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Scallop Enhancement Project

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Executive Summary

In 2017, a study commissioned by Seafish, on behalf of the Northern Ireland Scallop Association, highlighted four potential sites around the Northern Ireland coast for scallop reseeding. To ensure sites selected for enhancement are given the best chance of success, this desktop study has been prepared to assess further the possibility of scallop enhancement including the pros and cons of such a scheme. A review of literature on scallop enhancement initiatives was carried out, providing examples of the scallop enhancement techniques used in eleven countries (Northern Ireland, Isle of Man, England, Scotland, Ireland, Japan, China, France, America, Canada and New Zealand) and includes cases of closed areas, reseeding and sea-ranching.

Based on the case studies shown in this report across the UK, the introduction of closed areas appears to be the primary method used to enhance scallops. The use of spatial management has been described by Stewart and Howarth (2016) as "spectacularly successful" when implemented for scallop fisheries and Hilborn et al. (2004) described that, for sedentary species, marine reserves can provide "significant benefits in some cases". One of the biggest successes of a closed area for scallops appears to be Georges Bank, America, were an area of 17,000km^2 was closed in 1994 to all mobile gear to protect groundfish species including cod and haddock. At the time the closed areas were created, landings of scallops from Georges Bank were near the time-series minimum (Murawski et al. 2000). By July 1998 scallops had increased in abundance with densities inside the closed area being 14 times greater than those in adjacent open areas and of a bigger size class (Murawski et al. 2000; Stewart and Howarth, 2016). Increases in biomass, Landings per Unit Effort (LPUE) and landings also became evident in the areas outside the closed areas and have remained at record levels since 2001 (Hart and Rago 2006).

However, there are a number of negatives also associated with the use of closed areas (outlined fully in Table 2 within the full report). If the area is not selected correctly, there may be limited or no benefits derived. In order for the closed area to benefit fishing grounds, the larvae produced within the protected site must move to areas within fishing grounds. With scallops being a sedentary species, dispersal of adults (spillover) to fishing grounds will be minimal.

What is clear is that the scallop industry will need to be patient and not expect results in the short term. It is clear from all the case studies listed in this report that benefits can take many years to first appear, with the longer an area is closed the greater the benefits.

This review has shown that reseeding is used globally both in combination with closed areas or with rotational fisheries. However, in Europe, Australia and Isle of Man the results of reseeding has been disappointing as their results have not been as successful as in Japan (Bradshaw et al. 2001; Slater, 2006). The two main issues with reseeding are (1) sourcing seed (from a hatchery, spat collection at local site, spat collection from further afield); (2) survival of seed during transport; (3) retention and survival of seed. With reseeding coming at a cost in terms of getting the seed (collector cost/purchasing costs/preparation of reseeding area/monitoring) it is important that these are measured against the potential threats to its success.

Recommendation 1: Based on the literature review the closure of key areas for the purposes of scallop enhancement should be treated as an initial step, with closures to mobile gear as well as hand collection (diving) of scallops. This should create a high reproductive output in the closed area which has the potential to supply the greater Northern Ireland scallop fishing industry

Recommendation 2: Further enhancement strategies, such as reseeding could be implemented. However, knowing the potential negatives associated with reseeding, it is recommended that not all sites are reseeded. This would provide a unique comparison to glean the real benefit, if any, that reseeding has over a simple area closure. It is important to note that the purpose of the reseeding in the areas is not so that it can be fished at a future date (i.e. not a rotational fishery) but as a method of supplementing the scallops in the closed area. If natural spat could be collected in the local area this would be the cheapest option and would also mean that there is no risk to the genetic structure of the population

Recommendation 3: Sites must be monitored to determine success or failure. Monitoring should involve regular surveys of the areas which could be by divers, underwater television and/or grab sampling surveys. To monitor if there is any spillover of scallops from the closed area to the fishery, tagging experiments could be carried out. This enhancement work is being carried out to enhance the scallop fishery, therefore it is vital that the fishery is monitored to look for impacts that the enhancement is having on catches.

Contents

Recommended citation

McMInn, C (2020) Scallop enhancement project: Section 1. 50 pp

Scallop Enhancement Desktop Study

1.0 Project Background

In 2017, following discussions with the Northern Ireland Scallop Association, and with funding through Seafish, AFBI produced a report examining sites around the coast as potential locations for reseeding of scallops. Whilst 13 sites which had been identified by stakeholders were examined, four sites were highlighted as being most suitable (Figure 1)

- Whitehead
- Drumfad Bay
- South Bay
- Roaring Rock

The report stipulated, that for reseeding to be successful, any site used must be closed to mobile fishing gear.

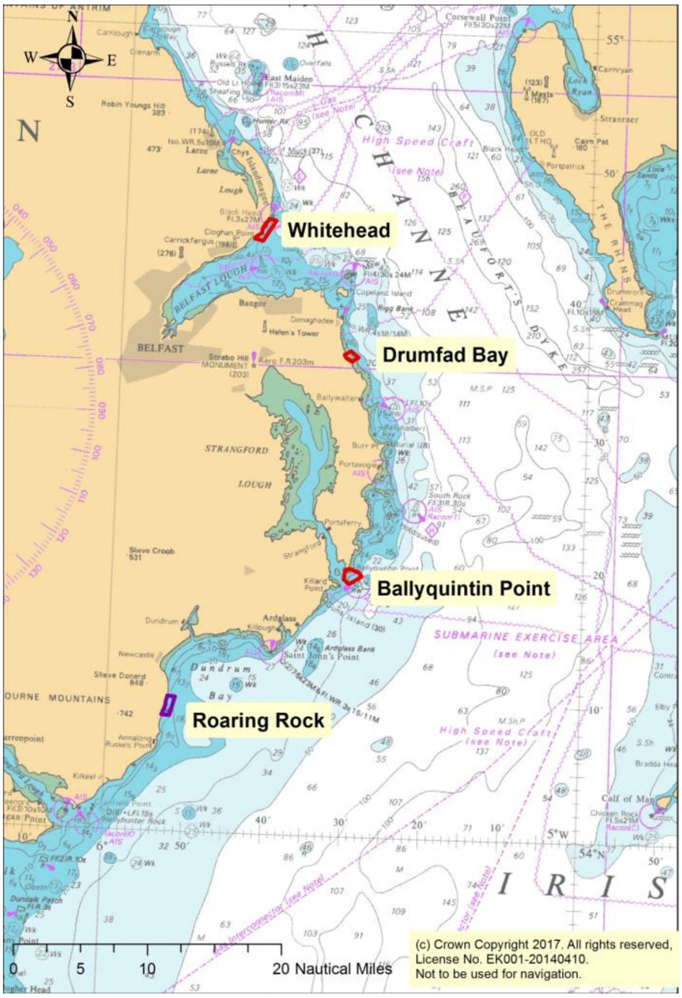

Figure 1: Sites selected for reseeding taking in to account the characteristics of the sites and feedback from the scallop fishing sector. Those outlined in red were drawn by the steering group and are ready for progression. The site outlined in purple (Roaring Rock) was a provisional extra site, with the boundary being an indication of a possible site.

To ensure that any/all sites selected for enhancement are given the best chance of success, AFBI have been funded by Seafish to assess further the possibility of enhancement including the pros, cons and costs of such a scheme. This work comprises of two Work Packages (WP).

Enhancement Options

This WP will comprise of a desktop study which will:

1. Review scallop enhancement in other regions to:
    - Outline the perceived positives and negatives of scallop reseeding
    - Discuss the logistics of scallop reseeding
    - Other scallop stock enhancement techniques used further afield including closed areas (Marine Protected Areas and other fisheries closures) without reseeding, and use of spat collectors
    - Propose monitoring to determine success
2. Make recommendations for scallop enhancement for the Northern Irish fishing industry

The review will outline if reseeding is the most suitable, cost effective method for enhancing the scallop stock in Northern Ireland inshore waters.

Larval Modelling

This WP will use hydrodynamic modelling to examine larval dispersal from the proposed reseeding sites which were selected during the initial 2017 report, providing a clearer indication of where scallop larvae would expect to settle. This will take the form of:

Phase 1: Particle tracking using fixed "die off" rates as a substitute for settlement rates. This will use models currently developed by AFBI. Whilst initially these models encompassed just the sea loughs, they have been extended to cover the area of the proposed reseeding sites.

Phase 2: An assessment on the feasibility of using "The Larval TRANSport Lagrangian" model (LTRANS v.2b) off-line particle-tracking model that runs with the stored predictions of a 3D hydrodynamic model. Whilst this is also a particle tracking model it also allows for larval characteristics to be included to simulate larval behaviour including vertical and horizontal movement, thus giving a more precise estimate of dispersal.

Phase 3 (outside the scope of this project; next FY): If Phase 2 proves feasible AFBI FAEB would develop this capability with new in-house modelling capability.

2.0 What are the options available

A number of methods have been used to enhance scallop stocks. Bell *et al*. 2008 expressed concerns that terminology used within this area is often confusing, with the terms “stocking”, “restocking”, “stock enhancement”, “supplementation”, “sea ranching”, “sea farming”, “reseeding”, “culture-based fisheries” and “enhancement” used interchangeably.

In addition to the above techniques, “simpler” methods have been used to enhance scallops. One such technique is spatial management, through the introduction of closed or protected areas. Spatial management has been categorised and described by the working group on evaluation of closed areas (Anon, 2007).

“Fisheries MPAs are spatially defined areas of the sea or an estuary where natural populations of commercial species (finfish and/or shellfish) are protected either in part or completely from exploitation and/or other detrimental human activities. Fisheries MPAS are a fisheries management tool e.g. for stock management and/or fish stock recovery. Fisheries MPAs can be permanent/non-permanent, gear type specific, fish species specific, vessel type/size specific, etc. There are two main subtypes of fisheries MPAs: closed areas and no take zones.”

“A closed area (aka ‘Fisheries Boxes’) is a fisheries management tool which relates to a sea area closed (either permanently or seasonally) to either a certain fishing gear (or vessel size), or for a certain target species usually for fish stock management/ recovery purposes. Since fishing is not totally prohibited, these boxes are not true no-take zones.”

“A No Take Zone (NTZs) is an area of sea that has been temporarily or permanently closed to all (not just some gear types) fishing to protect fish stocks and/or natural habitats. NTZ's can enable the ecosystem within the area to recover (at least partially) from the effects of fishing.”

For this report, the terms for the main methods described, will be as follows.

“reseeding” - the laying of juvenile scallops (either from natural collection or hatchery reared) onto the seabed.

“sea-ranching” - the enhancement of scallops in an area with the goal of fishing these scallops at a later date.

“closed areas” - an area which is closed to some/all fishing gears

3.0 Methods used in previous scallop enhancement initiatives.

A review of literature on scallop enhancement initiatives has taken place. This report provides examples of the scallop enhancement techniques used in eleven countries and includes cases of closed areas, reseeding and sea-ranching.

3.1 Northern Ireland

Reseeding

In 1999, the Centre for Marine Resources and Mariculture (C-Mar) identified six sites around Northern Ireland which, based on predator abundance and substrate type, could be suitable for seeding with juvenile scallops. At the time no scallops were present at any of the sites identified. Between February and April 1999 these six sites were seeded with scallops imported from Mulroy Bay, Ireland. Three of the sites received a further 70,000 scallops each in November 1999. Scallops were transported in fish boxes and damp packed (packing time was approximately 4 hours). The scallops were then transported by road, a journey which took around 3.5 to 4.5 hours before being transferred to the fishing vessels for seeding, a process which saw the fish boxes emptied over the side of the vessel. The following was reported at each site (all details taken from C-Mar report, 2000; Table 1 provides a summary of the results). During this work, no clear pattern of survival between different substrate types (from mud to firm sand) was recorded.

- Cloughan Jetty – immediately after reseeding, abundance on transects ranged from 0-110 scallops per 5m^2 with average density of 3.9±2.4 scallops per m^2. Dead scallops were at a density of 0.4±0.3 shells per m^2. One day post-seeding survival was estimated at 78%. Three months post seeding no live scallops were found. The percentage of scallops unaccounted for was 75%. Starfish abundance had decreased from 0.8 animals per m^2 after seeding to zero. No brown crab were reported.
- Groomsport Bay – One day post-seeding scallops were patchy, varying from 0-16 scallops per 5m^2 with and average density of 0.3±0.1 scallops per m^2. The survival was estimated at 12%. Three months after reseeding, the abundance of starfish increased from 0.6 animals per m^2 to 1.45 animals per m^2. Six months post seeding the abundance of scallops had increased significantly to 1.3±0.2 scallops per m^2. Survival was estimated at 52%. Nine months post seeding scallop abundance had decreased to 0.7 per m^2 and survivability to 14%. The percentage of scallops unaccounted for was 53%. Growth of scallops at this site was higher than for all other sites. A secondary seeding of scallops took place in November 1999, 75m south of the initial seeding site. Approximately 70,000 juvenile scallops were seeded. Two weeks later scallops were relatively evenly distributed with an abundance ranging from 1-18 scallops per 5m^2 with an average density of 0.7±0.2 scallops per m^2. The survival was estimated at 23%.The percentage of scallops unaccounted for was 68%.
- Ballyhalbert - One week post-seeding scallops were distributed patchy, varying from 0-80 scallops per 5m^2 with and average density of 2.7±1.7 scallops per m^2. The survival was estimated at 98%. Six months post seeding the abundance of scallops had decreased to 0.1±0.1 scallops per m^2. Survival was estimated at 5%. The percentage of scallops unaccounted for was 92%. Six months after reseeding the abundance of starfish, which had increased one month after seeding, was the same as that one week after seeding.
- Portavogie - One week post-seeding scallops were patchy, varying from 0-119 scallops per 5m^2 with and average density of 3.5±2.6 scallops per m^2. The survival was estimated at 76%. Six months post seeding the abundance of scallops had decreased to 0.4±0.1 scallops per m^2. Survival was estimated at 7%. The percentage of scallops unaccounted for was 86%. Nine

months after the seeding the abundance of scallops had decreased further to 0.3±0.1 scallops per m^2. A secondary seeding of scallops took place in November 1999, adjacent to the initial seeding site. Approximately 65,000 juvenile scallops were seeded. Two days later scallops were unevenly distributed with an abundance ranging from 0-175 scallops per $5m^2$ with and average density of 0.5 scallops per m^2. The survival was estimated at 15%. Throughout the trial, starfish numbers I the area remained low. However, brown crab numbers increased from 0.01 animals per m^2 one month after seeding, to 0.03 animals per m^2 six months after seeding.

- Newcastle - One month post-seeding average scallop abundance was 2.4±0.4 scallops per m^2. Only 9% of the seeded scallops could be accounted for. Six months post seeding the abundance of scallops had decreased to 0.7±0.2 scallops per m^2. Survival was estimated at 21%. The percentage of scallops unaccounted for was 64%. Six months after seeding, starfish abundance had increased to 0.18 animals per m^2 from 0.01 animals per m^2 one month post seeding. Seeding at this site was considered to be successful

  A secondary seeding of scallops took place in November 1999, 50m south of the initial seeding site. Approximately 65,000 juvenile scallops were seeded. One week later scallops were unevenly distributed with an abundance ranging from 0-250 scallops per $5m^2$ with and average density of 1.9±0.4 scallops per m^2. The survival was estimated at 59%.The percentage of scallops unaccounted for was 68%. Seeding at this site was considered to be successful
- Strangford Lough - One month post-seeding average scallop abundance was 4.5±1.3 scallops per m^2 equating to a survival rate of 76%. Three months post seeding the abundance of scallops had increased to 10.1±1.8 scallops per m^2. Survival was estimated at 100%. During this time a small increase in starfish was reported, with numbers increasing from 0.06 to 0.1 animals per m^2. Seeding at this site was considered to be successful

Table 1: Summary of findings from reseeding trails carried out in Northern Ireland in 1999. The table only indicates results from the first reseeding event. Those shaded are where reseeding was deemed successful (Source: Data taken from C-Mar report)

	Cloughan Jetty (50,000 seeded)		Groomsport (25,000 seeded)			Ballyhalbert (25,000 seeded)			Portavogie (50,000 seeded)			Newcastle (50,000 seeded)		Strangford Lough (30,000 seeded)		Mulroy Bay (130,000 seeded)			
Days after reseeding	0	69	1	69	163	5	42	147	5	42	147	34	149	31	97	0	15	128	182
Estimated number alive	39,200	0	2900	13786	13100	27000	20889	1333	34889	18000	3645	36636	10500	22700	50341	28200	43864	50250	16193
Average density - living scallops m2	3.9	0	0.3	1.4	1.3	2.7	2.1	0.1	3.5	1.8	0.4	2.4	0.7	4.5	10.1	1.9	2.9	3.4	1.1
Estimated number dead	4400	12800	400	2571	5175	600	4889	444	1556	1000	3509	8523	7500	2838	5079	2700	2833	6300	8148
Average density - dead scallops m2	0.4	1.3	0.04	0.3	0.5	0.1	0.5	0.04	0.2	0.1	0.2	0.6	0.5	0.6	1	0.2	0.2	0.4	0.5
% scallops unaccounted	13	74.5	87	27	27		35	92	26	62	86	9	64	15		76	64	57	81
Estimated survival (%)	78	0	12	55	52	98	76	5	70	36	7	73	21	76	100	22	34	39	12
Abundance starfish	0.8	0.23	0.61	1.45	1.27	0.1	0.24	0.1	<0.07	<0.07	<0.07	0.01	0.18	0.06	0.1	0.3	0.6	0.8	0.7
Abundance crabs	0	0	0	0.02	0.02	0	0	0		0.01	0.03	0.02	0	0.01	0	0	0	<0.1	

3.2 Isle of Man

Closed Areas

Scallops have been fished in the Isle of Man since 1937 (Brand *et al*. 1991). In 1989, with overfishing reducing stocks, the Port Erin inshore fishing grounds on the South West coast of the island were closed to fishing, an exclusion zone of almost 2km^2. Mobile gear was banned but static gear fishing was allowed to continue in the area. In 1989 when the closed area had initially been introduced, approximate scallop densities both inside and outside of the area were 0.5 animals per100m^2 (Beukers-Stewart *et al*. 2005).

In 1994, the closed area was used to examine the effects of scallop dredging on benthos (Bradshaw *et al.* 2001). As part of this work, scallops were looked at both inside and outside of the closed area. It was found that, whilst not significant due to high variation in numbers, and whilst there was an increase in numbers in both areas since previous studies, scallop abundance was consistently higher inside the closed area than outside where fishing was ongoing. Also, whilst the fished area was dominated by scallops 4 to 5 years of age, within the closed area there was a high proportion of scallops aged nine. Bradshaw *et al.* (2001) concluded that the scallop population in the closed area was starting to resemble a natural scallop population.

Whilst there initially was only a small increase in densities within the closed area, a study by Beukers-Stewart *et al.* (2005), showed that recovery of the scallops accelerated with the duration of protection, and by the early 2000's there were notable differences between inside and outside of the closed area. In 2003, the density of scallops in the closed area, as reported by diver surveys, was 14.05 animals per 100m^2, 4.85 times higher than the density on the fished grounds (Figure 2). For legal-sized scallops, the difference was even more significant, with densities in the closed areas being 7.76 times higher than those outside. The shift towards older, larger scallops within the closed area was noted, with 41.3% of scallops in the closed area being older than 5 years and 52.4% larger than 130mm. This is in comparison to 5.1% of scallops in the fished grounds being 5 years plus and only 11.9% being larger than 130mm. It was concluded in the study that this build-up of scallops within the closed area was significant for fisheries management, as the high densities within the closed area would enhance local reproductive potential and therefore larval export to fishing grounds. Indeed, scallop densities in the fished areas did also increased, though not as significantly (Beukers-Stewart *et al*. 2005). By 2006, scallop density in the closed area was 10 times greater than the fished area, and scallop biomass was twenty time higher (Brand, year unknown).

Whilst predation is a considered problem with closed areas, as they are also protected from removal and damage by fishing gear, the study of the closed area showed no significant difference in the density of predators, other than that of the common starfish *Asterias rubens*, a primary predator of scallops, between the closed and fished areas (Beukers-Stewart *et al*. 2005). Indeed, in 2003, abundances of the common starfish were found to be significantly higher in the fished area compared to the closed area.

These results were supported by Brown (2013), who analysed dive data collected from the closed area to examine differences in epibenthic megafaunal species composition between the fished and unfished area (Figure 3). Data used was collected over an eighteen year period, between 1989 and 2006, on a mostly annual basis. Within the closed area, as this current report has seen from other studies, the abundance of scallops increased. The common starfish was lower in the closed area than the fished area. With the increased abundance in scallop, diversity indices within the closed area showed a decline from 2002 to 2006 (however, this was only for a sub-set of species used in the analysis).

In 2008, Douglas Bay became the second area around the Isle of Man which was closed to fishing by mobile gear. Laxey Bay and Niarbyl Bay were also restricted to fishing for scallops (king and queen) and in 2009 Ramsay Bay was designated as a Marine Nature Reserve (MNR) thus becoming closed to fishing. These closures were supported by the Manx fishing industry (Brown, 2013).

The Isle of Man now have a network of 10 closed areas which includes fully protected marine reserves, static gear only areas and stock enhancement zones. It also has two scallop fishery closed areas.

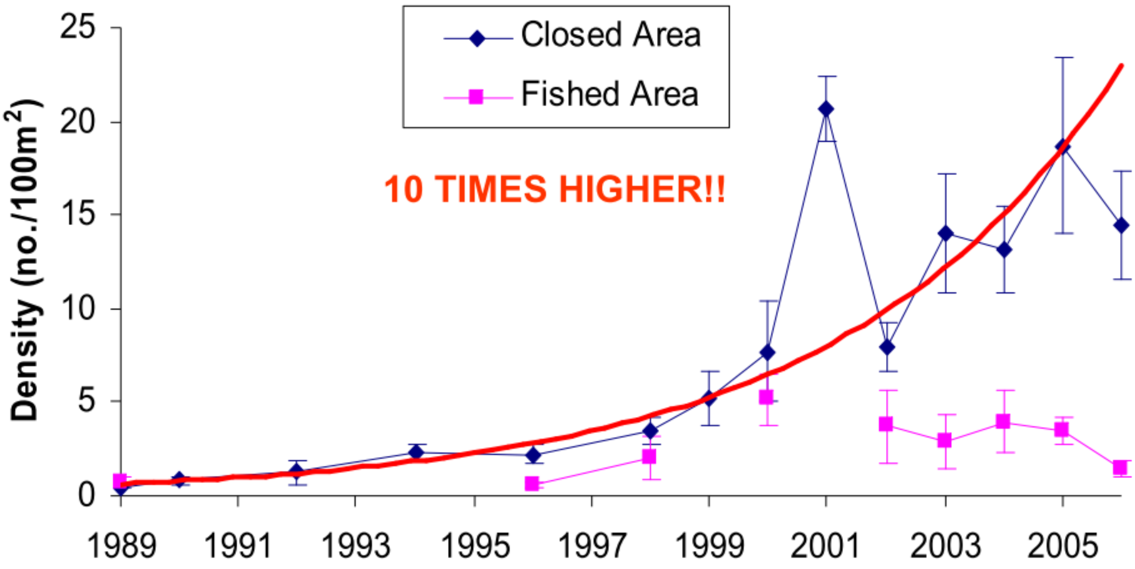

Figure 2: Density of scallops within and outside of the closed area from closure to 2006. (Source: Brand, year unknown)

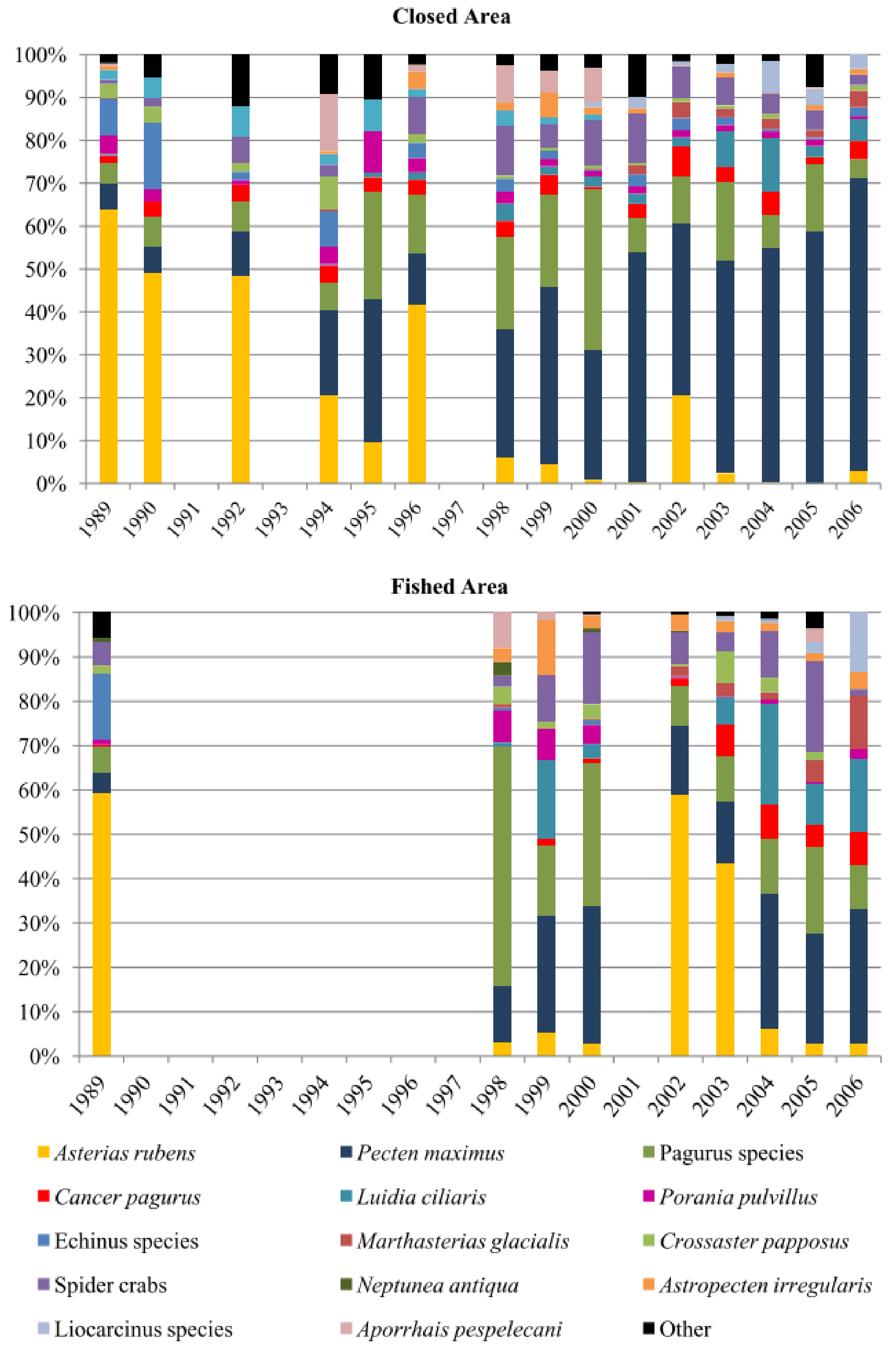

Figure 3: Proportional densities (mean no. per 100m^2) of the main invertebrate epibenthic species estimated by dive surveys in the closed and fished areas between 1989 and 2006 (Source: Brown, 2013).

Reseeding

To examine further enhancement of the scallop population in the Isle of Man, in June 2003 approximately 50,000 scallops were transferred to a small area of seabed (around 1 km^2), adjacent to the original closed area at Port Erin. The scallops came from the Isle of Skye and were transported using a vivier lorry (around 24 hour journey time). The scallops used as seed were mainly two (mean shell length 55mm) and three (mean shell length 69mm) year old. The scallops had been grown to this size via suspended culture. Prior to the area being reseeded, the area was dredged for four days to reduce the number of predators, and then dive studies were carried out to estimate the abundance of scallops. Following reseeding, the area was closed to fishing for three years. Beukers-Stewart *et al.* (2006) examined the effects of reseeding. After two weeks they found that scallops which were encrusted with epifauna had lower survival rate (33%) than clean scallops (60%). Also, the number of starfish and brown crab had increased in the seeded area 20-fold.

After three months the density of scallops in the seeded area had decreased to less than 1% of the original reseeded density. However, there was no increase in the density of dead scallops in the area. With the density of scallops outside the reseeding area increasing from 0.75 m^2 prior to reseeding to 5.0 m^2 three months post seeding, it would suggest that the reduction in abundance within the seeded area is due to the movement of scallops to outside the seeded area (Beukers-Stewart *et al*. 2006).

One year after reseeding, reseeded scallops were found up to 500m from the initial reseeding site and it was believed that re-seeded scallops accounted for at least 28 % of all scallops in the closed area (Brand and Beukers-Stewart, 2004).

By 2005, the density of scallops in the closed area (but outside of the re-seeded plot) had increased more than ten-fold since re-seeding, from 0.75 scallops per 100 m^2 to 7.99 scallops per 100 m^2 (Brand and Beukers-Stewart, 2005).

Hold *et al*. (2010) attempted to identify the contribution that the Port Erin reseeded site had on the neighbouring fishing grounds, in terms of larval dispersal, by looking at the genetics of both the native Isle of Man scallops and those from the Isle of Skye from where the reseeded scallops originated. However, no genetic differentiation was found between the Isle of Man and Isle of Skye scallops meaning that the offspring of the transplanted Isle of Skye seed could not be traced.

In 2009, Laxey Bay was reseeded with 100,000 juvenile scallops (age 1-2) from Mulroy Bay scallop farms, Ireland, whilst Niarbyl Bay was initially reseeded with 5,000 scallops (majority of which were between 100-120mm) captured from local fishing grounds and then, later in the year, by a further 110,000 wild scallops (Allison, 2016).

In 2016 Allison reported on findings from Laxey and Niarbyl Bays. It was found that in Laxey Bay scallop densities remained consistently low, even after reseeding. They attributed the lack of change to the limited timeframe of the closure (7 years) which may be insufficient to see recovery. Other possible reasons for the lack of recovery may be the site reaching carrying capacity, environmental factors, poor larval supply, low quality stock, lack of enforcement, high predation, inadequate scallop habitat (Allison, 2016). Allison (2016) found the reseeding of scallops was more successful in Niarbyl Bay which had a greater abundance of newly recruited juveniles. They believed this was due to the fact that Niarbyl Bay had a lower predator density, had a habitat associated with scallop nursery habitat, had been reseeded with wildstock (which believed to have a thicker shell and therefore be less susceptible to predation than cultivated stocks) and the seeded scallops were larger (107mm) so were less vulnerable to predation compared to smaller (51mm) cultured scallop that Laxey Bay was reseeded with (Allison, 2016).

Spat collection has been trialled in the Isle of Man at different locations. The collectors used were single line collectors anchored on the seabed with collectors (onion bags) attached at intervals. Settlement varied greatly between sampling sites, even those which were closed. Settlement was found to occur in peaks of short duration, primarily from mid-July to early August (Brand *et al.* 1991). However, the numbers were deemed not viable as they did not reach the minimum of 250 which was considered at the time by the Seafish Authority to be economic for small scale cultivation (Wieland and Paul, 1983).

3.3 England

Closed Areas

In Devon, an Inshore Potting Agreement (IPA) was established to reduce gear conflict. Whilst initially this was on a voluntary base, it was enforced by government legislation in 2002. The area protected by the agreement is around 500km^2. The area is split into an area which can exclusively be used by static gear fishermen targeting crab and lobster whilst other areas are open seasonally to mobile fishing gear including scallop dredges. Normal scallop fishing occurs outside of the protected area. Kaiser *et al.* (2007) examined the impacts that protection had on the scallop population in the area by comparing sites opened to scallop fishing year round, grounds which were closed to fishing but had been fished illegally within 18 months of the study, and sites which had never been fished by towed gear. They found that the mean abundance of scallops was highest in the non-fishing areas and lowest in the fished areas directly surrounding the IPA area. The abundance of scallops above the minimum landing size (MLS) was 12.83 times higher in areas from which mobile gear had been excluded compared to areas where fishing occurred either seasonally or year-round. Scallop abundance was also high in areas which were protected but had suffered short bursts of illegal fishing. However scallops in the illegally fished areas were smaller than those in the protected areas, perhaps with the larger scallops removed by the illegal fishing. Importantly noted was that the weight of the gonad of scallops from the protected areas was 19-24% higher than in the fished areas giving a "… reproductive output of up to 15.9 times greater than in areas that experience chronic scallop dredging…". This may result in higher spawning success, with egg size directly related to survivability (Kaiser *et al*. 2007).

3.4 Scotland

Spat Collection

Scotland is the primary area of scallop culture in the UK with a number of trials and commercial production ventures having taken place (Strand *et al*. 2016)

The use of systems to collect scallop spat was trialled along the west coast of Scotland during the 1980s. The collectors used were made from net bags of 6mm mesh containing microfilament netting which were suspended in strings. The work showed there was great variation in the number of spat settling on the collectors ranging from more than 20,000 scallops per string in the North West to 464 in the south west. Peak settlement was reported between 2-5m off the seabed and during the months of May to July (Fraser and Mason, 1987). Whilst not concentrated on Scotland, reasons outlined by Strand et al (2016) for irregular supply of spat globally include pollution, insufficient broodstock, sea surface temperature, water turbulence, hydrology and feed availability

From the above study, Raasay Bay off the Isle of Skye proved to be the area with the most consistent settlement and became the primary area in the UK for spat production, initially using suspended techniques and some bottom production. Spat or larger juveniles from this area were used in aquaculture and trials across other areas of Scotland and farther afield (Strand *et al*. 2016).

Closed Areas

In 2008, off the Isle of Arran, Lamlash Bay No-Take Zone (NTZ) was introduced. The area is 2.67km^2. Examination of the site four years after closure showed that important nursery habitats such as hydroids were two times as abundant inside the NTZ when compared with outside. This increase in habitat complexity led to increased scallop settlement, with juvenile scallops being 350% more abundant inside the NTZ than outside. The density of adult scallops has also increased, and in 2012 legal sized scallops were 60% more abundant in the NTZ. Further evidence of success was the 185% greater reproductive biomass of scallops (weight of scallops which are sexually mature) within the NTZ than on adjacent fishing grounds (Howarth and Stewart, 2014). This is due to the increased abundance of larger and older scallops within the NTZ

Hatchery

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. Scot-Hatch 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). Scot-Hatch 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).

In the south-west of Scotland seabed grow out of spat was recently trialled. The scallop spat of around 35-45mm was stocked on the seabed at densities of 5-10 scallops per m^2. This meant that initially each hectare of seabed was being seeded with approximately 100,000 spat. These numbers however, reduced due to natural mortality and predation. During this work they showed that survival rates were increased by using creels to remove crustaceans (mainly crabs) as a form of predator removal. Time to MLS is usually around four years, with current harvest by divers (Strand *et al*. 2016).

3.5 Ireland

Spat Collection

In Ireland the main source of cultivation is Mulroy Bay on the west Coast. Here, spat collected naturally from collectors is used to support grow-out and cultivation of scallops (Strand *et al.* 2016). This area first gleaned interest when, in the 1970s, significant numbers of scallop spat were reported attached to ropes deployed for mussel cultivation. Cultivation began in the area in the 1990s and continues today with a five-year rotational harvest (Strand *et al*. 2016). In events of high spat availability, spat from the area is also supplied to other areas, including the UK and France, for reseeding purposes. This is in despite of findings that scallops from Mulroy Bay are distinct from others

3.6 Japan

Spat Collection

Culture of the Japanese scallop, *Patinopecten* (*Mizuhopecten*) *yessoensis*, represents a quarter of global scallop production (Miyoshi *et al.* 2019). Bell *et al.* (2006) described the Hokkaido scallop fishery as "… undoubtedly the greatest success story in marine stock enhancement…" with the enhancement providing consistent annual harvests of around 300,000 tonnes per year. In Hokkaido, the hanging culture of scallop engages around 1300 vessels (Kosaka, 2016). The success of this fishery is attributed to its simple and effective methods for catching and rearing massive numbers of spat, ideal habitat for growth of scallops, survival rates for spat of greater than 30%, removal of predators, and, involvement of the fishing industry directly through financial, monitoring and enforcement roles (Bell *et al.* 2006).

In Japan, natural spat collection has been used successfully since the 1970s being used for both hanging and bottom cultivation. The success appeared after a change in technique of collecting juvenile spat. Whilst historically spat had been captured by placing bunches of cedar leaves in the water, onion bags filled with mesh were introduced (Uki, 2006). The scallop spat can enter the bag to settle on the internal mesh. The spat then grows and becomes too big to escape. Predation is low as not only can predators not access the internal mesh of the onion bags, but with scallops kept above the seabed, predator access to the bags is minimal (Kleinman *et al*. 1996). The style of bag can also be changed to minimise predation (Kosaka, 2016).

With the collection of natural spat being the key to the success of the fishery, effort is placed on this stage of this process which Kosaka (2016) described in four stages.

1. Monitoring of the gonad index (weight ratio of the gonad to soft body) to estimate time of spawning;
2. Monitoring larvae to determine where and when to set the collectors;
3. Setting collectors where the larvae are common;
4. Counting and measuring attached collected spat to plan for timing of intermediate culture.

Approximately three months after settlement, when the spat are about 10 mm shell height, they are harvested from the collectors and transferred to intermediate culture in pearl nets at a density of 50-60 spat per net (FAO, 2020). This period is known as intermediate culture or 'chukan-ikusei' (Kosaka, 2016). After 10 weeks, the seed will have grown to 20-30 mm. With survival rate of 90% being common the scallops require thinning to 15-20 scallops per net. This continues until the scallops have grown to around 50 mm when they will be transferred to the grow-out stage (FAO, 2020). Figure 4 provides a schematic of the Japanese culture method.

Grow-out to market size is either by sowing year-old seed on bottom lays (as part of a rotational fishery) or in various forms of hanging culture. In suspended culture scallops may be grown out in pearl nets, lantern nets or ear-hung. Scallops are often ear-hung in pairs from either horizontal lines in shallow water or vertical lines in deeper conditions when they are approaching 10 cm in size. In this method a hole is drilled in the ear of the shell and a loop of thread is passed through the hole and attached to vertical or horizontal lines in shallow water lease areas. In suspended culture, marketable sized scallops (100 mm) are available for harvest in year 2-3 (earlier in more favourable conditions of food supply and temperature).

Reseeding

When seed quantity is surplus to suspension culture requirements, the excess from nursery culture at 20-30 mm shell height is sown on bottom lays. Bottom lays are usually sown with around 50 mm seed in March at densities of 5-6/m^2. When production initially took off, the carrying capacity was exceeded (when adult densities on the bottom were higher than 10 scallops per m2) which led to mass mortalities (Dao, *et al.* 1999).

Before seeding the area, measures are taken to remove starfish and urchins, using a mop dredge, and octopuses, using pots or longlines (Kosaka, 2016). If high densities are reducing the growth rate, the area will be thinned to reduce densities.

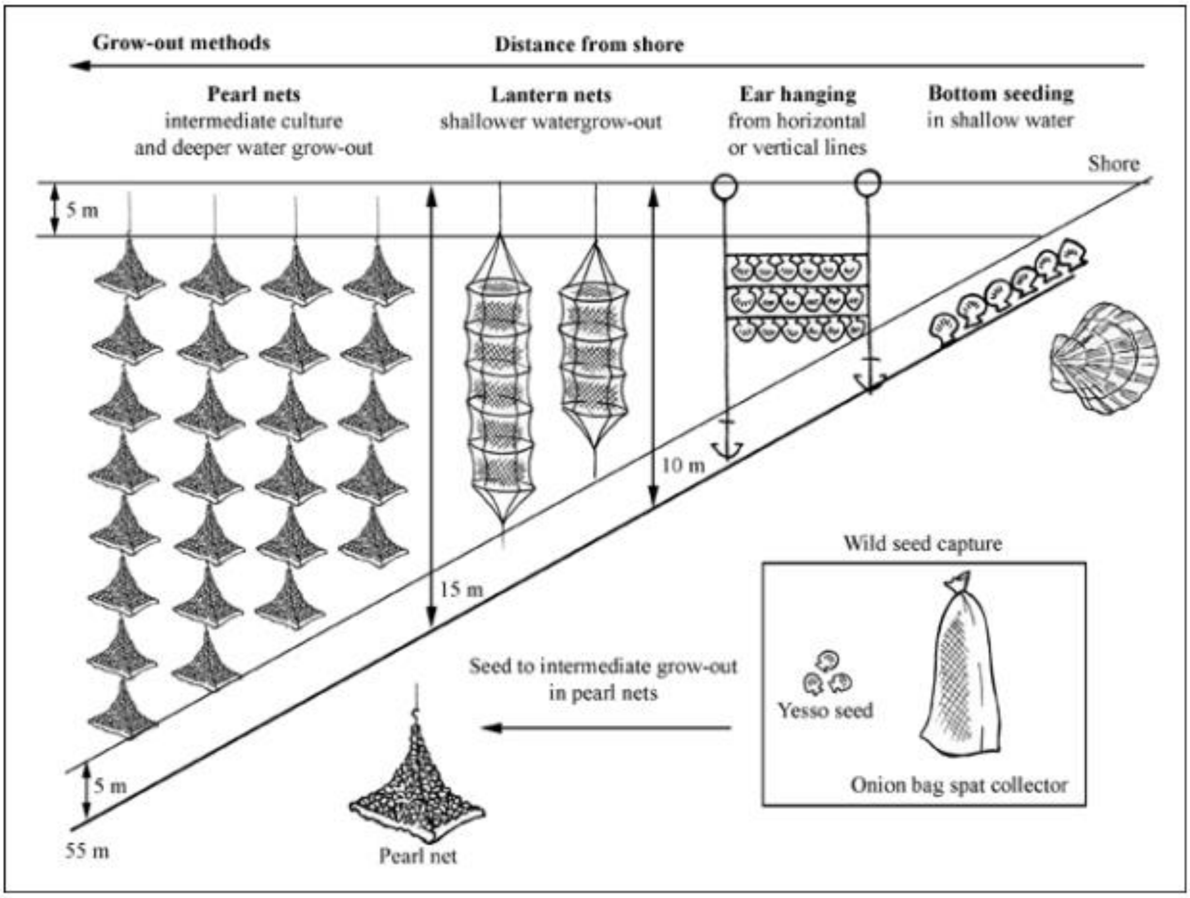

Figure 4: Production cycle of *Patinopecten yessoensis* (Source: www.fao.org)

3.7 China

Spat Collection

China is the world leader in scallop aquaculture, where a number of different scallop species are cultured, including the native species *Chlamys farreri* and *Mimachlamys nobilis*, as well as non-native scallop species including *Argopecten irradians* and *Patinopecten yessoensis*. The details on the Chinese scallop culture of scallops is taken from the review provided by Guo and Luo (2016). Initially, the culture of scallops in China was based on hatchery produced seed. However, as aquaculture grew, cultured populations were so big they provided a large broodstock that allowed for natural seed collection. Now there is little hatchery produced spat in China. In terms of spat collection and grow out, the techniques used are similar to those described for Japan. For the Chinese scallop, the culture process takes around 20 months. In May larval settlement is investigated before placing spat collectors in the water in June. Spat in collectors is left to around October when, at around 5-10mm, they are over-wintered in lantern nets until February. When they reach 30mm they are ready for grow out, also primarily in lantern nets, which lasts until harvest in November/December when the scallops are 60-70mm.

3.8 France

Reseeding

In the Bay of Brest, with scallops being depleted, hatchery reared scallops are used to enhance stocks. In the 1970s the French carried out experiments to try and catch natural spatfall on collectors. However, the numbers caught were not sufficiently high. After the failure and trialling of seeding of spat imported from Scotland and Ireland, they began using hatchery reared spat (Strand *et al*. 2016). The initial programme was slow to start as for the first twelve years the aquaculture output was limited and suffered fluctuations. However, by the end of the 1990s production had increased and in 2000 10 million juveniles were sown in to the Bay of Brest (Alban and Boncoeur, 2008).

The juveniles (from the hatchery) are held in cages at sea for 6-10 months until they reach 3cm (Fresard and Boncoeur, 2006). Once at the required size (3cm) they are seeded on fishing grounds during the summer, when there is a fisheries closure which allows the spat time to grow and for their shells to strengthen (Dao *et al*. 1999). Some of the juveniles are laid on natural beds whilst others are laid on an area closed to fishing for a period of three years at a time. The juveniles are laid at densities of 1-3 individuals per m^2 (Dao *et al*. 1999). These scallops reach harvestable size at around three years old when they can then be fished. This enhancement, which has been ongoing since 1983, was initially introduced to enhance natural recruitment in the area but has reoriented towards sea-ranching, and at the start of the 2000s, accounted for two thirds of scallop landings from the area (Fresard and Boncoeur, 2006). These scallops reared through aquaculture can be identified by the presence of a stress ring on their shell due to the relaying process (Fresard and Boncoeur, 2006).

Morvezen *et al*. 2016 examined scallops from wild beds in the Bay of Brest France, which are seeded by hatchery produced spat. They found that the genetic stability in allelic richness was maintained in the wild populations. They suggest that this result may be due to the care taken in the hatchery which includes renewing the broodstock annually. Hold *et al*. 2013 also examined the potential effects of enhancing scallop stock with hatchery reared seed. They concluded that, prior to seeding a site with hatchery reared seed, there should be an idea of the population size so that the effect can be estimated. They found that if the population of native animals was less than 10^8, enhancing the area with even a small number of hatchery reared seed has the potential to have negative effects on the effective population size by reducing the resilience of the population to the conditions they had previously become adapted to and thus reducing survival rates.

The restocking of scallops in the Bay of Brest has been threatened by the invasive species *Crepidula fornicata* (slipper limpet) which was accidently introduced in the 1940s. The slipper limpet threatens the scallop fishery in the area due to competing with the scallops for space thus reducing suitable habitats for scallops. Also, it reduces the income to the fishery as fishers have to scrape the scallops clean on the vessel which costs an average of 15.5 hours of fishers' time per tonne of scallops (Fresard and Boncoeur, 2006), time which could otherwise be spent fishing.

3.9 America

Closed Areas

In 1994, following reduced number of several fish species, 17,000km^2, split over three areas, on Georges Bank, was closed to all mobile gear, including scallop dredges (Figure 5). These areas were initially closed to protect groundfish species including cod and haddock. At the time when the closed areas were created, landings of scallops (*Placopecten magellanicus*) from Georges Bank were near the time-series minimum (Murawski *et al.* 2000). By July 1998 scallops had increased in abundance with densities inside the closed area being 14 times greater than those in adjacent open areas and of a bigger size class (Murawski *et al*. 2000; Stewart and Howarth, 2016). In 1999 a video camera survey observed densities of scallops within the three closed areas ranging from 0.25 to 0.59 scallops/m^2 (Stokesbury, 2002). The scallops in the area were large and, with an estimated abundance of 650 million scallops, estimated abundance within the areas surveyed (1,938 km^2) was 17,000 tonnes (Stokesbury, 2002).

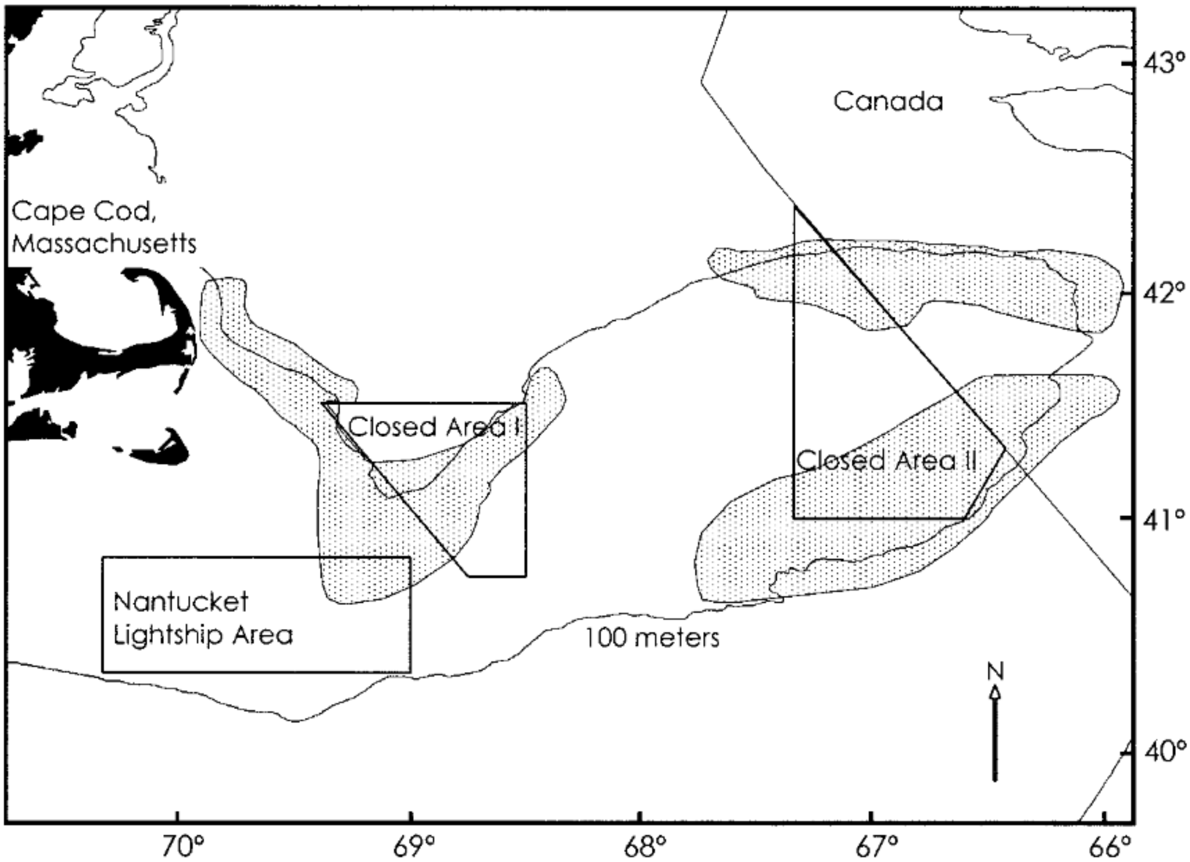

Figure 5: Map of Georges Bank showing the three closed areas (Closed Area I, Closed Area II and Nantucket Lightship Area). The shaded area represents historic scallop fishing grounds (Figure taken from Stokesbury, 2002).

By 1998 increases in biomass, Landings per Unit Effort (LPUE) and landings became evident in the areas outside the closed areas on Georges Bank and have remained at record levels since 2001 (Hart and Rago 2006). With shucking at sea, catch rates exceeded the capacity the shucking capacity of a seven man crew (Hart and Rago, 2006). It is important to note that at this time closures were not the only management in place. There was also limited access, effort reduction and crew size limitation, but Hart and Rago (2006) felt that “Area closures induced the most striking effects on sea scallop abundance and biomass”.

One of the three areas closed in the Great South Channel is the Nantucket Lightship Closed Area (NLCA). This MPA, which is 6167 km^2, has some of the highest densities of scallops ever observed on Georges Bank, an average of 1.67 scallops per m^2 (Stokesbury *et al*. 2007). Due to the high densities of scallops, a short term fishery was allowed between August and October 2000, when 584 tonnes were harvested.

In 2004 formal rotational management of scallops was introduced, establishing four types of area which have moveable boundaries (Stokesbury *et al*. 2016).

1. Open areas (managed through days at sea which is assigned annually based on fishing mortality targets).
2. Year round closed areas
3. Temporary closed areas to protect small scallops until they reach commercial size (areas identified by industry/surveys.
4. Access areas, areas open to the Limited Access fleet for restricted fishing (currently five: Nantucket Lightship, Closed Area I, Closed Area II, Hudson Canyon, Elephant Trunk, Delmarva)

Hart (2003) examined the impacts of the short-term rotational fisheries on scallops. They explained two types of rotational fishery: pulse rotation and symmetric rotation. They found that a more substantial gain in maximum yield-per-recruit (up to 30% greater than constant fishing) can be obtained if the rotational closure is timed to exploit an unusually large year class, with the only costs being through administration and enforcement of the system. In their study, symmetric rotational gave less benefit than pulse rotation.

Stokesbury and Harris (2006) examined the impact that these short-term fisheries had on the epibenthic community of Georges Bank closed areas. They carried out a before-after-control-impact (BACI) study coinciding with the initial short term fishery in 2000. They found that changes in the biodiversity of the fished area were similar to those reported from the closed area, which were due to natural disturbance. Numbers of scallops, bryozoans and hydroids increased in both the fished and unfished areas over the study period. Sponges were the only taxa shown to increase in the unfished area and decrease in the fished area. They suggested that the limited differences in the areas were due to the fact that scallops, and many of the species associated with them, tend to live in high energy environments and so are adapted to some disturbance. Also, to note that the dredges used are New Bedfords which sit on two shoes and slide over the seabed, causing lower impact that toothed dredges (Stokesbury and Harris, 2006).

Scallop stocks on Georges Bank are surveyed annually using video surveys. These surveys, reported by Stokesbury *et al*. (2007) showed that, in the NLCA MPA, the mean scallop density significantly increased between 1999 and 2002, remained constant from 2002 to 2004 and then decreased by 50% between 2004 and 2005. This decrease equated to approximately 6484 tonnes of harvestable scallop meat, worth about US $100 million (Stokesbury *et al.* 2007). A drop in scallop abundance in the NLCA MPA had been predicted due to natural mortality as a high proportion of the scallop were old, there was limited recruitment in to the area, scallops abundance tends to fluctuate cyclically, and mass mortalities have occurred historically. At the time predation by starfish was not felt to be the problem as the scallops were large and had outgrown the risk of predation. However, during the short fishery in 2004, fishermen reported cases of scallops infested with boring sponges (*Cliona vastifica*) and polychaete worms (Polydora species) which can weaken the shell increasing the predation risk. Also, meat was reported to be grey, flaccid and stringy which could have been caused by clionid infestation or prokaryotic infection (Stokesbury *et al*. 2007).

The success of scallops on Georges Bank has been further helped by extreme recruitment events. In 2014 mass recruitment led to an estimated 31 billion recruits present on Georges Bank, with a total scallop population of 39 billion (Bethoney *et al.* 2016).

Whilst the closures have provided large scallop densities within the protected sites, the increase in the scallop population did not significantly alter the recruitment on Georges Bank (Tian *et al*. 2009).

Tian *et al*. investigated the dispersal of scallop larvae from the closed sites using an individual-based population dynamics model (IBM) of sea scallop coupled with the hydrodynamic model FVCOM to track the drift and dispersal of larvae during their pelagic phase in the area. In the area there are three major systems which make up the current framework. They showed that, in the American regions, the three closed areas contributed 60% of the total spawning. With scallops in the closed areas being bigger and therefore more fecund than those outside, total spawning may be even higher than the 60% predicted by the model. The model showed that, due to the three primary currents in the area, high retention of larvae was apparent in the northern and north-western areas of Georges Bank (Tian *et al.* 2009).

Davies *et al*. (2015) also examined scallop larval dispersal from the closed sites on Georges Bank. They found that closed areas CAI and CAII appeared to be the most important in terms of fecundity and larval dispersal. Within these two areas egg densities was found to increase by a factor of 100 in some areas. Whilst they found increases in larval settlement both within and outside of the closed areas, larval loss was still high, estimated at 99.91%, due to mortality, unsuitable settlement substrate and loss from site through dispersal. Based on the models produced, areas CAI and CAII were shown as the most important larval sources to other areas of Georges Bank. The larval supply to these areas thus benefited the fishing areas (Davies *et al*. 2015).

In surveys carried out from 2000-2003, to examine predation on Georges Bank reported that sea star densities were greater in the closed area (0.13-0.6 animals per m^2) that the open areas (0.04 to 0.34 animals per m^2) (Marino II *et al*. 2007).

In 2009, Stokesbury *et al.* (2010) examined scallop (*P. magellanicus*) densities at Fippennies Ledge, Jeffreys Bank, Jeffreys Ledge and Cashes Ledge, sites which had been closed to scallop fishing since 2002. They also looked at scallop densities on Platts Bank which has had little or no scallop fishing since the 1980s. All these areas are in the Gulf of Maine. They expected similar results to what was achieved at Georges Bank. They found that these sites in the Gulf of Maine had scallop densities ranging from 1.56-61.5 scallops per m^2, 2.6-18.8 times higher than those reported on Georges Bank in 1999, four years after closure. They reported high densities of small scallops and a lack of large individuals, relating this to irregular recruitment and growth limitation due to the high densities (Stokesbury *et al.* 2010).

From 1998 to 2001, two areas were operated as rotational fisheries in the Middle Atlantic Bight. These measures, alongside strong recruitment to the area, saw increases in scallop biomass by an order the magnitude between 1997-2005, with marked increases in landings and LPUE (Hart and Rago, 2006).

Whilst Georges Bank has proved a success, other examples in America have not proven as effective. Tuya *et al*. (2000) examined the effectiveness of Marine Protected Areas in the San Juan Islands, Washington, USA. For the study they compared three research preserves which had been established eight years prior and from which marine organisms could only be removed for research purposes; two MPAs which had been established one year prior to the study, which were voluntary no-take zones except for salmon; three sites with no protection. They found no differences in abundance of species, including scallops (*Chlamys rubida*, *Chlamys behringiana* and *Hinnites giganteus*) between the sites. They attributed this to the protected sites being poorly situated, with poor larval supply to the areas due to unfavourable currents leading to a lack of recruitment (Tuya *et al*. 2000).

In North Carolina, Peterson *et al.* (1996) tested the hypothesis that stocks of the bay scallop *Argopecten irradians*, had not recovered following a red tide outbreak as they were recruitment limited. To examine this, between 1992-94 they transplanted 385,000 adult bay scallops from a site where they were abundant to the test site with low abundance. The transplantation of scallops was found to enhance the adult densities in the sites from less 1 in 1992 and 1993 to 15 per m^2. Recruitment at two of the four sites was 568% greater than before the scallops were laid, whilst in the control sites it was only 34%. With restoration of the bay scallop still taking place, alongside enhancement of the stock by releasing cultured larvae, since 2000 there has been a slow recovery of stocks (Robinson *et al*. 2016).

As part of their research, Peterson *et al*. (1996) also examined survival of scallops in transport to the relaying site, a period of six hours. The scallops were collected by hand, transported one hour by boat in plastic collars and then held either:

1) Out of water under refrigeration at 10°C;
2) In mesh bags used as controls suspended in the waters of central Bogue Sound from the dock on which flow treatments were also established;
3) In a flow-through seawater system with flow rate of 0.267 1 S-' sufficient to retain ambient O_2 concentrations;
4) In the same flow-through seawater system but with flows reduced to 0.028 1 S-' so that O_2 concentrations were allowed to fall by 50 percent;
5) In the same flow-through seawater system with a flow (0.067 1 s-') and O_2 concentration intermediate to the fast- and slow flow conditions.

The results (figure 6) show that the highest mortality was attributed to those scallops held under low flow conditions. Those transported in refrigeration of in high flow showed mortalities of around 10%. Based on the results Peterson *et al*. (1996) believed that the scallops could survive longer than the 6 hours of the trial duration.

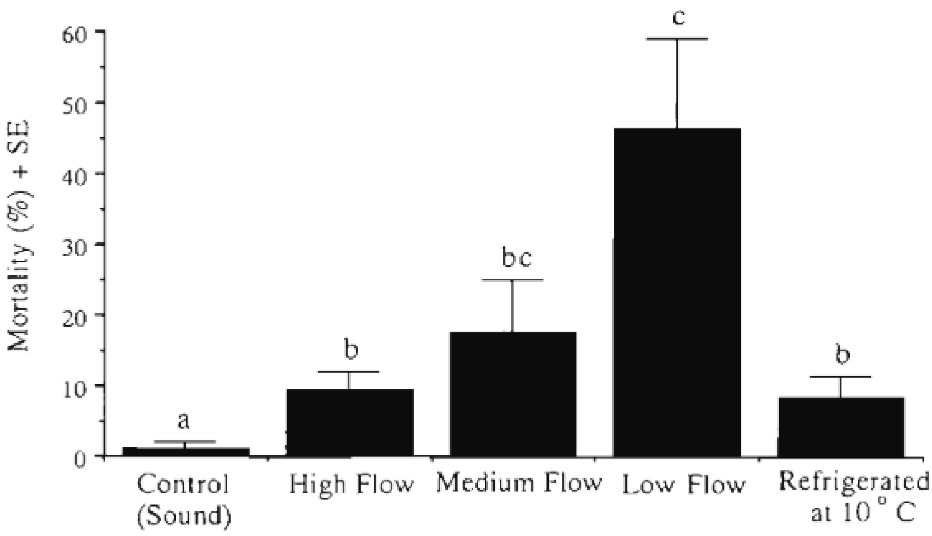

Figure 6: Mortality associated with scallops held under different conditions which mimic potential transport conditions (Source: Peterson *et al*. 1996)

On the west coast of America cultivation of various species of scallops has been trialled but with little success (described by Parsons *et al*. 2016). For pink and spiny scallops, whilst natural spat could be collected, the spat was mixed with rock scallop spat. Also growth was too slow for the process to be economically viable. Whilst the Weathervane scallop has a fast growth rate which would lend itself to cultivation, collection of juveniles naturally was not possible and hatchery rearing of this species is difficult. Whilst there is the capability to rear spat of the rock scallop in a hatchery, the problem comes with getting this spat through the nursery and growout stages in an economically viable manner.

3.10 Canada

Reseeding

Reseeding was trialled near Lunenburg, Nova Scotia with experiments carried out by Hatcher *et al*. (1996). Prior to any reseeding work, the natural density of scallops in the area was 0.4±0.11 per m^2. In November 1990, over 10,000 juvenile *Placopecten magellanicus* (ranging in size from 4 to 26mm) from a commercial hatchery were put on to an unconditioned natural seabed. On initial reseeding, scallops dispersed rapidly but with little mortality. However there was evidence that in the first few hours after reseeding, predators aggregated in the area. The density of starfish within the $40m^2$ scallop release site increased from 150 to about 2000 within 6 days of reseeding whilst the number of crab increased from two to 150. Within the first 5 days there was an estimated mortality of 24% on the scallop seed. However, whilst a proportion of this is attributed to predation, there is also the possibility that a large proportion of this mortality was due to handling mortality. After one year 40% of the seeded scallops were alive within about 100m of the reseeded site. A two to five fold increase in total scallop density was recorded (up to 2 per m^2).

Also in Lunenburg, Nova Scotia, in the 1990s further reseeding was trialled and is reported on by Barbeau *et al.* (1996). Two sites were seeded with juvenile scallops in late summer 1991 (5,600 scallops from a hatchery and 16,000 scallops from spat collectors released at each site) and late winter 1992 (18,000 scallops reseeded at one site and 13,000 scallops at the other, all from spat collectors). Displacement of seeded scallops increased over time after each seeding event, with displacement quicker during the summer reseeding and slowing as water temperatures decreased. This dispersal was noted to be more of a diffusion process, not influenced by local hydrodynamics. Predation was found to be the major cause of loss of seeded scallops, with crabs being a more important predator of seeded scallops than starfish (Barbeau *et al.* 1996).

To examine predation on seeded scallops, Wong *et al*. (2005) carried out an experiment in New Brunswick, Canada, in 2001 and 2002. Juvenile scallops (16.0 ±4.9mm shell length) were hand seeded onto the experimental plots at either a density of 6 scallops per m^2, or 69 scallops per m^2, plus a reference plot that was left unseeded and had a natural density of 1 scallop per m^2. Whilst scallop densities were different initially, by day nine there was no longer differences in densities. Estimated dispersal rates ranged from 17-58% (Wong *et al*. 2005).

The main sources of predation on these sites were sea stars and crab. The initial density of reseeded scallops did not affect the density of starfish or crabs. Whilst starfish density was not affected by the time of seeding, crab densities were highest 1-4 days after seeding (Wong *et al*. 2005).

In addition, to examine alternative prey species, scallops were hand-seeded on plots at 5 scallops per m^2. Mussels at different densities were then added to these alternative prey plots. Whilst the density of mussels had no effect on the density of crabs on the reseeded plot, starfish were more abundant on the site seeded with 5 mussels per m^2 rather than 30 mussels per m^2. The presence of mussels may have provided short term protection for the seeded scallops as mortality of scallops seeded alone was higher than for those seeded with mussels (Wong *et al*. 2005).

The use of pearl nets was trialled for the giant scallop in New Brunswick by Parsons and Dadswell, 1992). One year old scallop spat was obtained from spat collectors. All spat used was 10-15mm shell height. Scallops were stocked at varying densities in pearl nets, ranging in densities from 15-90 spat per net (equivalent to 136-818 spat per m^2). The scallops were sampled at 5, 8 and 12 months to investigate the impact of the stocking density. The scallops held at the lowest density showed faster growth, were heavier and had greater meat yields in comparison to those at the higher densities. With space not being the limited factor in this experiment, food availability was believed to be the critical factor affecting growth. Mortality was not an issue at any of the densities, with the only mortality arising initially due to the handling of the scallops.

3.11 New Zealand

Reseeding

In 1983, there was large scale seeding of the scallop *Pecten novaezelandiae* in Golden Bay, New Zealand. Natural spat was set on catching bags on longlines. The spat was allowed to grow for several months before being transported to growing sites in bulk bags which are periodically sprayed with seawater, then released directly by shaking over the site. Additionally, scallop spat which has attached to the outside of the collector bags and then fell off to the seabed beneath, are recaptured using modified dredges and used for seeding (Mincher, 2008). In 1992, more than 1 billion spat were released from collector beds on to the seabed and 204 million scallops were transplanted onto grow out sites from intermediate sites (Dredge *et al*. 2016).

Handley *et al*. 2016 reported on the mortality of scallops due to the handling process of reseeding. They found that scallop of or greater than a certain size (25.9mm) were robust to handling processes which involved emersion for at least 6 hours. They reported a mortality of all spat handled during the experiment of 7.5%. This is much less than had previously been predicted and led to the conclusion that the current simple transport methods used for reseeding do not adversely affect the survival of spat for reseeding (Yandle, 2006).

In 1989, after seeing the promise of reseeding, industry agreed to pay an additional levy to support the enhancement programme (Yandle, 2006). Following from this and with the introduction of the quota management system, control of the enhancement programme became the responsibility of the commercial fishers (the quota owners). The Challenger Scallop Enhancement Company was established by the fishers to govern the fishery. Since 1996 there has been additional management of the fishery including an additional levy on quota holders, a daily catch system and dockside monitoring. The Company has also commissioned an enhancement and research vessel aimed at improving the success of seeding and management of the fishery. Annual catch limits set by area are in place each year based on survey and assessment results (Dredge *et al*. 2016).

4.0 Lessons Learned

4.1 Closed Areas

The application of closed areas has been used as a method to enhance or improve the conditions of commercial species, protected species and/or designated environmental features. Indeed, based on the case studies shown in this report across the UK, the introduction of closed areas appears to be the primary method used to enhance a species or feature. The use of spatial management has been described by Stewart and Howarth (2016) as "spectacularly successful" when implemented for scallop fisheries and Hilborn *et al*. (2004) described that, for sedentary species, marine reserves can provide "significant benefits in some cases". As indicated by Beukers-Stewart *et al*. (2005) the characteristics of scallops, relatively sedentary which allows for retention in the closed area, increased fertilisation success in high densities, long-lived larvae allowing for dispersal outside of the closed area, makes them likely to benefit from closed areas. Halpern and Warner (2002) supported this by suggesting that due the biology of scallops, closed areas should result in significant increases in average levels of density, biomass, and likely diversity within 1–3 y, and these values persist through time. Ward *et al.* 2001 provide a useful schematic on how closed area can lead to enhancement of a species within the protected area and for the nearby fished areas.

Also, the implementation of closed areas allows the habitat within the protected area to recover and become more complex, with species such as hydroids and bryozoans becoming more established. This provides benefits to scallops by providing increased settlement structures for scallop spat.

Botsford *et al*. (2003) provided the principles of how closed areas can be effective:

Principle 1: The effects on yield per recruit of adding reserves is essentially the same as increasing the size limit.

Principle 2: The effect on yield of adding reserves is essentially the same as decreasing fishing mortality.

Principle 3: Reserves for preserving biodiversity are most effective for species with low rates of juvenile and adult movement, while reserves for fishery management are most effective for species with intermediate rates of adult movement.

Principle 4: Larger fractions of coastline in reserves are required for species with longer dispersal

In a review of literature on the direct and indirect effects of closed areas, Babcock *et al.* 2010, reported that in 78% of the studies examined, populations of exploited species increased over time in reserves, with effects appearing within five years of the introduction of protection. Following on from this initial increase results then became mixed with examples of reserves which continued to increase, others which stabilised, and ones which declined after the initial increase. They also showed that recovery of the fished species on occasions led to indirect effects on other species in the reserve. However these were slower to appear, taking up to thirteen years or longer (Babcock, et al., 2010).

Molloy *et al.* 2009 showed similar results on the effectiveness of marine reserves. The review highlighted that older reserve effectiveness increased significantly with reserve age. Indeed, only reserves that were more than 15 years in operation reliably increased the overall fish densities (Molloy *et al*. 2009)

Whilst spillover of adult animals may not be a significant advantage of closed areas for highly sedentary species, larval dispersal could be a significant factor in improving the stock outside of the closed area. Nowlis and Roberts (1998) used fishery population models to assess the potential for areas permanently closed to fishing to enhance long-term fishery yields. From the model they concluded that, for species which have larvae capable of dispersing widely across reserve boundaries and adults which do not move across reserve boundaries, "marine reserves will provide catch enhancements to any overfished fishery…".

A review prepared by Halpern (2003) reported that "…*that marine reserves, regardless of their size, and with few exceptions, lead to increases in density, biomass, individual size, and diversity in all functional groups"*. They found that the diversity of communities and the mean size of the organisms within a reserve are between 20% and 30% higher relative to unprotected areas and the density of organisms is roughly double in closed areas, while the biomass of organisms is almost triple.

Whilst there is a mass of literature on the benefits of closed areas, problems can arise within closed areas. Habitat quality and predation risk can greatly affect the success of a closed area (Ward *et al*. 2001). Stokesbury *et al*. 2007 highlighted that the carrying capacity of an area (resource availability, recruitment, inter- and intraspecific interactions, and space) will feed in to the success of a closed area. When these factors become limiting, increased natural mortality will reduce population growth within the closed area (Lizaso *et al*. 2000). In addition, scallops, like other marine bivalve populations suffer natural mortality from many sources, including abiotic temperature, salinity, oxygen concentration, siltation, burial by shifting sediment, movement to unfavourable habitats by current, parasitism, and disease (Dame 1996 cited in Stokesbury *et al*. 2007). Therefore, whilst removal or reduction of fishing effort in closed areas may lead to rebuilding of stocks, the resource cannot be guaranteed indefinitely, and natural mortality must be considered and monitored (Hilborn *et al*. 2004).

Much of the literature discusses the importance of management, both within the closed area, and in the adjacent fished areas. Ward *et al*. (2001) stated that "The positive effects of marine sanctuaries are lost if the surrounding area is not managed effectively, therefore conventional fisheries management should continue to apply outside the reserve". The success of the Australian subantarctic Heard Island and McDonald Islands (HIMI) Marine Reserve is in part related to the collaboration between managers and the fishing industry, with commercial fishers keeping watch on the reserve and reporting illegal fishing. The industry also play a role in monitoring the success of the MPA by undertaking an annual survey (Brooks *et al*., 2019).

Figure 7 provides a schematic of how closed areas can benefit species both inside and outwith its boundaries. Table 2 provides a list of the pros and cons associated with closed areas.

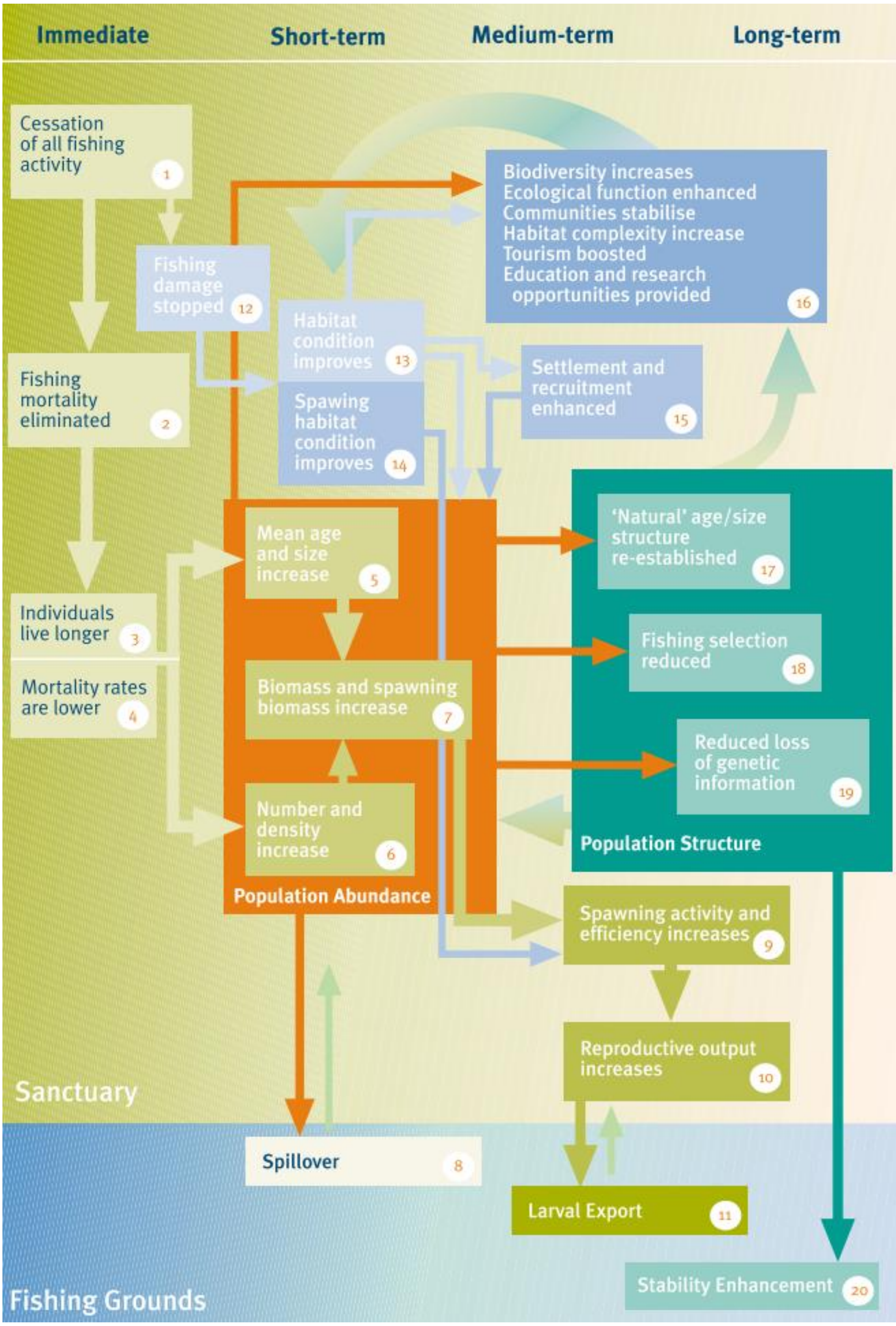

Figure 7: Conceptual model showing the pathways by which the establishment of a closed area could lead to environmental enhancement within the reserve and potentially to enhancement outside the closed area through the processes of spillover, larval export and stability enhancement (Source: Ward *et al.* 2001). As scallops are predominately sedentary species, the process of adult spillover will be relatively small.

Table 2: Pros and cons associated with closed areas

	Pro	Con
Biological	Increased densities of scallops	Dispersal of adults (spillover) unlikely as scallops sedentary
	Eliminate mortality of scallops and other species from indirect damage by fishing gear and discard/bycatch mortality.	Potential for mass mortalities, possible crowding (limiting recruitment and growth), increased predator densities, and increased frequency of disease (Stokesbury, 2015).
	Increased settlement substrate and refuge for juvenile animals	Larval retention in area would mean no benefit to the fishing grounds outside the closed area
	Potential dispersal of scallop larvae to fishing grounds "larval dispersal"	May take several years before any benefits are noted.
	Protection/restoration of habitat – increased habitat complexity	Carrying capacity of an area will eventually be reached (Lizaso *et al*. 2000).
	Increased reproductive output	
	Increase in size and age of scallops	
	Improves habitat for scallop settlement	
	Restore natural population structure	
	Potential to increase biodiversity	
	Protection of spawning sites	
	By protecting natural supply of larvae can maintain genetic structure of the area.	
Social	Reduce conflict between fishing gears.	Displacement of fishing
	Provide study areas for natural processes which can feed in to protecting the stock through stock assessments.	Illegal fishing on high density grounds
		Assessment of benefits can be difficult.
Economic	No cost associated with maintaining closed area	Enforcement costs
	No labour of site required unless for removal of starfish	
	Does not require detailed stock/ system data (Ward *et al*. 2001).	

4.2 Reseeding

Similarly to scallops benefiting from increased densities in a closed area, reseeding increases populations to levels where local densities are high enough that there is a higher reproductive output. This review has shown that reseeding is used globally both in combination with closed areas or with rotational fisheries. However, in Europe, Australia and Isle of Man the results of reseeding has been disappointing as their results have not been as successful as in Japan (Bradshaw *et al*. 2001; Slater, 2006). The two main issues with reseeding are (1) sourcing seed; (2) survival of seed during transport; (3) retention and survival of seed. With reseeding coming at a cost in terms of getting the seed (collector cost/purchasing costs/preparation of reseeding area/monitoring) it is important that these are measured against the potential threats to its success.

4.2.1 Sourcing scallop seed

"Spat supply is one of the major limits to aquaculture of scallops, with settlement being" unpredictable (Tremblay *et al*. 2020).

Whilst collecting natural scallop spat has proved a major success on Japan, in other areas it has been less successful. The main reasons for this as laid out by Bell *et al.* (2006) is the failure to meet the pre-requisites of a good supply of spat, low predation, retention of larvae, incentives for fisherman to invest in capture, release and rearing of spat. From spat collection trials around the UK it is noted that settlement onto collectors is extremely variable, even between areas close together, and is unreliable.

If spat is collected it tends to be grown in suspended culture for a period before being available for further ongrowing in suspended or bottom culture. A problem with this as noted by Lafrance *et al*. (2003) is that, with suspended scallops growing faster, the shell tends to be lighter than bottom grown scallops of the same size. This leads to increased problems with crab predation when the scallops are laid on the bottom for ongrowing. However, with regards starfish predation, cultured scallops clapped more and longer than wild scallops therefore mounting a stronger escape response to starfish (Lafrance *et al*, 2003).

Collectors shown to have a limited effective life of not more than a month, with settlement not occurring on collectors held for more than a month at sea during a trial in the West of Ireland (Wilson, 1987).

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 1980s 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).

The lack of a sufficient and predictable supply of scallop seed has led to a number of different scallop hatcheries being established to try and provide a regular supply of scallop seed. Hatchery enhancement of marine and coastal stocks has been criticized by some on the grounds that it is not effective, not economically feasible, prevents alternative solutions from being implemented and that it endangers the genetic structure of populations (Bartley, 1996). Though appearing to be minimal in scallops, inbreeding depression can cause a reduction of effective population size, known as Ryman-Laikre effect (Morvezen et al, 2016). This can be mitigated by using a large broodstock which is renewed regularly and genetically monitored.

4.2.2 *Survival of seed during transport*

It is vital that when scallops are reseeded they are still viable and have not been impacted in the long term by their transport to the reseeding site. A number of studies have examined the survivability of scallop seed during transport. An example has already been provided as part of the American studies (section 3.9). Scallops are negatively impacted by long periods out of water. However, it is more cost effective to transport shellfish out-of-water than in-water (Allison, 2016).

Christopherson *et al*. (2008) examined the transport of juvenile and adult *Pecten maximus* to predict the impacts of emersion and temperature on survival. Experiments were carried out at different sites and times of the year using scallops from Ireland (from natural spat fall, intermediate and bottom culture), Norway (spat and juveniles were hatchery reared whilst adults were wild caught) and Spain (from hatchery or wild production). Scallops were split into size categories (small spat, < 2mm, large spat, 15-30mm, juveniles, 30-50 mm and adults, >100mm). Transport was simulated by keeping the scallops in moist atmosphere in transportation boxes for 0 (control), 3, 6, 9, 12, 18 and 24 h at temperatures ranging from 3°C to 20°C. Different sized polystyrene fish boxes, cooler boxes and bags were used and pre-soaked buffering material such as wood shavings, seaweed and newspaper was placed on the bottom of the containers and as a cover on top of the scallops. They showed that the smaller the animals being transported, the shorter the length of emersion they could survive. Small spat showed a high survivability at 9 hours which had reduced to 80% after twelve hours. If emersion periods are combined with a temperature which is too high or too low this led to 100% fatalities. They reported that recovery of the transported scallops depended on the ambient temperature of the seawater from where they were taken from. Whilst a temperature below 12°C yielded good survivability, the best results came when the temperature was equal to the ambient temperature of the sweater or 2-5°C below the ambient temperature. In conclusion they recommended that scallops be transported for a maximum of nine hours at a temperature the same or lower than the temperature of the seawater from where they came (Christopherson *et al*. 2008).

4.2.3 *Retention and survival of seed*

The presence of predators can be the main determining factor in the successful reseeding of an area. Newly transplanted juvenile scallops are more vulnerable to predation as they are initially weaker, stressed, and unable to escape effectively (Fleury, *et al*. 1996). The main predators of scallops in Northern Ireland waters are starfish and crabs.

As scallops start to recess, get bigger and develop a stronger shell, predation is reduced (Brand, 2016). Therefore it is important to give the reseeded scallops as long as possible to gain these characteristics after reseeding. Indeed in many reseeding trials some level of predator control/removal is carried out to prepare the area for the scallop seed. However, starfish and crab are scavengers and accumulate in areas where there is disturbance and dead/dying animals, through chemosensory stimuli. When an area is reseeded there will naturally be some mortality and this can lead to an influx of predators to the area. Therefore it is important that predator control measures continue until the scallops have reached a size larger than that attacked by predators.

When a site is reseeded, there will be initial dispersal of the scallops. Stokesbury and Himmelman (1996) examined the movement of the giant scallop *Placopecten magellanicus* in Gulf of St. Lawrence, Canada. While this scallop is one of the most active swimmers, the theory is true for many pectinids. Using tagged scallops, they found that the scallops had the greatest movement away from the release site within the first two weeks after reseeding. By week three the dispersal rate had levelled off. They found that the rate at which the scallops moved was higher in unfavourable habitats and when predator densities were high (Stokesbury and Himmelmann, 1996). In order to prevent this dispersal of scallops away from the reseeding site it is important that the correct site is used.

Table 3 provides a list of the pros and cons associated with reseeding.

Table 3: Pros and cons associated with reseeding of scallops and the different methods of getting seed.

	Pro	Con
Reseeding general	Increases density of scallops quickly.	Predation or reseeded spat
	May be useful at estimating biological parameters used in stock assessments, such as natural mortality.	
Collecting seed using spat collectors	Provides settlement substrate in areas which have been disturbed and settlement substrates are not naturally present	Cost associated with spat collectors
	Should have no impact on genetics as using seed native to the area	High mortality on small seed once relayed on bottom
		Irregular supply
		Biofouling of collectors
		Release of abundant particulate or soluble organic materials to the sediment below (Huang *et al.* 2019)
Buying seed from other locations (natural)		Cost associated with purchase of seed
		May impact genetic structure
		Transport issues and costs
		Irregular supply
		High mortality on small seed
		Scallops in poor health/fouled will have a low survival rate
		Can cause complications in stock assessment models (Hart *et al.* 2013)
		Potential introduction of invasive species
Reseeding – hatchery seed	Regular supply	High cost
		May impact genetic structure
		Thinner shell so higher mortality on small seed once relayed on bottom
		Seed may not be as viable as natural seed.

5.0 Recommendations

Based on the literature review the closure of key areas for the purposes of scallop enhancement should be treated as an initial step. Closed areas have been shown to greatly enhance scallops which are held in the protected site, producing scallops which are bigger, older and more abundant. This will create a high reproductive output in the closed area which has the potential to supply the greater Northern Ireland scallop fishing industry (see Work Package 2 report). With the only costs coming from enforcing the closure, this would appear to be the most cost effective of all the options examined.

It is suggested that the closed areas are only closed to mobile gear which could damage the seabed, as well as hand diving for scallops. This report has noted the effects predation can have on any scallop enhancement programme. By allowing fishing by static gear to continue in the area, there is an active manner of predator reduction, with brown crab being a primary targeted species of static gear fishermen in the area. If additional enhancement was to be carried out within a closed area, further predator control measures should be utilised prior to reseeding, including the removal of starfish.

Four sites have been selected as potential scallop enhancement sites in Northern Ireland. If these are closed to mobile gear fishing, further enhancement strategies, such as reseeding could be implemented. However, knowing the potential negatives associated with reseeding, it is recommended that not all sites are reseeded. This would provide a unique comparison to glean the real benefit, if any, that reseeding has over a simple area closure. It is important to note that the purpose of the reseeding in the areas is not so that it can be fished at a future date (i.e. not a rotational fishery) but as a method of supplementing the scallops in the closed area when initially established.

Reseeding options such as collecting natural spat fall with collectors (either within the closed area or from purchasing from a producer) or using hatchery reared spat have been examined. If natural spat could be collected in the area this would be the cheapest option. In addition, catching spat from scallops which are in the area would mean that there is no risk to the genetic structure of the population. To date there have been no trials at collecting scallop spat in our waters. One recommendation would be to trial such spat collection in the area to see if this is an option. This could be a potential Fisheries Science Partnership (FSP) with industry leading the deployment and retrieval of collectors and science assisting with the analysis of the collectors.

What is clear is that the scallop industry will need to be patient and not expect results in the short term. It is clear from all the case studies listed in this report that benefits can take many years to first appear, with the longer an area is closed the greater the benefits.

A strong recommendation is, that no matter what option is used, the sites must be monitored to determine success or failure. Monitoring should involve regular surveys of the areas which could be by divers, underwater television and/or grab sampling surveys. To monitor if there is any spillover of scallops from the closed area to the fishery, tagging experiments could be carried out. Pomeroy *et al.* 2005 suggested a number of goals and indicators which can be used to monitor the success of an MPA (Table 4)

This work is being carried out to enhance the scallop fishery, therefore it is vital that the fishery is monitored to look for impacts that the enhancement is having on catches. This could be by examining Catch per Unit Effort (CPUE) or Catch per Unit Area (CPUA) in the areas which are believed to most benefit from enhancement (these will be highlighted in the Work Package 2 report).

Table 4: Potential goals and monitoring indicators for a closed area as set out in Pomeroy *et al*. 2005

	Goal	Indicator
Biophysical	Marine resources sustained or protected	Focal species abundance
	Biological diversity protected	Focal species population structure
	Individual species protected	Habitat distribution and complexity
	Habitat protected	Composition and structure of community
	Degraded areas restored	Recruitment success within the community
		Food web integrity
		Type, level and return on fishing effort
		Water quality
		Area showing signs of recovery
		Area under no or reduced human impact
Governance	Effective management structures and strategies maintained	Existence of decision making and management body
	Effective legal structures and strategies for management maintained	Existence and adoption of management plan
	Effective stakeholder participation and representation ensured	Local understanding of MPA rules and regulations
	Management plan compliance by resource users enhanced	Existence and adequacy of enabling legislation
	Resource use conflicts managed and reduced	Availability and allocation of MPA administrative resources
		Level of resource conflict
		Existence and application of scientific research/input
		Existence and activity level of community organisations
		Degree of interaction between managers and stakeholders
		Proportion of stakeholders trained in sustainable use
		Level of training provided to stakeholders in participation
		Level of stakeholders participation and satisfaction in management process and activities
		Level of stakeholder involvement in surveillance, monitoring and enforcement
		Clearly defined enforcement procedures
		Enforcement coverage

		Degree of information dissemination to encourage stakeholder compliance
Socioeconomic	Food security enhanced or maintained	Local marine resource use patterns
	Livelihoods enhanced or maintained	Local values and beliefs regarding the marine resource
	Non-monetary benefits to society enhanced or maintained	Level of understanding of human impacts on resources
	Benefits from the MPA equitability distributed	Household income distribution by source
	Compatibility between management and local culture maximised	Stakeholder knowledge of natural history
	Environmental awareness and knowledge enhanced	Perceptions of non-market and non-use value
		Material style of life
		Quality of human health
		Perceptions of seafood availability
		Household occupational structure
		Community infrastructure and business
		Number and nature of markets
		Perceptions of local resource harvest
		Distribution of formal knowledge to community
		Percentage of stakeholder group in leadership positions
		Changes in conditions of ancestral and historical sites, features and/or monuments

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