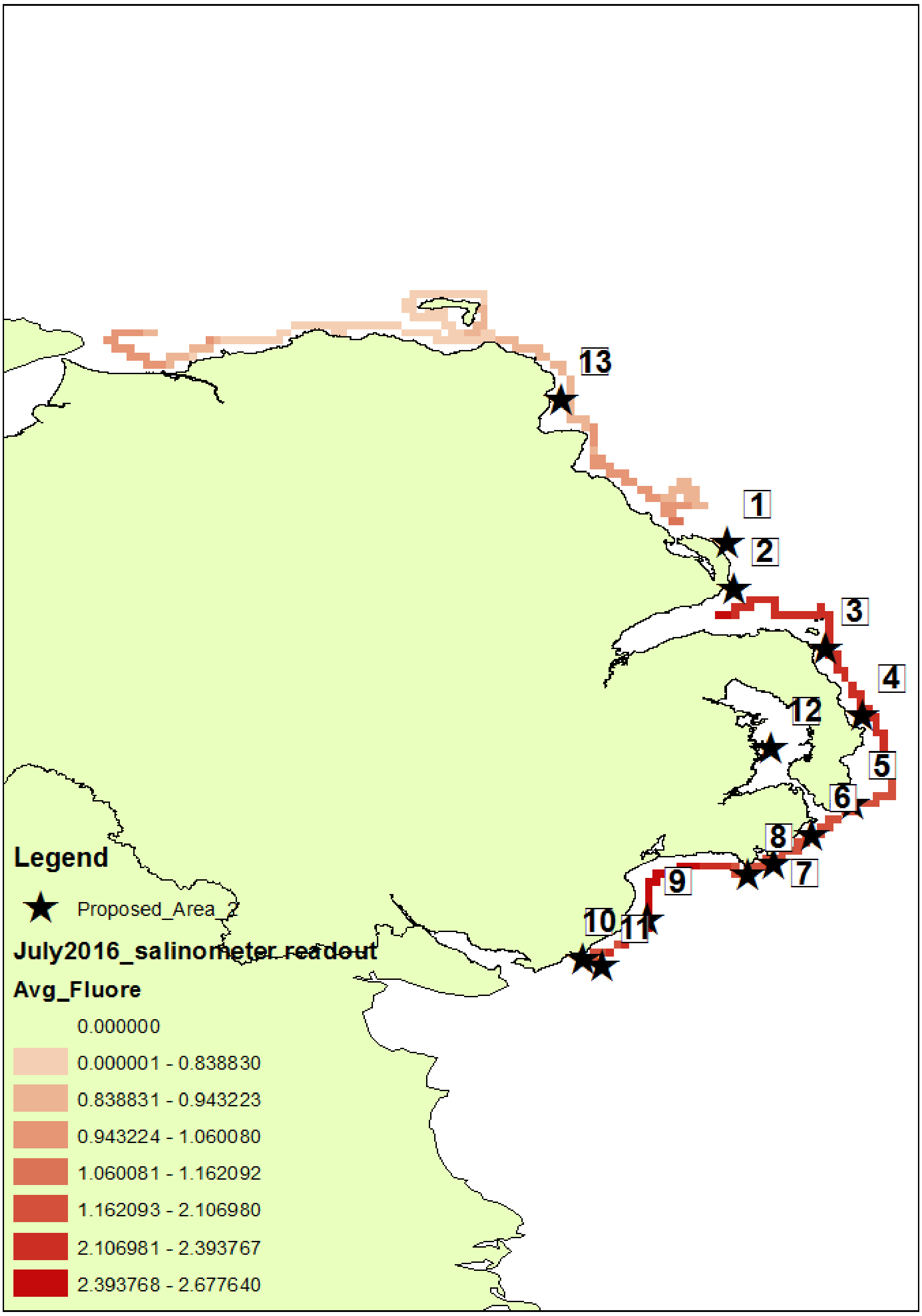

Figure 15: Fluorescence readings recorded by the flurometer (5m depth) during July 2016.

The general spatial trends in the modelled and measured data corroborates in that the County Down coast shows higher food availability than the County Antrim coast. The modelled data showed considerable variation between the seasons which was not always consistent between sites. However, sites 1 and 13 consistently have the lowest chlorophyll a concentration whilst sites 4 and 7 had the highest food availability in summer and sites 3 and

4 had the highest food availability in autumn. In terms of how this may affect growth, length data from the AFBI annual scallop survey was analysed. Figure 16 shows that scallops from the County Down coast are larger than those from the East Antrim coast. This could be in part due to the food available (alongside other factors such as temperature).

Figure 16: Average size of age 7 (a) and 9 (b) scallops during the survey period, in each chart the darkening colour represents increasing size (each colour does not represent a specific length of scallop but is simply to show the larger size at age along the County Down coast)..

Key Message 3:

Based on comparison between areas, site 13 has the lowest food availability and therefore scope for growth and fecundity could be limited. Whilst we are unaware of any thresholds for food availability of *P. maximus*, due to reduced chlorophyll a concentration, especially during autumn, we believe this is an important consideration if site 13 was to be utilised.

5.4.4 Bed stress

Modelled & remotely-sensed datasets

Bed stress has been noted by a number of researchers as affecting both the settlement of larvae and the subsequent retention of seed/young scallops, and indeed has been found an important predictor in the distribution of adult scallops (Le Pennec *et al.*, 2003, Smith *et al.*, 2007, Szostek, 2015). Bed stress is a function of the energy near the seabed (e.g. from tidal currents or waves) and the bed friction coefficient, and reflects physical disturbance at the seabed. Thresholds have not been clearly specified due to the multiple different methods of calculating bed stress, such as whether this refers to (a) tidal bed stress, or (b) wave-induced bed stress, or (c) a combination of both tide and wave-induced bed stress. Furthermore, bed stress can either represent the maximum potential stress, or the mean, and authors differ in their opinion of which is most appropriate. Finally, there are a number of methods of calculating bed stress, which can make comparison of values between separate studies problematic. Dare *et al.,* (1993) reported that denser aggregations of harvestable scallops (*P. maximus*) in the English Channel were found at fairly low mean tidal bed stress areas, and suggested that the hydrodynamic regime had a greater influence on scallop distribution than seabed substrata *per se*. Szostek (2015) found that *P. maximus* biomass did not correlate with bed shear stress (tidally-induced only), and noted that scallops appear to "tolerate a greater range of BSS than many of the benthic organisms identified in this study. This makes them an ideal species for harvesting; resilient to physical disturbance and able to survive over a broad range of habitat types." However, it was also noted that scallops beds at commercial densities are found scallops only where tidal bed shear stress is less than 2 N m^{-2} in the English Channel (Szostek, 2015), but tidal bed stress does occur up to 3 N m^{-2} in adjacent areas. Due to the comparatively shallow nature of all the potential reseeding sites (< 50m depth), combined bed stress is deemed appropriate for consideration, which takes into account the effects of both tidal currents and wave energy. A nominal bed stress threshold of 2 N m^{-2} has been applied to select sites from, with bed stress above this threshold potentially affecting dispersal of seed to non-suitable areas (away from the reseeding site), or being prohibitive to effective recessing of young scallops into the sediment. However, very low bed stress usually coincides with a depositional environment, thereby increasing the silt content of seabed substrata, which can also be detrimental to scallop survival.

Near-bed tidal currents are correlated with bed stress, and seabed substrata, especially sediment silt content. As such, these may be useful in understanding the suitability of a site, although with both seabed substrata and bed stress data available the tidal current information relates perhaps more to the dispersal of larval, should seed grow into reproductive adult scallops. When tidal current data are coupled with information on stratification, it is possible to estimate gross hydrodynamic patterns. Wind-forcing will naturally impact the surface layers of the ocean, and can over-ride the effects of tidal currents in terms of net water movement in such surface layers, but in deeper water the effect is less pronounced. Dare *et al.,* (1993) noted that in the English Channel at a fairly local scale there is a significant coincidence of commercially important scallop aggregations either with gyres (Bays of Seine, Saint Brieuc and Morlaix) or with weak flows in large embayments (e.g. south Cornwall). A greater degree of larval retention, and hence self-recruitment, should occur in such locations and perhaps explains the maintenance of such stocks. Tidal current data will be considered further in Section 7 in terms of potential for larval transport pathways from reseeded sites.

Measured & Instrument datasets

Measured data is not currently available from which to calculate bed stress.

From evaluating the combined tidal and wave bed stress site 3 exceeded the nominal threshold of 2 Nm^{-2} (Table 9), with the next highest bed stress found at site 13 (1.27 Nm^{-2}). The lowest bed stress was found at sites 6 and 12 (0.24 Nm^{-2}). These low bed stress values may coincide with a depositional environment increasing the silt content of the seabed sediments which may have a detrimental effect on scallops.

Table 9: Modelled/remotely-sensed bed stress at the 13 proposed reseeding sites

Site:	1	2	3	4	5	6	7	8	9	10	11	12	13
Bed stress (combined tide and wave) Nm-2	0.95	0.37	2.01	0.72	0.25	0.24	0.33	0.28	0.28	0.26	0.36	0.24	1.27
Tidal bed stress Nm-2	0.89	0.32	1.98	0.69	0.15	0.13	0.15	0.07	0.06	0.05	0.13	0.12	1.25
Wave stress Nm-2	0.05	0.06	0.03	0.04	0.10	0.11	0.19	0.21	0.22	0.21	0.23	0.12	0.02
Seabed Tidal Current (max) ms-1	0.37	0.23	0.35	0.23	0.03	0.07	0.11	0.08	0.11	0.07	0.12	0.02	0.55
Seabed Tidal Current (min) ms-1	0.07	0.11	0.18	0.05	0.04	0.02	0.03	0.02	0.01	0.01	0.01	0.00	0.15

Key Message 4:

Site 3 exceeded the nominal threshold of 2 Nm^{-2} and is therefore considered unsuitable for reseeding. As there are no published thresholds for minimum bed stress we cannot advise on whether the low bed stress values at sites 6 and 12 could be prohibitive to successful reseeding.

5.4.5 Suspended Particulate Matter

Modelled & remotely-sensed datasets

It has been noted above that suspended particulate inorganic matter (SPIM) is deemed to reduce food assimilation efficiency (MacDonald *et al*., 2006) and could affect the scope for growth and fecundity of adult scallops. In addition, high concentrations of SPIM can also cause damage to the scallop gill therefore reducing future feeding capacity MacDonald *et al*., 2006). Although SPIM regional data is not available from the modelled and remotely-sensed data source, total non-algal suspended particulate matter (SPM) is available, and shows notable spatial and temporal fluctuations (Table 10) which could be considered alongside food availability in a relative manner to highlight potential constraints to scallop growth between the reseeding sites.

Table 10: Modelled/remotely-sensed SPM at the 13 proposed reseeding sites

Site:	1	2	3	4	5	6	7	8	9	10	11	12	13
SPM_February g/m3	5.96	7.34	8.81	8.26	7.78	8.80	9.51	13.05	18.90	16.84	11.34	No Data	9.24
SPM_March g/m3	5.05	6.48	9.00	11.33	8.06	6.17	7.13	6.27	6.45	5.47	4.87	3.89	8.21
SPM_April g/m3	3.43	4.55	4.76	4.52	1.86	2.09	2.45	2.77	0.71	1.56	1.58	No Data	4.28
SPM_May g/m3	1.11	2.83	5.15	2.51	1.38	1.98	1.26	0.74	0.56	2.84	1.82	No Data	3.83
SPM_June g/m3	1.19	0.97	1.72	1.53	1.13	0.81	0.82	0.48	0.44	0.67	0.55	No Data	1.37
SPM_July g/m3	0.65	0.82	0.73	0.77	0.82	1.09	0.87	0.73	0.68	0.77	0.73	No Data	0.45
SPM_August g/m3	1.70	1.83	2.14	3.02	2.34	1.78	1.93	1.90	2.63	1.15	0.83	No Data	1.53
SPM_September g/m3	2.15	2.46	3.41	3.63	1.26	1.22	0.81	0.95	0.53	0.60	0.50	No Data	1.06
SPM_October g/m3	2.19	2.84	No Data	4.49	4.15	4.88	7.57	6.74	3.95	4.94	5.18	No Data	2.62

Measured & Instrument datasets

Data relating to the amount of SPIM was plotted for Belfast and Strangford Lough sites which were in the proximity to the potential reseeding sites 2 and 12 (Figure 17).

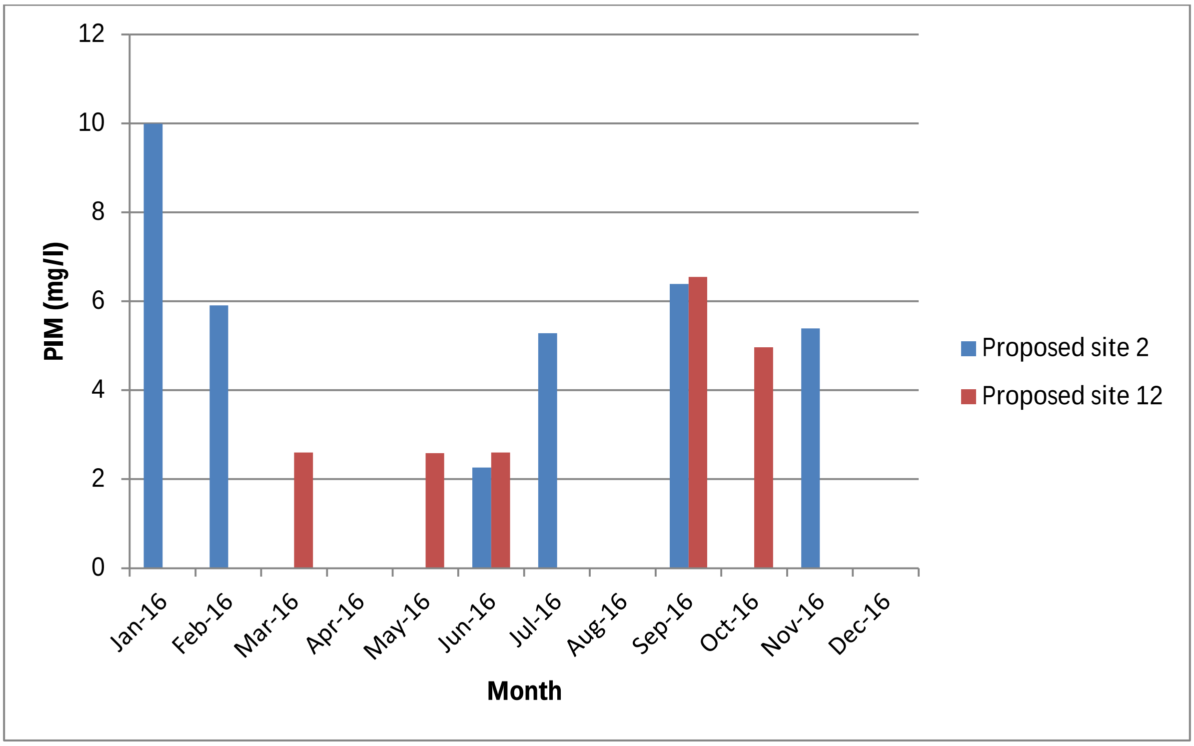

Figure 17: SPM readings for Belfast Lough (blue) and Strangford Lough (red)

From the modelled data here was wide variation in SPM throughout the year of analysis (2014) with highest values found in February and lowest values reported in June. A similar trend was reported from the measured PIM in 2016 (for Belfast and Strangford Lough), with highest values in winter (January – no modelled data available for January 2014) and lowest levels in summer (June). Individual sites also showed wide variation throughout the year. In order to take account of the monthly variation the average SPM for each month was calculated and those sites which had an SPM greater than the average were flagged. Proposed reseeding sites 3 and 4 had the highest number of above average monthly SPM values (6 out of 8 months and 7 out of 9 months respectively). Sites 6, 8, 9 and 11 had only two months where the SPM values were above the monthly average.

As only one year's SPM data were accessed it is possible that significant storm events have affected levels at certain sites and this trend might not follow the same temporal pattern every year.

Key Message 5:

Levels of non-algal SPM were consistently higher than average at sites 3 and 4. As SPM can reduce feeding efficiency high levels may have a detrimental effect on scallops.

5.4.6 Predation

Measure & Instrument datasets

The proposed reseeding sites were overlaid on to the AFBI survey stations. Where there was an overlap the bycatch data from the annual scallop survey was used to examine the abundance of predators (starfish and crabs) at the proposed reseeding sites. However, as the survey is based on a random sampling method not all stations have been sampled and those which have are not sampled each year. Analysis was therefore carried out on the last year which that station was sampled. Table 11 provides a summary of the availability of data and the year which data is taken from. Predator data was examined for reseeding areas 1-5.

Table 11: Scallop reseeding sites were linked to AFBI survey stations. The bycatch data of those which had been sampled was used to look at predator abundance in the area.

Reseeding Area	Survey Box	Last surveyed	Survey Box used
1	91	2015	91
2	84/85	1999	86 (surveyed 2015)
3	74	2004	75 (surveyed 2016)
4	57/58	2015	57
5	42	2015	42
6	Outside of survey area		
7	Outside of survey area		
8	Outside of survey area		
9	20	Never surveyed	
10	Outside of survey area		
11	Outside of survey area		
12	Outside of survey area		
13	Dredging not permitted in area.		

In 2015 the potential reseeding sites 1, 2, 4 and 5 were surveyed. Of these sites reseeding site 2 was the most diverse with 16 bycatch species recorded. Reseeding site 4 had 9 species, site 1 had 8 species and site 5 had 4 bycatch species. In 2015 the average number of species caught per tow over the entire survey area was 10 species. At reseeding sites 2, 4 and 5 the common starfish, Asterias rubens, was the most abundant bycatch species. At site 1 the most abundant species was the brittlestar, Ophiothrix fragilis. Reseeding site 3 was not surveyed in 2015 but was randomly chosen for the 2016 survey. At this time 7 bycatch species were recorded from this area (the average number of bycatch species per tow in 2016 was 11). No common starfish were recorded at reseeding site 3. From all bycatch in these areas the abundance of all starfish and crabs was calculated against the abundance of scallops in that area (Table 12).

Table 12: Abundance of starfish and crab species at the reseeding sites, reported from the annual AFBI scallop survey (* surveyed in 2016, all other sites were surveyed in 2015; **does not predate on scallops rather predates on *A. rubens*).

Species	Abundance 100m^2				
	Reseeding site 1	Reseeding site 2	Reseeding site 3*	Reseeding site 4	Reseeding site 5
Pecten maximus	0.323	1.476	0.573	0.877	0.633
Asterias rubens	0.032	0.111		0.431	0.162
Astropecten irregularis	0	0		0	0.015
Cancer pagurus	0	0.028		0.014	0.074
Carcinus maenas	0	0		0.029	0
Crossaster papposus	0.016	0.028	0.106	0.129	0
Henricia spp	0.016	0.014		0	0
Inachus spp	0	0.056		0	0
Liocarcinus depurator	0	0.014		0.086	0.029
Luidia ciliaris*	0	0.056		0	0
Marthasterias	0.032	0		0	0
Pagurus spp	0.032	0.056	0.015	0	0
Porania pulvillus	0.016	0		0	0
Stichastrella rosea	0	0.014		0	0

<u>Key Message 6:</u>

Reseeding site 4 had the highest abundance of predators whilst reseeding site 3 had the lowest abundance of predators. As the presence of predators can be the main determining factor in the successful reseeding of an area, areas with high predators should be avoided. In addition some form of predator control should be implemented at the reseeding area.

5.4.7 Toxic Algal Blooms

As traditionally only the abductor muscle of scallops is eaten, the impact of toxic algal blooms on scallop culture can be underestimated or ignored (Shumway and Cembrella, 1992). The presence of some toxic algal blooms has been shown to cause a decrease in growth rate and reproduction as well as mass mortalities in bivalves including *P. maximus* (Chauvaud *et al*., 1998).

Measured & Instrument datasets

A review was carried out on data collected between 2012 and 2016 on the toxin producing algae. The areas reviewed were Belfast Lough, Larne Lough, Strangford Lough, Killough, Dundrum Bay and Carlingford Lough. Figure 18 shows the location of stations sampled.

Dinoflagellates, which are the most common component of toxic algae, have negative impacts on scallops. For example, the potential paralytic toxin producing species *Alexandrium* has been shown in the laboratory to inhibit the egg hatching success and larval survival of the scallop species *Chlamys farreri* (MacDonald *et al.,* 2006). *Alexandrium* was rarely detected in the 5 year period reviewed for the areas shown in Figure 18. Cell numbers were always low and no associated toxins were detected in shellfish tested as part of the official control programme undertaken by the Food Standards Agency Northern Ireland (FSANI).

Species responsible for producing diarrhetic shellfish toxins (DST's), including members of the *Dinophysiaceae* family as well as *Prorocentrum lima*, were recorded in water samples but not in high numbers. No DST's were detected in shellfish tested as part of the official control testing programme.

Members of the diatom species *Pseudo-nitzschia,* potential producers of domoic acid which causes amnesic shellfish poisoning, were regularly present in water samples. They reached bloom proportions on a small number of occasions in Dundrum Bay (April and May 2014 and

July 2015) and Belfast Lough (July 2012 and July 2015). Only the blooms in Belfast Lough were associated with the production of shellfish toxins in mussels above the regulatory level and resulted in the closure of a number of shellfish beds in the Lough.

The only other monitored species to reach bloom proportions during the 5 year period was the haptophyte, *Phaeocystis*. It reached bloom proportions in Killough and Dundrum Bay in May 2016 but no adverse effects of the bloom were reported during the period.

Key Message 7:

Between 2012 and 2016 species which reached bloom proportions were recorded from Dundrum Bay, Killough and Belfast Lough. The proposed reseedings sites 2, 7, 8 and 9 are adjacent to the sites where blooms were recorded. Scallops reseeded at these sites may therefore be affected by future blooms.

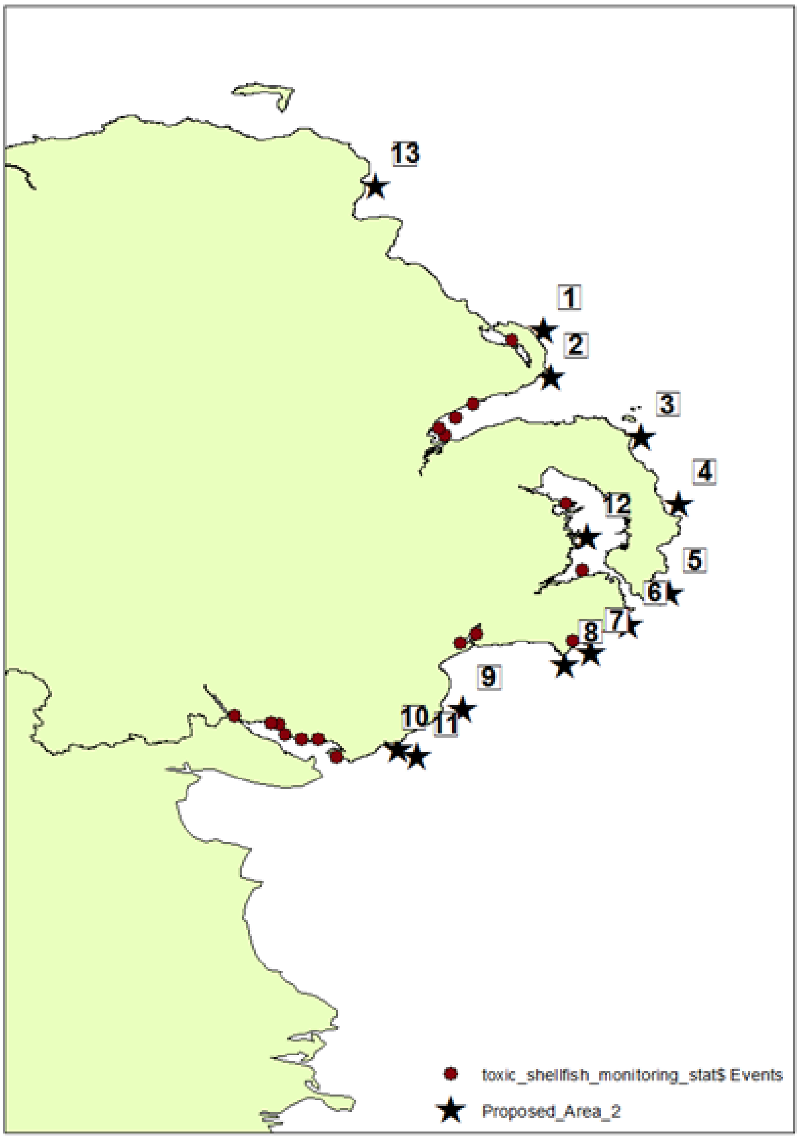

Figure 18: Location of sampling stations which monitor toxic algal blooms (red dots) in relation to the position of the proposed scallop reseeding sites.

5.4.8 Validation

To act as validation of local conditions, the location where juvenile scallops identified from grab samples or pipe dredge samples had been found are also presented alongside a number of the modelled/remotely-sensed datasets (Table 13).

Table 13: Local conditions from modelled/remotely-sensed datasets where juvenile scallops were found in grab or pipe dredge samples.

sample_id:	SK A3 60690	FHT1_1	FHT9_2	01102002_4b	05022003_2a	05022003_2b	maerl/ROV2	maerl/ROV1
Seabed temperature (Spring) °C	8.02	7.87	7.87	7.93	7.89	7.89	7.88	7.88
Seabed temperature (Autumn) °C	12.65	12.83	12.84	12.66	12.77	12.78	12.79	12.79
Mixed layer depth - autumn (m)	23.89	60.59	60.34	22.05	39.38	42.16	53.66	53.94
Bed stress (combined tide and wave) Nm-2	1.03	3.05	4.58	0.85	0.44	0.48	1.32	1.33
Tidal bed stress Nm-2	1.00	3.04	4.57	0.78	0.42	0.46	1.30	1.31
Wave stress Nm-2	0.03	0.02	0.02	0.07	0.02	0.02	0.02	0.02
Seabed Tidal Current (max) ms-1	0.42	0.35	0.65	0.43	0.40	0.43	0.62	0.57
Chl a concentration (Spring) mg/m3	1.85	1.18	1.01	1.31	1.70	1.70	1.41	1.41
Chl a concentration (Summer) mg/m3	1.65	0.84	0.79	0.80	0.93	0.93	1.09	1.09
Chl a concentration (Autumn) mg/m3	1.70	1.03	1.00	1.50	NoData	NoData	0.31	0.31

Juvenile scallops are found in well mixed waters i.e. where the mixed layer depth exceeds the seabed depth which supports the theory discussed in section 3.3. Chlorophyll a concentrations are quite similar between sites with the highest levels off County Down. Notably combined tide and wave bed stress exceeds the 2.0 Nm^{-2} nominal threshold at two sites off Fair Head (FHT1_1, FHT9_2) due to high tidal bed stress. It is suggested that juvenile scallops utilise the sheltered areas between boulders and bedrock outcrops which will have reduced bed stress at a fine resolution. The modelled data accessed is at a broad resolution and may not reveal finer scale processes that could explain juvenile scallop use of this habitat. Such habitat harbours filamentous algae and extensive bryozoan and hydroid turf which are good attachment surfaces for scallop spat. Adult scallops were not found in notable numbers in such habitat. Note that the sites identified as having juvenile scallops present are based upon data from a variety of surveys which were not designed to evaluate juvenile scallop distribution (e.g. many grab sampling surveys are not completed at an appropriate time of year).

6. *Time of spawning*

AFBI carry out an annual scallop survey of the Northern Ireland coast. Figure 19 shows the stations which are currently sampled. From this survey the CPUE of scallops is calculated along with other biological characteristics such as gonad weight, muscle weight, age and size.

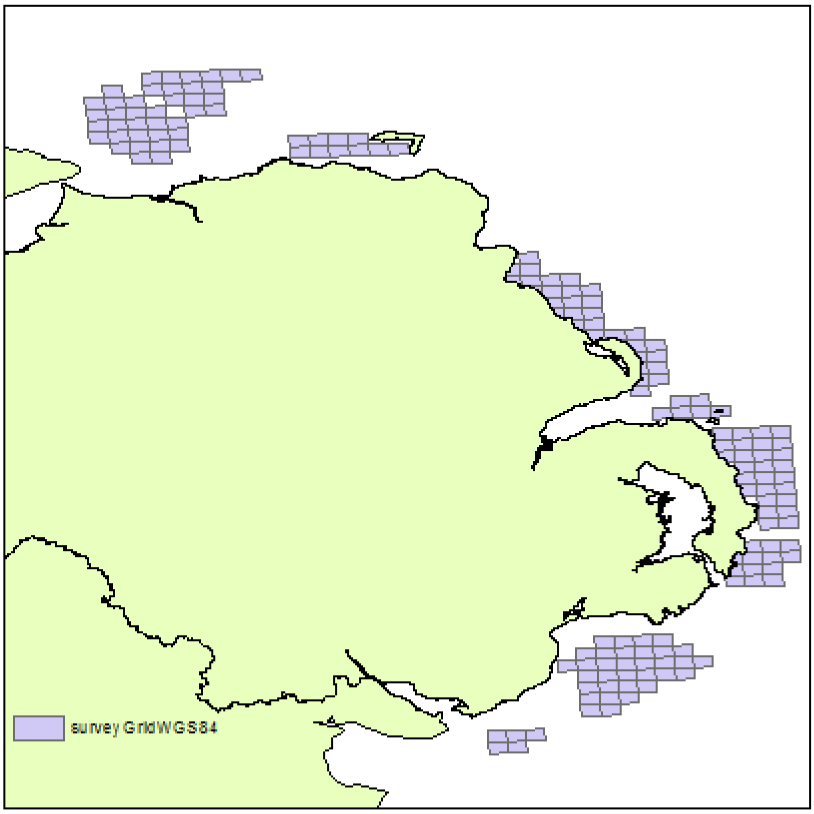

Figure 19: Current extent of the AFBI scallop survey (purple grid).

Data collected during the AFBI survey was used as an indicator of the time of spawning by scallops in Northern Ireland. In order to determine the season in which a scallop was spawned, the width of the first growth band was measured. The larger the band the longer the scallop has had for growth prior to its first winter. Therefore large first band widths tend to represent scallops spawned in spring whilst small first band represent scallops spawned in the autumn. The age of the scallops (determined by counting the annual growth rings on the flat shell) was used to determine the year in which a scallop was spawned (for example, a five year old scallop collected during the 2005 survey would have been spawned in 2000). As the majority of sites selected for reseeding are along the Antrim and Outer Ards peninsula, survey results from these areas have been used for analysis.

The width of the first growth band for the area of interest is shown in Figure 20. Figure 21 shows the first band width of scallops spawned in each year. This again shows what can be considered as the autumn and spring peaks. For some years there are two peaks in the width of the first band, representing spring and autumn spawned animals. During the earlier years the primary peak in spawning is skewed to the right. However, in 1996 the width of the first band is much more varied, with no main peak at any size class. Following 1996 there is a shift in the peak in band width. This appears to indicate a shift in the main spawning season from spring to autumn.

Key Message 8:

Survey data shows an apparent shift in time of spawning for native populations of scallops around Northern Ireland. As yet we are unsure what has triggered this shift. For scallops the time of spawning can be genetically predisposed or environmentally mediated. Therefore if scallop seed is transported from outside Northern Ireland for reseeding the expected time of spawning will be unknown.

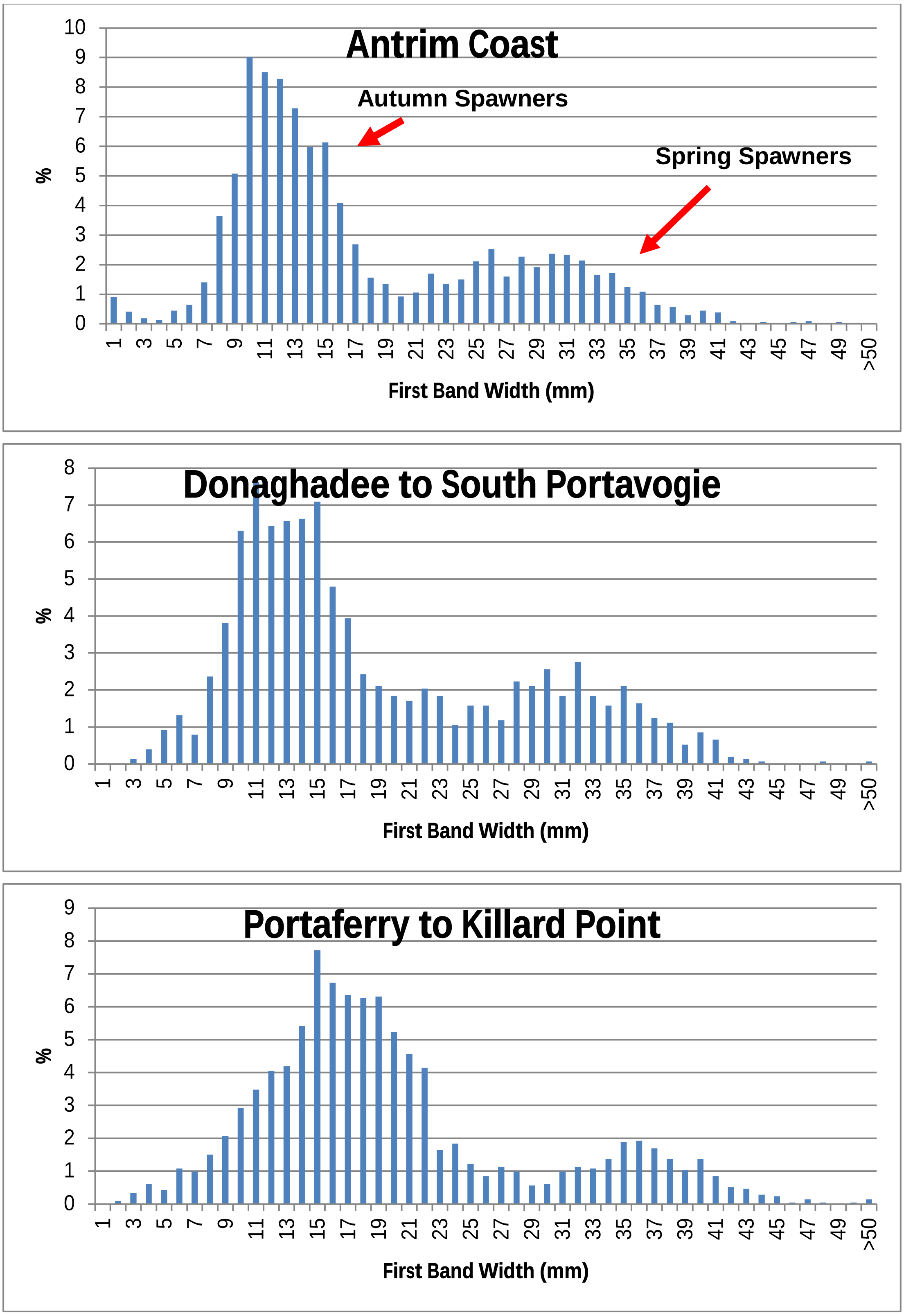

Figure 20: Size of first band width (mm) from three sites of interest sampled during the annual scallop survey.

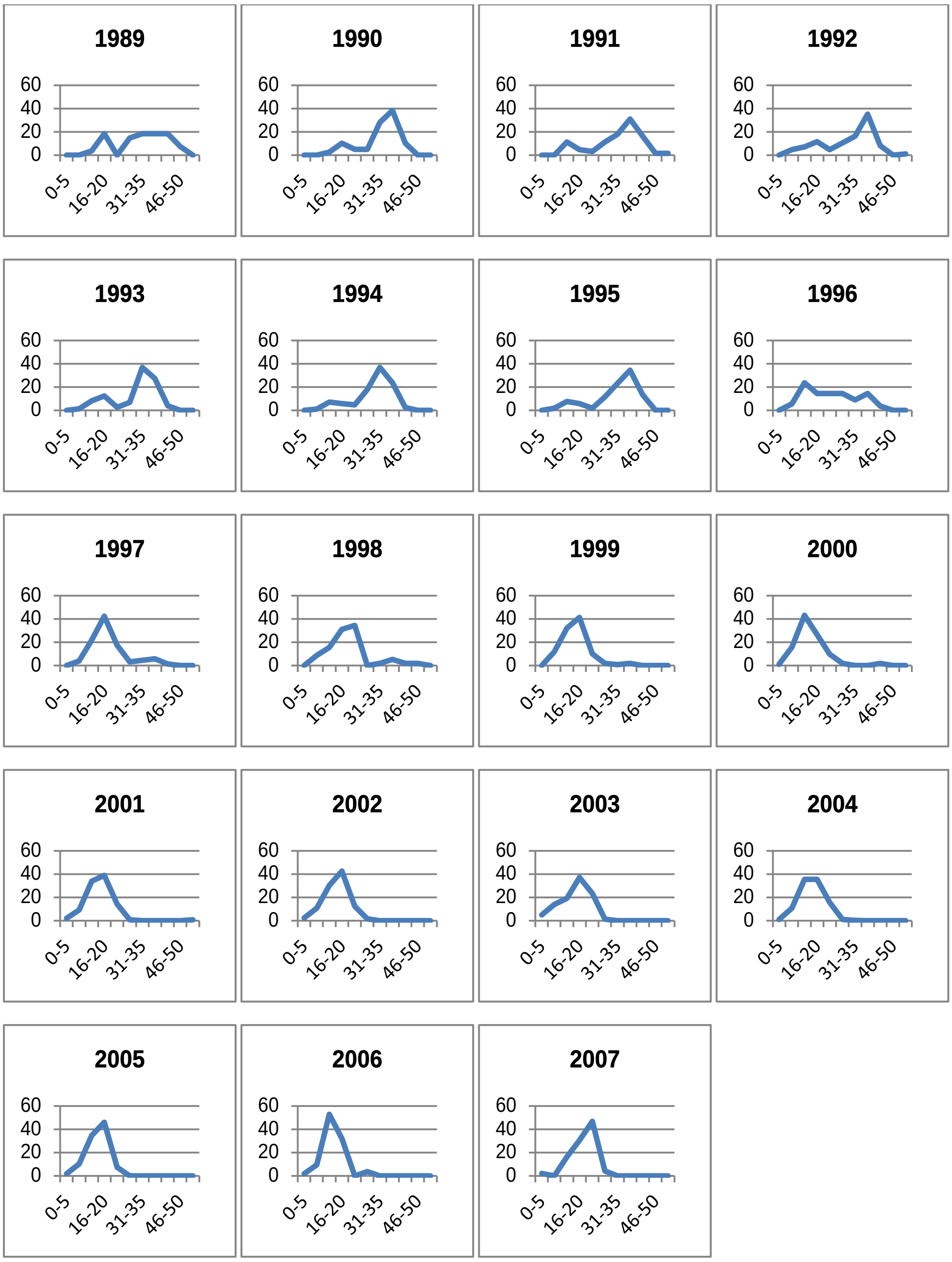

Figure 21: First band widths of scallops by year spawned for the survey Area between Portaferry and Killard Point.

7. Potential larval dispersal routes

In 2007 as part of an investigation into blue mussel (*Mytilus edulis*) seed resource in Northern Ireland, dispersal of mussel larvae was modelled (McQuaid *et al*., 2007). The model which used the Princeton Ocean Model (POM), modelled the entire Irish Sea domain at 2km grid scale. The model was run with “larvae” released in April and August and tracked for 21 days. The model simulated the environmental conditions of 1995 (for which data was available for calibration and validation). However, 1995 was exceptionally warm leading to a stable well-defined thermal front in the western Irish Sea. This means that “larvae” will become trapped in the Irish Sea gyre and there will be little movement over the thermocline produced by the gyre.

The model released “larvae” at the mouth of Carlingford Lough and Strangford Lough, along the Outer Ards peninsula and from within Belfast Lough. The model showed a strong seasonal affect, with particles released in April being transported offshore and southwards (prevailing winds are north-westerly to south westerly) whilst those released during August were distributed all along the coast (prevailing winds blows from an easterly direction). With no wind, particles from Strangford and Belfast Loughs are carried in to a narrow, well mixed area of water along the coastline which is separated from the stratified water by the thermal front. In the region of the gyre particles are transported into the gyre’s early formation. During August when the gyre is well established all particles are released in to the gyre. When the model was run with wind, in April the thermal fronts are less apparent the particles are influenced by tidal currents. However, in August the thermal fronts and gyre are well defined and the presence of wind is not enough to overcome the thermal structures. Based on this it would be expected that there would be similar dispersal of *P. maximus* larvae.

A summary of further relevant larval modelling studies is provided in Table 14. Although, again, these studies have not focussed on *P. maximus*, those that have treated larval behaviour as passive, and following similar pelagic larval durations to those documents for scallops may have relevance to understanding the dispersal of larvae from the potential reseeding sites. These results are presented below.

Table 14: Summary of relevant published pelagic larval dispersal models in the Irish Sea.

Target species	Pelagic larval duration	Larval behavioural strategies	Hydrodynamics			Literature
			Model domain and type	Model resolution	Model time period	
Modiolus modiolus	30 days. Cohorts of 10,000 larvae were released from the seabed at the four sample locations (representing a single point within the reef and corresponding to collection sites for genetic material), and at six times throughout the season, with start dates chosen on the 1st of each month (April to September).	Passive larval transport	Three-dimensional (3D) hydrodynamic model (sbPOM) of the Irish Sea. Release sites of Wales (North Pen Llŷn), Isle of Man (Point of Ayre) and Northern Ireland (Ards Peninsula and Strangford Lough).	1/30° (longitude) by 1/60° (latitude), giving a resolution of approximately 1.85 km, 20 vertical terrain-following layers	01 April to 30 September 1990 - simulation was run one month before start of study period so that baroclinic currents were fully developed	Gormley et al., 2015
Modiolus modiolus	Trickle spawning over 56 days. For each location 200 particles were released every 5 min simulating a trickle-spawning reproductive behaviour.	Neutrally buoyant inert particles	Mike-21 (DHI) model covers Strangford Lough in Northern Ireland and part of the Irish Sea from South Rock in the North (N 54°24', W −5°27') to St John's Point in the South (N 54°16', W −5°36') . Wind drift also incorporated. Whilst the initial hydrodynamic conditions were derived as depth averaged velocities, in the particle tracking model a logarithmic velocity profile was used to estimate the change in velocity with depth. Release sites in Strangford Lough: Hadd Rock in the North Basin; Craigyouran and Round Island Pinnacle in the South Basin, Eastern shore and Black Rock in the South Basin, Western shore.	Flexible grid mesh equating to approximately 50m resolution within Strangford Lough	September to October 2010 for 56 days incorporating 4 neap and 4 spring cycles.	Elsäßer et al., 2013
Ostrea edulis	Particles were given a maximum age of 10 days before they were removed from the simulation to provide a proxy for either settlement or death. To simulate the re-suspension of larvae either on its own or with sediment back into the water column re-suspension was allowed when the bed shear stress exceeded a critical shear stress of 0.001 N/m2. Trickle spawning simulated throughout the four month summer period with 200 particles released every 5 min.	Assumed passive larval transport	Mike-21 (DHI) model covers Strangford Lough in Northern Ireland and part of the Irish Sea from South Rock in the North (N 54°24', W −5°27') to St John's Point in the South (N 54°16', W −5°36') . Wind drift also incorporated. Whilst the initial hydrodynamic conditions were derived as depth averaged velocities, in the particle tracking model a logarithmic velocity profile was used to estimate the change in velocity with depth. Release sites were a number of intertidal and subtidal sites throughout Strangford Lough.	Flexible grid mesh equating to approximately 50m resolution within Strangford Lough	1995, 1998 and 2001 the tidal flows were simulated from June to August when peaks in spawning of O. edulis in Strangford Lough have been reported.	Smyth et al., 2016
Molluscs, polychaetes & echinoderms with a variety of larval behaviour strategies, focussed on those inhabiting estuarine or sheltered soft sediments (e.g. *Cerastoderma edule*, *Mytilus edulis*)	26-30 days	Passive, Tidal at 0.001 ms-1, Tidal at 0.003 ms-1, Tidal at 0.005 ms-1, Diel at 0.001 ms-1, Diel at 0.003 ms-1, Diel at 0.005 ms-1 strategies	Three-dimensional (3D) hydrodynamic model Princeton Ocean Model (POM) of the Irish Sea, incorporating Mellor and Yamada level 2.5 turbluence closure . Spatial and temporal variability was modelled to include tidal variation, release location, temperature and wind conditions that control formation of frontal zones, eddies and other oceanographic features. 40 release sites modelled, from Belfast Lough to Solway Firth to Burry Inlet (Wales) to Waterford Bay.	1/30° (longitude) by 1/60° (latitude), giving a resolution of approximately 1.85 km, 20 vertical layers, with minimum and average resolutions at mean sea level of 9.6m and 4.3m respectively	01 April to 30 September 1990 - simulation was run one month before start of study period so that baroclinic currents were fully developed	Robins et al., 2013
Cerastoderma edule	28 days. Larval cohorts were released 6 times with start dates chosen each month (April–September). The simulations were repeated at different dates in order to assess the variance in dispersal.	Passive transport, tidal-stream transport, and diel transport	Three-dimensional (3D) hydrodynamic model Princeton Ocean Model (POM) of the Irish Sea, incorporating Mellor and Yamada level 2.5 turbluence closure . Spatial and temporal variability was modelled to include tidal variation, release location, temperature and wind conditions that control formation of frontal zones, eddies and other oceanographic features. Release sites in south Irish Sea: Burry inlet south, Burry Inlet north, Dale, Bannow Bay, Tramore, Flaxfort Strand.	1/30° (longitude) by 1/60° (latitude), giving a resolution of approximately 1.85 km, 20 equally segmented sigma-layers gave minimum resolution at mean sea level of approximately 10 m.	01 April to 30 September 1990 - simulation was run one month before start of study period so that baroclinic currents were fully developed	Coscia et al., 2013

Gormley *et al.,* (2015), modelled the dispersal of *Modiolus modiolus* larvae from Strangford Lough and the Ards Peninsula. The results from both release sites show a net southward transport, with autumn spawning resulting in the greatest dispersal distance, with larvae reaching Dublin Bay. Spring spawning resulted in greater retention in the general area of the release site (Figure 22).

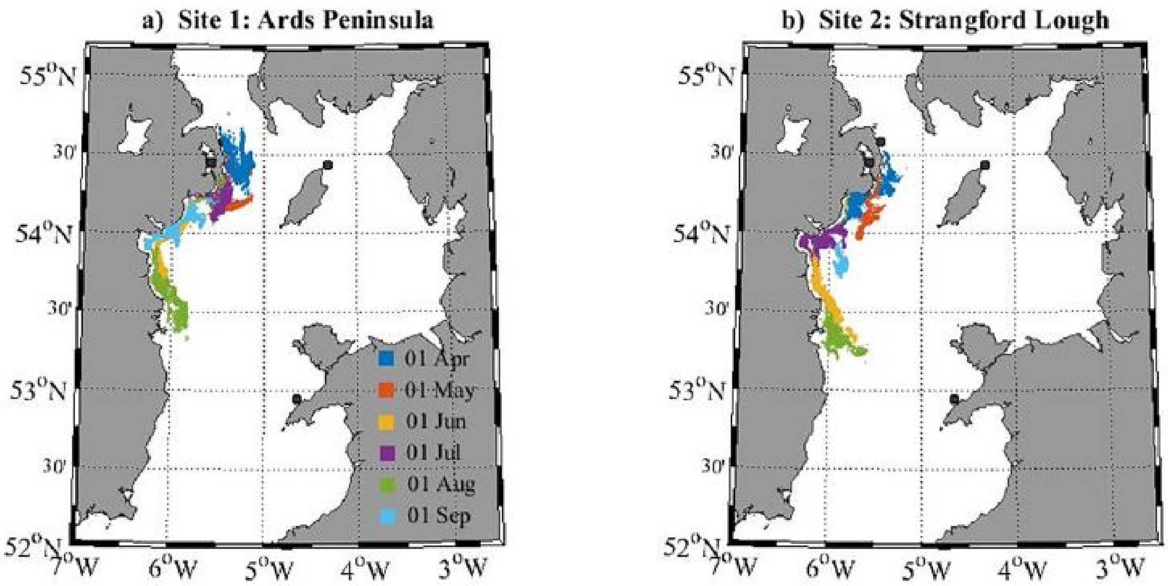

Figure 22: Larval dispersal maps for each simulated cohort of 10,000 larvae within the northern Irish Sea. Panels (a) and (b) displays the particle tracking model output, after a 30-day pelagic larval duration, from six release dates (01 April—01 September), released from the distinct source locations (black circles). Source: Gormley *et al.,* (2015).

In contrast to the findings of the model above, Elsäßer *et al.,* (2013) larval transport model for *M. modiolus* suggested little indication of connectivity between beds on the western side of Strangford Lough and those near Hadd Rock in the North and Craigyouran and Round Island Pinnacle in the East, and very little connectivity between release sites within Strangford Lough and areas outside of the Lough. Wind has very little influence on particle dispersal at the release sites due to the water depth. The Hadd Rock release site is the closest release site modelled to the potential reseeding site of Scott’s Hole, and the model results are shown in Figure 23, indicating that only extremely low numbers of larvae escape Strangford Lough. Most dispersal was largely in a north-south direction, staying close to release sites. Notably the model developed for this study is at a higher spatial resolution to that of Gormley *et al*., (2015).

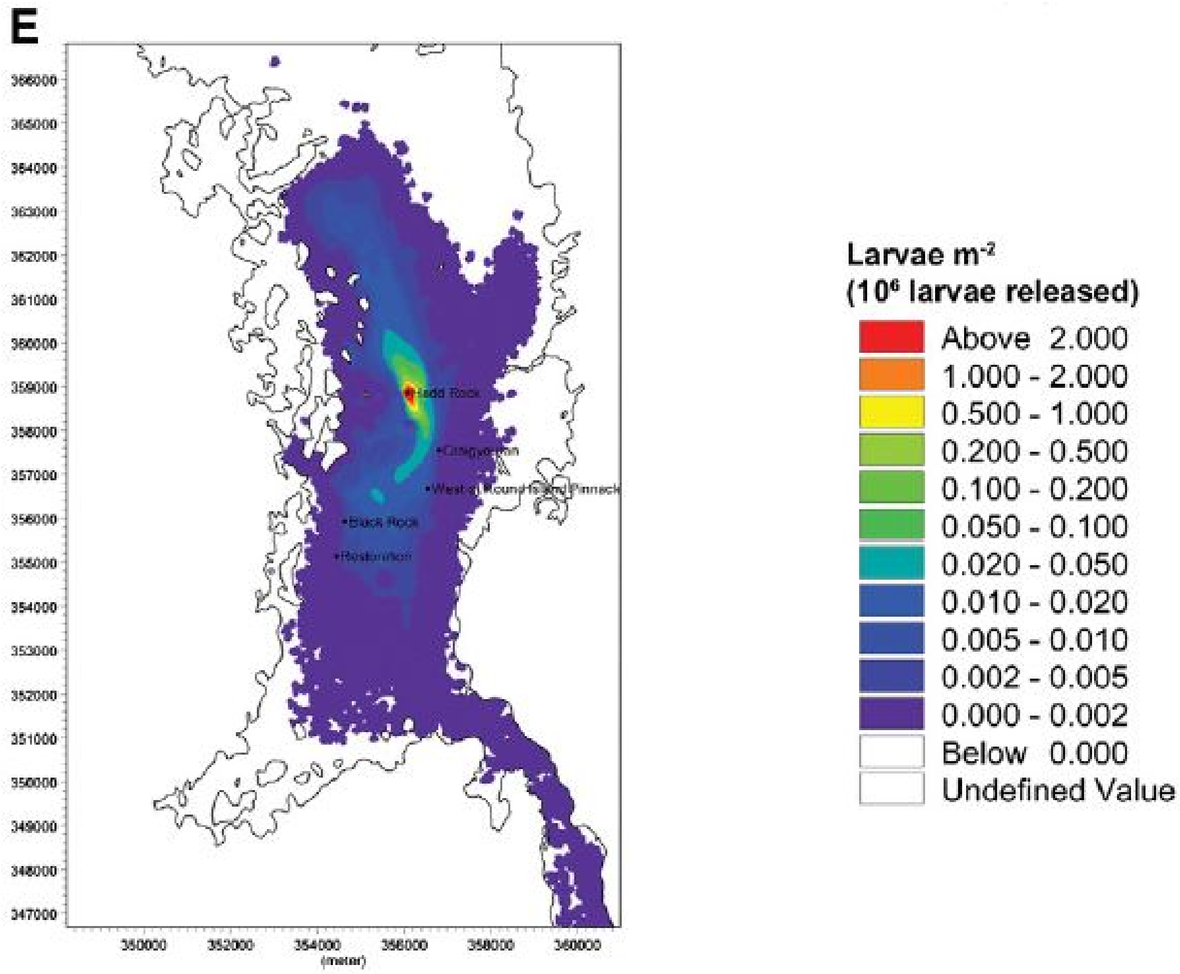

Figure 23: Predicted particle distribution after 56 days from Black Rock with wind dispersion. Release of particles is constant simulating trickle spawning, timestep 5 min, 200 particles per timestep. Source: Elsäßer *et al.,* (2013).

The study of larval dispersal and connectivity in the Irish Sea by Robins *et al.*, (2013) indicated that there is a level of connectivity between Belfast Lough, the mouth of Strangford Lough, Dundrum Bay and Carlingford Lough, with dispersal notably to the south of release sites. Passive larval behaviour modelled with release of 60,000 larvae simulated over 28 days shows a mean dispersal distance of approximately 750 km from Belfast Lough, approximately 500 km from the mouth of Strangford Lough, approximately 400 km from Dundrum Bay, and approximately 600 km from Carlingford Lough. Where larvae showed diel migration or tidally affected swimming behaviour, these distances were reduced. There was a notable impact of the onset of thermal stratification increasing the strength of residual baroclinic currents, which led to greater dispersal – therefore larvae released later in the summer or early autumn had greater dispersal distances than those released in spring. The new southward movement of passive larvae released from Belfast Lough or further south in NI waters is corroborated by the SMILE hydrodynamic model (Ferreira *et al.*, 2007), as demonstrated by continual tracer release from Belfast Lough (Figure 24).

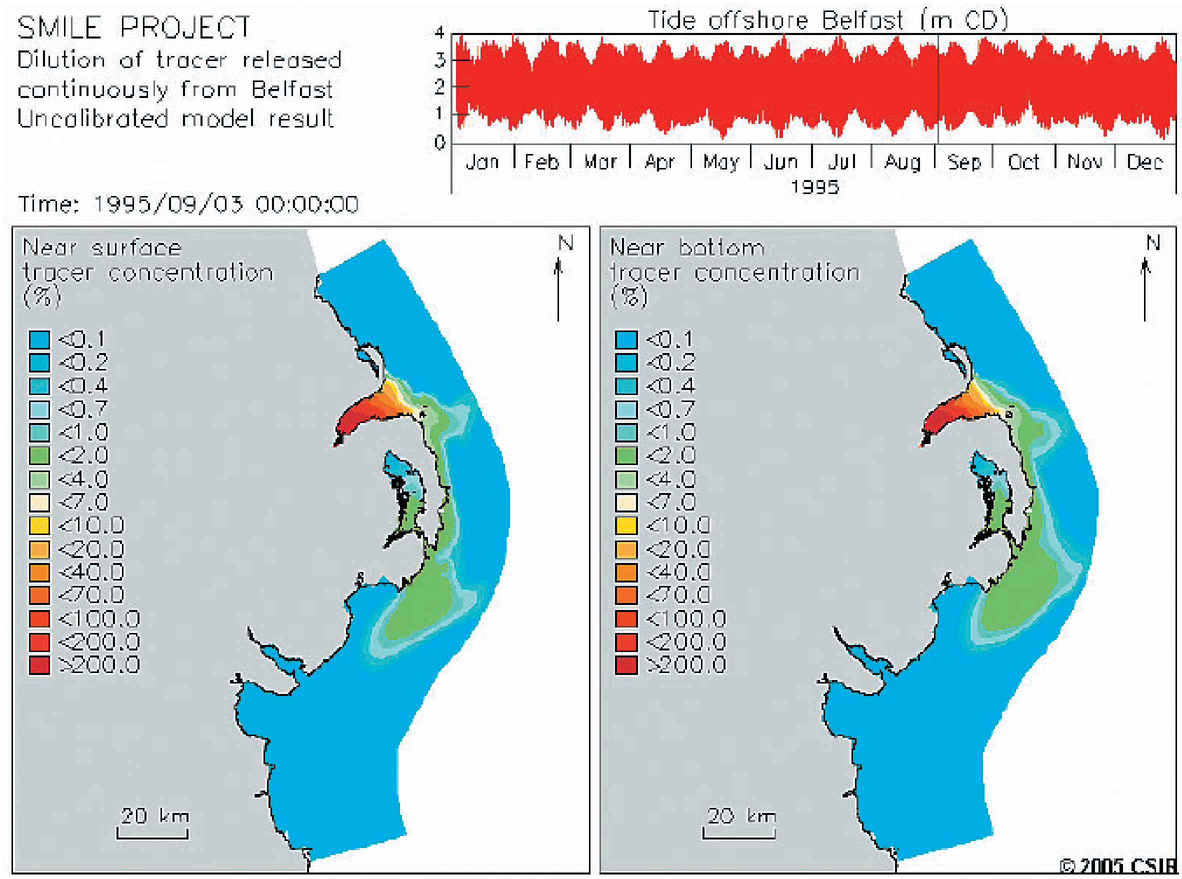

Figure 24: SMILE hydrodynamic model tracer release study from Belfast Lough, run over a full spring-neap tidal cycle. Source: Ferreira *et al.*, 2007

Tracer release studies from Carlingford Lough indicate a more complex pattern of dispersal, with some tracer travelling north to Dundrum Bay, and some tracer dispersing south towards Dundalk Bay (Figure 25). For the surface tracer, a greater concentration was found moving south of the mouth of Carlingford Lough.

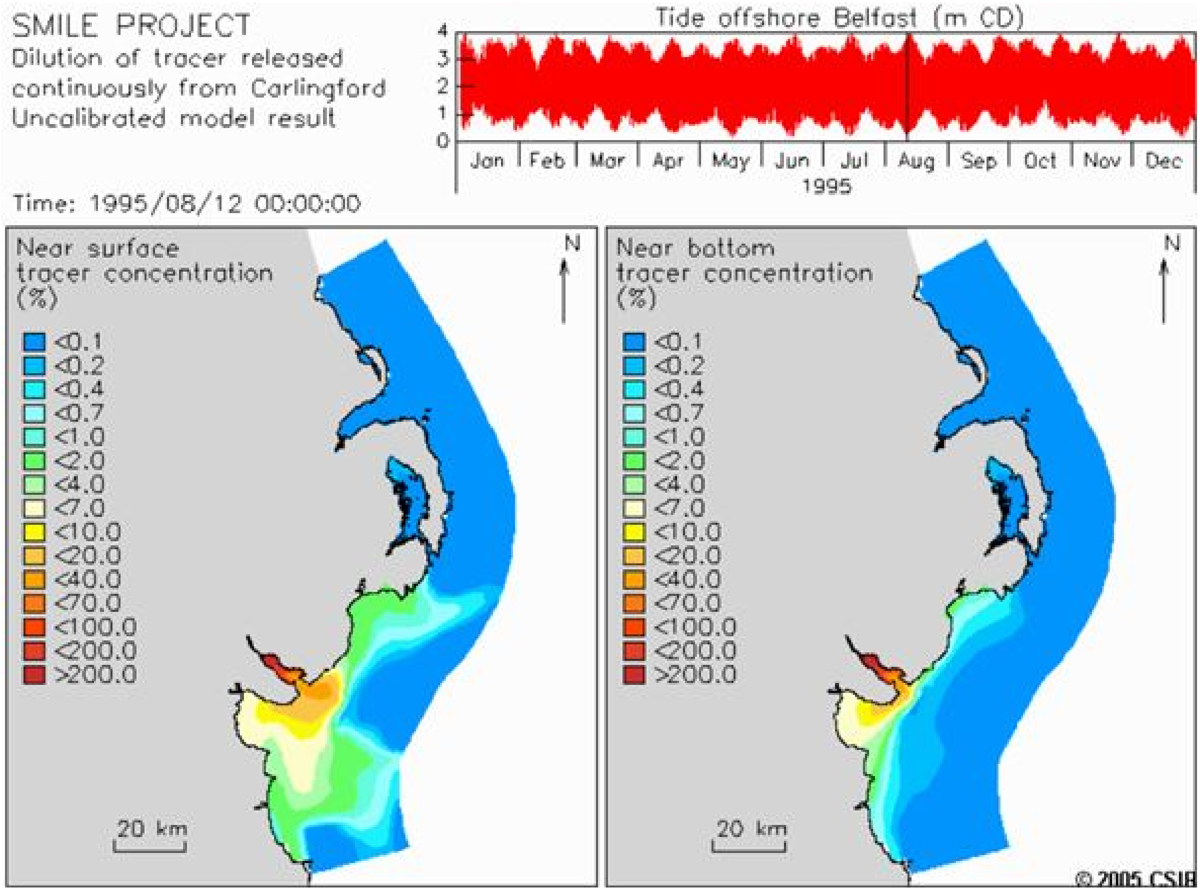

Figure 25: SMILE hydrodynamic model tracer release study from Carlingford Lough, run over a full spring-neap tidal cycle. Source: Ferreira *et al.*, 2007

The POLPRED tidal prediction software was accessed for all predictions in 2014 (at a 1.8 km resolution), and the strongest and weakest tidal currents extracted. The selected potential reseeding sites are presented along with the mean tidal current direction (maximum and minimum speeds) from the mid water column layer in Figures 26 and 27. It is clear that there is a notable split between current directions north of Belfast Lough, and those south of Belfast Lough. In general, there appears to be a net movement north along the Co. Antrim coast, while there is a net southward movement along the Co. Down coast. It could be assumed that larvae released from inshore reseeding sites [1] and [2] are more likely to disperse northwards, potentially dispersing minimally as currents are not as strong as they are further north along the Co. Antrim coastline, whereas the reseeding sites [4], [5], [7] and [8] and more likely to have larvae dispersed in a southward direction, although again the currents particularly over sites [7] and [8] are less strong and may reduce dispersal distance unless spawning coincides with the establishment of the western Irish Sea gyre (via thermal stratification). The gyre impacts areas immediately offshore of sites [7] and [8], and causes the establishment of baroclinic residual currents which may have a notable effect upon larval dispersal, driving dispersion further and in a south to south-east direction. Tidal current data is not are an appropriate resolution to understand its effects on site [12], although from the studies noted above it appears likely that a majority of larvae released from this site may be retained within Strangford Lough.

Key Message 9:

It is clear that there is a notable split between current directions north of Belfast Lough, and those south of Belfast Lough. In general, there appears to be a net movement north along the Co. Antrim coast, while there is a net southward movement along the Co. Down coast.

Key Message 10:

Where spawning coincides with the spin-up of the western Irish Sea gyre the potential reseeding sites 7 and 8 may be affected by baroclinic currents resulting in greater dispersal distances potentially away from suitable habitat.

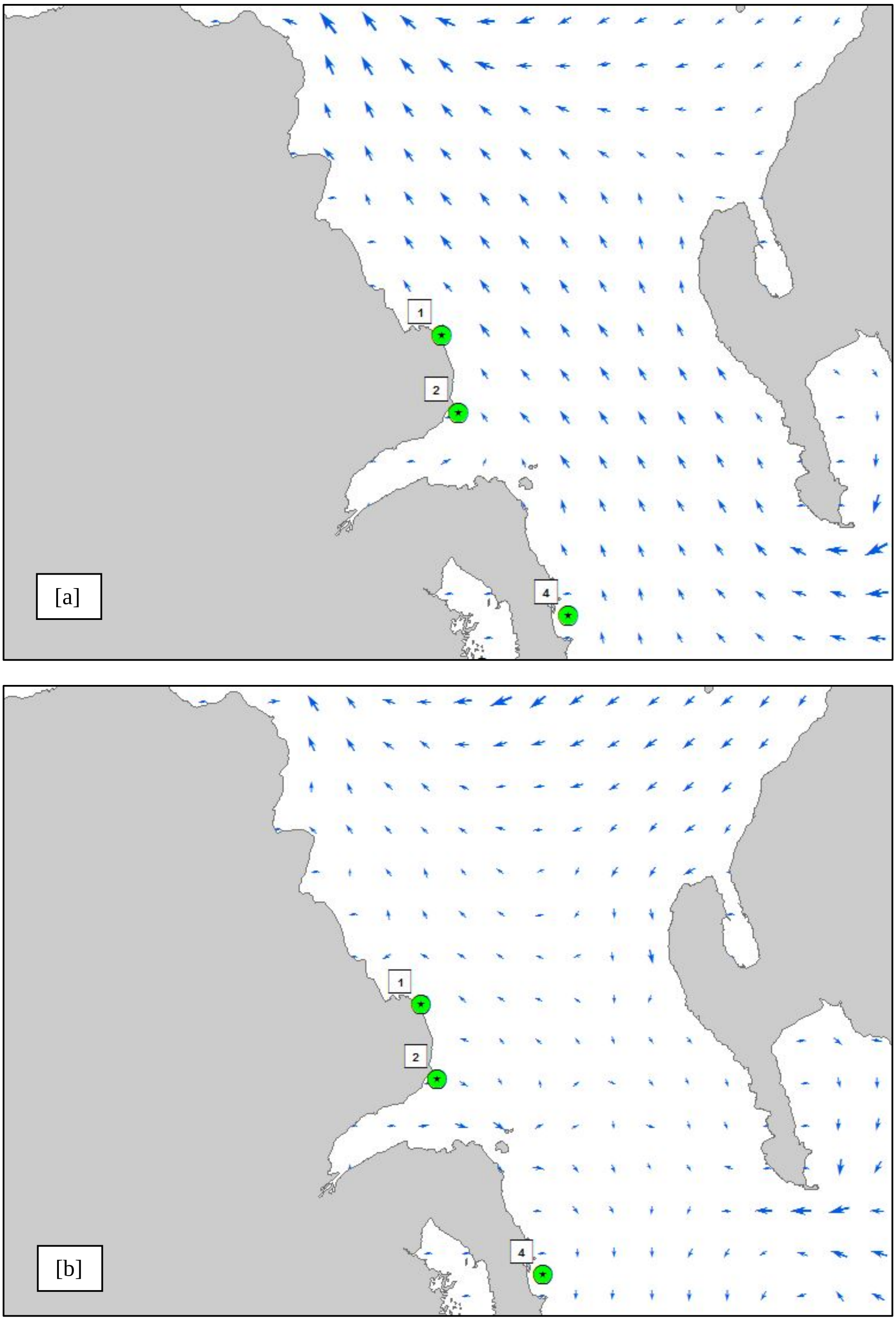

Figure 26: (A) Maximum tidal current speed in mid water column, and (B) minimum tidal current speed in mid water column, based on POLPRED data from 2014. Potential reseeding sites are overlain.

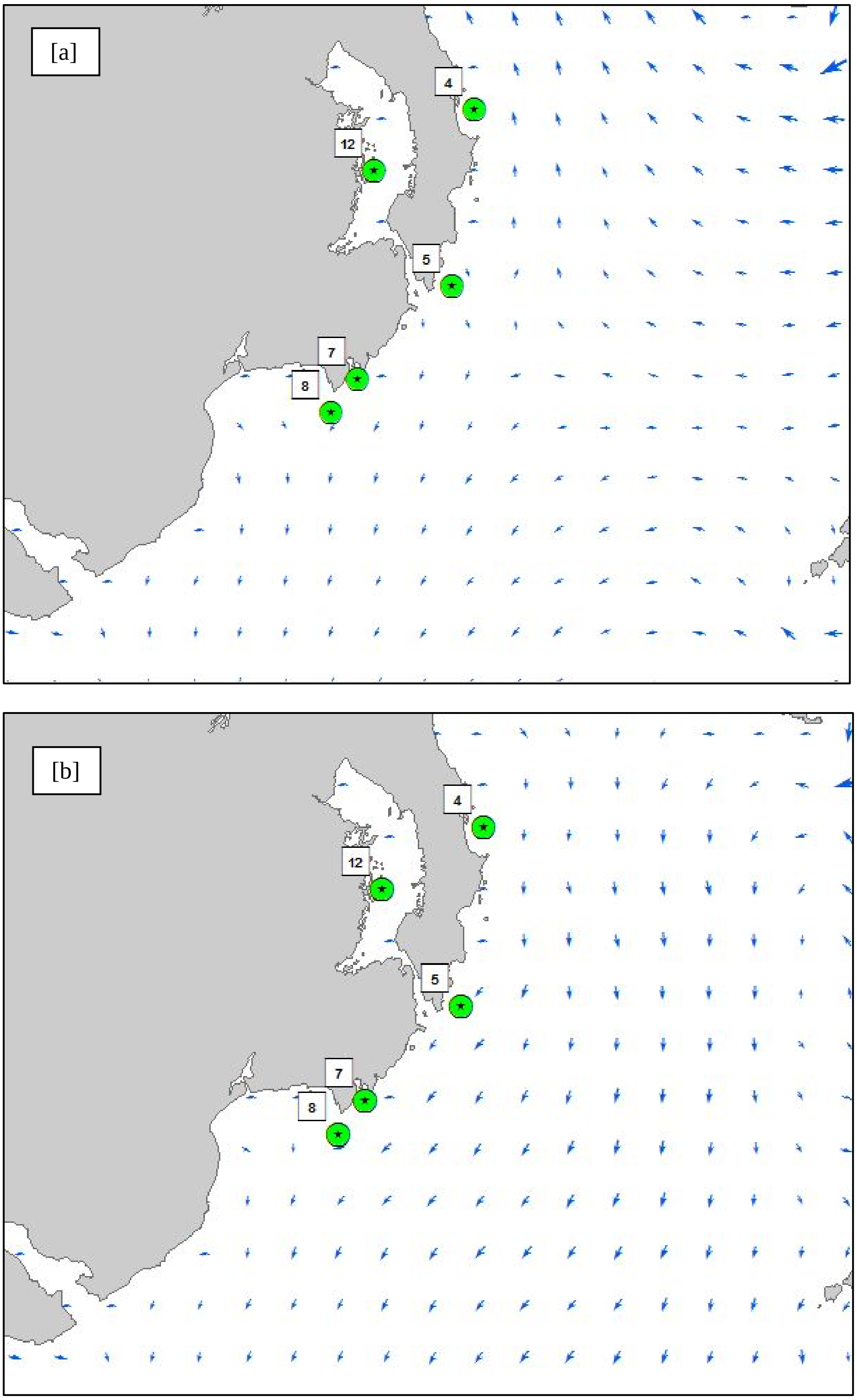

Figure 27: (A) Maximum tidal current speed in mid water column, and (B) minimum tidal current speed in mid water column, based on POLPRED data from 2014. Potential reseeding sites are overlain.

8. Stakeholder Engagement

Following review of the proposed sites as outlined in sections 5-7, a meeting was held with the project steering group (AFBI, Seafish and selected members of the Northern Ireland Scallop Association) to discuss findings. A summary was provided which scored each proposed site based on its characteristics (salinity, thermal stratification, food availability, bed stress, SPM, predation, toxic algal blooms, dispersal direction and dispersal distance). Table 15 provides a summary for each site. The highest scoring areas were then examined on nautical charts by the fishermen and suggestions were proposed for refined site boundaries. These are available in Figure 28. The highest scoring sites were 1 and 5. However, based on suggestions from the fishermen, it was decided that sites 1 and 2 could be combined as could sites 5 and 6. They also wanted to create a site between proposed sites 3 and 4. It was determined by the stakeholders that these sites would provide good potential for larval dispersal along the entire County Down coastline.

The steering group discussed the protection of the potential reseeding sites and believed that these sites must be closed to bottom scallop dredging, with enforcement the defining factor of reseeding success. They believed enforcement could be made simpler by using the land boundary as one side of the reseeding closed area. They also believed that using boundaries already established could aid the simplicity of closing sites for reseeding purposes. Taking this on board they highlighted that the proposed reseeding site 5 could be positioned to be fully/partially within the extended Strangford Lough Marine Conservation Zone boundary.

Maps of each site proposed for progression are provided in Appendix 1.

Figure 28: Sites selected for reseeding taking in to account the characteristics of the sites and feedback from the scallop fishing sector. Those outlined in red were drawn by the steering group and are ready for progression. The site outlined in purple (Roaring Rock) was a provisional extra site, with the boundary being an indication of a possible site.

Table 15: Summary of the 13 proposed reseeding sites, providing scores for each of the site characteristics which have been examined in this report. Green means the site scored favourably (score 1); amber, no data available; red, site was least favourable (score 0); grey means that the larvae would potentially leave NI waters (sites 10 and 11) or be caught in Strangford Lough (site 12) and therefore could not be fished (score -1).

Site / Characteristic	1: Muck Isl./ Moyle Interconnector	2: Black Head/ Cloghan Point	3: Donaghadee Sound	4: Ballyhalbert Bay	5: Ballyquintin Point	6: Killard Point/ Gun Island	7: St. Johns Point, Ardglass	8: Killough	9: Roaring Rock/ Russell's Point, Annalong	10: Cranfield Point inshore	11: Cranfield Point offshore	12: Scott's Hole Strangford Lough	13: Red Bay
Salinity	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Thermal stratification	Green	Green	Green	Green	Green	Green	Green	Red	Red	Red	Red	Green	Green
Food availability	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Red
Bed stress	Green	Green	Red	Green	Green	Red	Green	Green	Green	Green	Green	Red	Green
SPIM	Green	Green	Red	Red	Green	Green	Green	Green	Green	Green	Green	Green	Green
Predation	Green	Green	Green	Red	Green	Amber	Amber	Amber	Amber	Amber	Amber	Amber	Amber
Toxic algal blooms	Green	Red	Green	Green	Green	Green	Red	Red	Red	Green	Green	Green	Green
Dispersal distance	Green	Green	Green	Green	Green	Green	Amber	Amber	Green	Grey	Grey	Grey	Amber
Dispersal direction	North	North	South	South	South	South	South; may be affected by Irish Sea gyre	South; may be affected by Irish Sea gyre	South	South	South	Within Strangford Lough	North; unless extreme wind forcing drives south
Total score	8	7	6	6	8	6	5	4	5	4	4	4	5

9. Discussion

The aim of this desktop study was to determine potential sites which could be closed to bottom dredging for the purposes of scallop reseeding which would then act as sources of larval production to replenish the surrounding fished areas.

Barbeau *et al*., (1996) stated that whilst bottom culture is less labour intensive and has a lower cost than suspended culture, it produces lower yields. The key points they raised as an explanation for this lower yield are

- **Increased mortality due to predation**
- Interspecific competition
- **Adverse environmental conditions such as extreme temperatures and salinity or heavy sedimentation**
- **Strong wave action**
- **Toxic algal blooms**
- **Dispersal due to high densities of seeded scallops**
- **Inappropriate substratum type**
- **Dispersal due to local hydrodynamics.**

Those highlighted in bold have been examined in this report and have been used to select the most appropriate sites for reseeding (Table 15). In many cases more than one data set was used to examine each characteristic of the sites e.g. modelled and measured data sets. Using this combination of data sets provides confidence in the suitability of the sites. From the study sites 1 and 5 had the most optimal conditions for scallop reseeding. Stakeholder discussions highlighted the importance of larval dispersal direction to the scallop fishermen, with this factor outweighing some of the other site characteristics. For example, replenishing the commercial scallop beds of the County Down coast were of significant importance. The sites had the most suitable characteristics along the County Antrim coast were at Islandmagee. Dispersal of larvae from this site is likely northward but may not extend as far as the North Coast. The East Antrim coast is not fished as intensely as the County Down and North Coasts and was of less importance for replenishment from reseeding at the stakeholder meeting.

Based on examination of sites and feedback from the steering group, three sites have been selected for possible reseeding. These areas are

1. Blackhead (between proposed sites 1 and 2)
2. Millisle (just south of proposed site 3)
3. Ballyquintin Point (proposed site 5)

They also proposed that a fourth potential site should be located at Annalong (proposed reseeding site 9).

In terms of sourcing scallops to reseed there are three main options:

Option 1: Purchase of seed

This was the method which was used in the 1999 C-Mar reseeding trial, with scallop seed purchased from Mulroy Bay. At this time there was plenty of seed available and the price of purchasing seed was thought to be considerably low. However, scallop seed is no longer readily available. Options for sourcing seed are, as before, to purchase seed which has been caught naturally and ongrown to a certain size or, to purchase seed which has been reared in a hatchery. Whilst this option is the least labour intensive for the purchaser, it is costly and, as already mentioned, scallop seed is not readily accessible. In addition, whilst the hatchery option would allow you to use Northern Ireland scallops as the broodstock, bringing scallops in from areas outside of Northern Ireland has the potential to modify the genetics of the stock producing less viable scallops. Also, as scallop spawning may be a genetic trait, the time of spawning for scallops brought in from outside Northern Ireland would be unknown.

Option 2: Translocation of Northern Ireland scallops

This option would see scallops moved from a fishable area to the reseeding site where they would be protected from future fishing and left to act as a breeding stock. This would limit the genetic impact of reseeding and would be of little cost to the Scallop Association. It would mean that you are lowering the density of scallops in an additional area; however, this is already the case due to the levels of fishing around the entire Northern Ireland coast. It is not recommended that scallops are removed from a currently unfished area as these could be already acting as a brood source for the population.

Option 3: Using spat collectors

Spat collectors work by providing larvae with a suitable settlement substrate. Spat collectors are routinely used in mussel production. For example, in the Dutch mussel industry 110m nets are anchored in position from April to September to collect spat which is then stripped of the nets and used for bottom culture (Bates, 2006). Whilst the use of spat collectors would be the most labour intensive they could be used to provide a regular supply of scallop spat. In order for spat collectors to be successful the correct material needs to be selected and knowledge of the spawning an recruitment patterns is required to ensure the collectors are placed in the water at the correct time.

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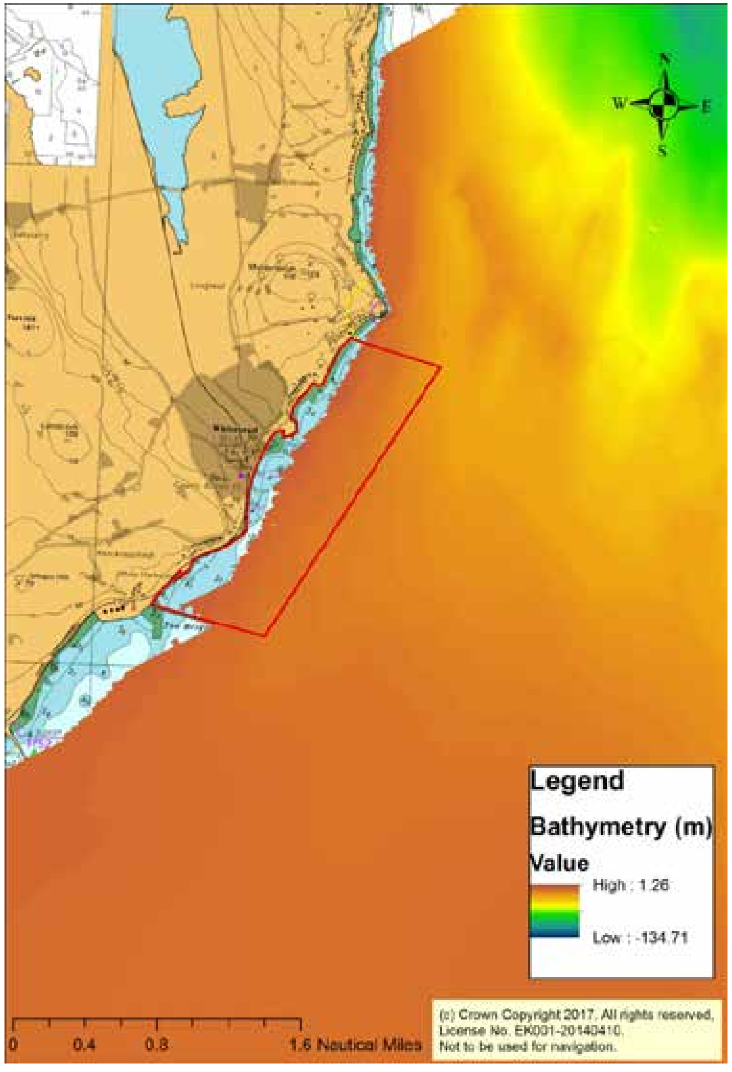
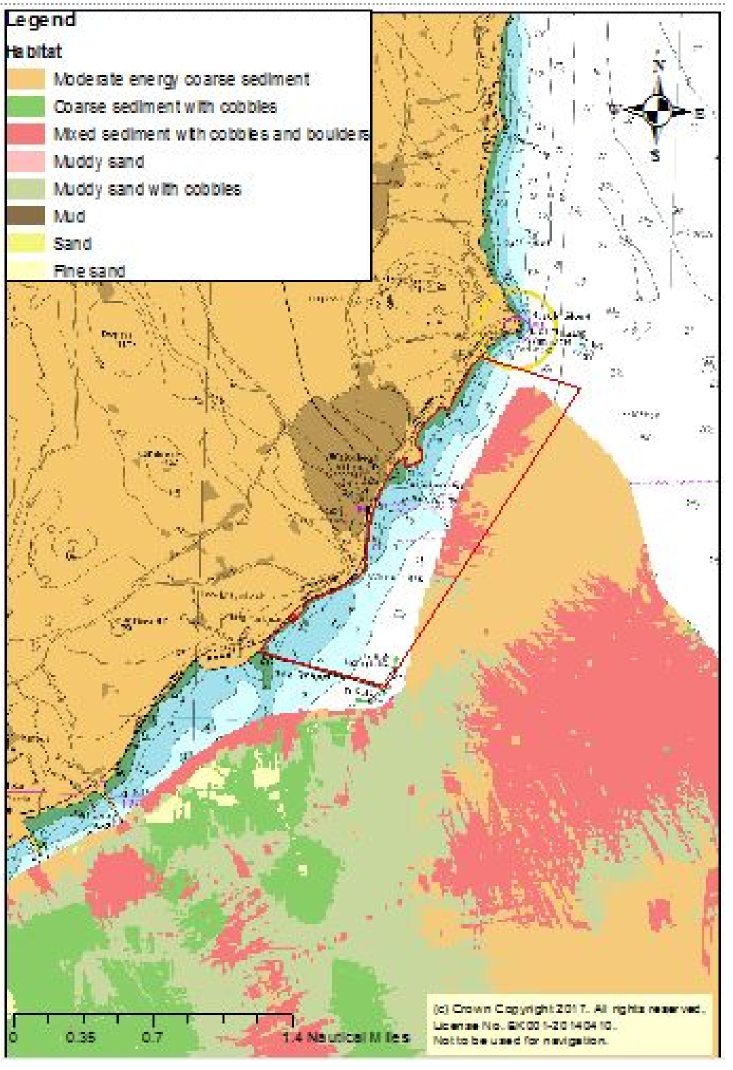
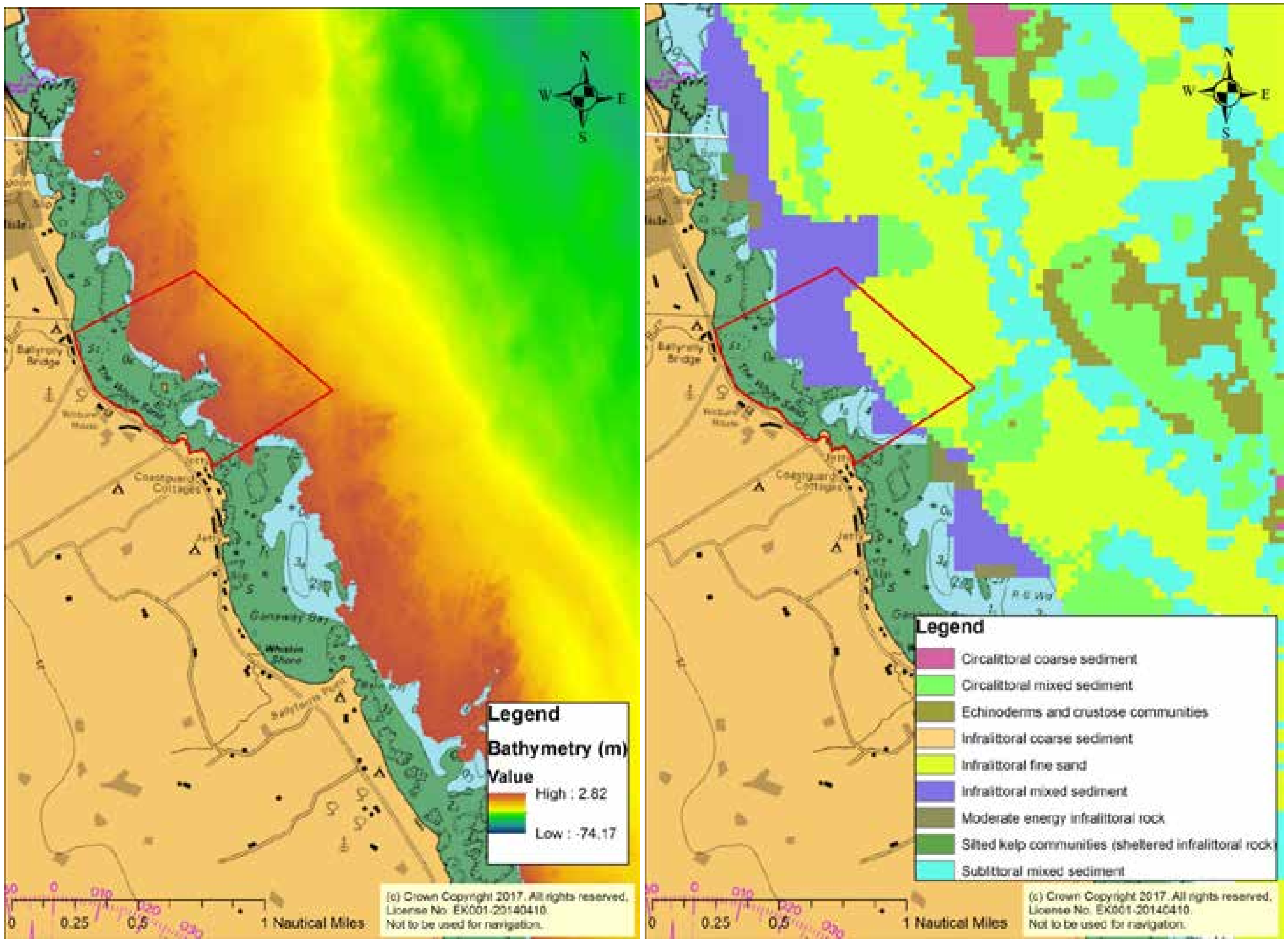
Appendix 1: Sites selected for scallop reseeding

A-Whitehead (Bathymetry and habitat maps)

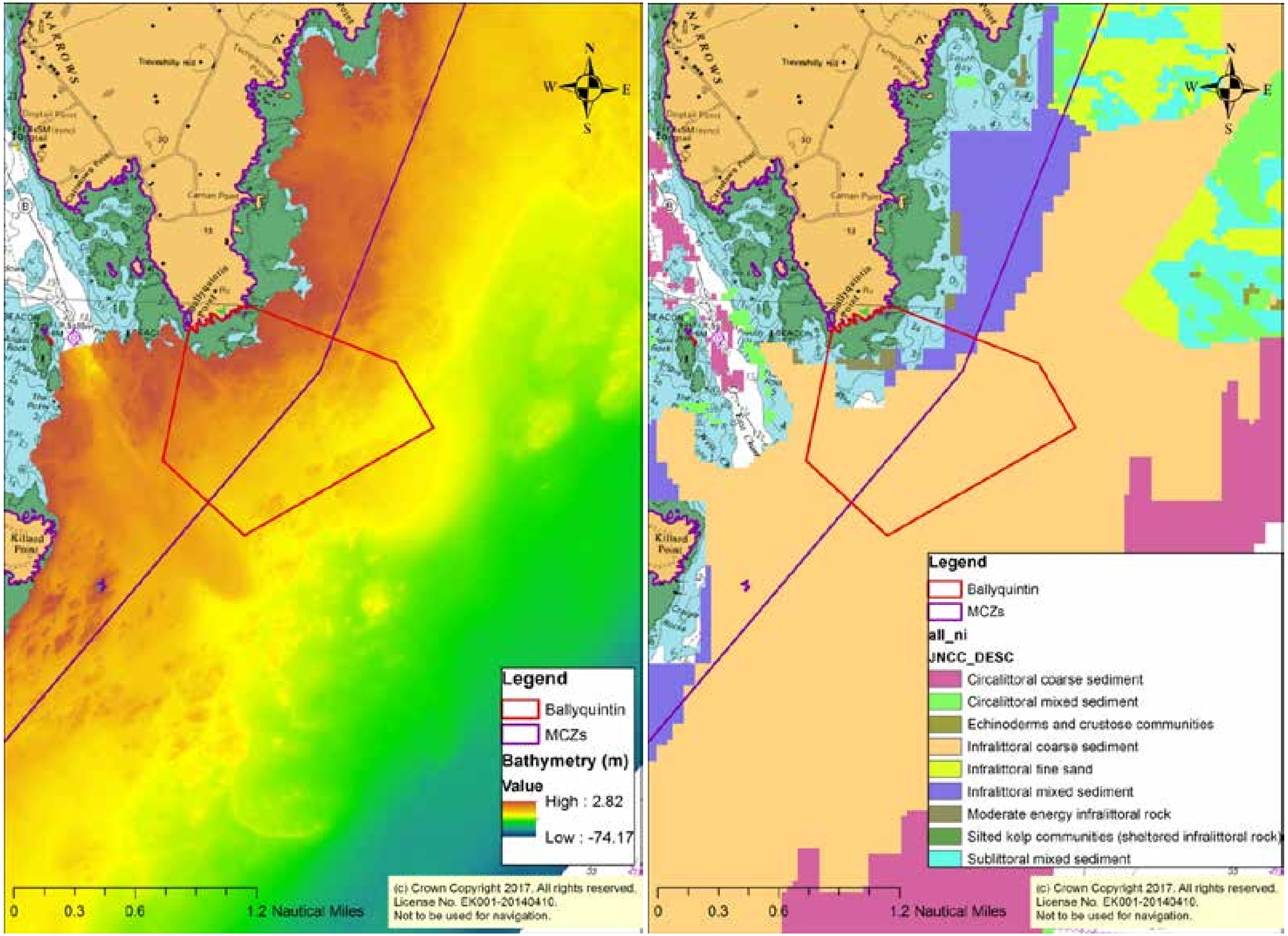




B-Drumfad Bay (Bathymetry and habitat maps)



C- Ballyquintin Point (Bathymetry and habitat maps)



D- Proposed site with future potential, Roaring Rock (Bathymetry and habitat maps)