Ostrea edulis the "Native Oyster" in Strangford Lough Northern Ireland: Population Dynamics and Species Management Recommendations 2021-22

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Summary

Strangford Lough has supported prolific populations of the "Native Oyster" *Ostrea edulis* since the Mesolithic through to the mid-1800s however, intense overexploitation rendered the species biologically extinct by the 1900s. The oyster remained largely absent from the lough until the late 1990s when a spawning release from a commercial stock seeded the north and eastern lower intertidal. Within five years the native oyster population had increased from a few thousand to more than 1.2 million. This inadvertent restoration of *O. edulis* in Strangford Lough is considered by many working in the field as the most successful one-off spawning and settlement event within the species' natural range and indeed is the envy of restoration managers throughout Europe and the UK.

Even though the Lough's population has been greatly reduced it is still the topic of great scientific significance. The Lough's predominantly intertidal population is regarded as unique for the species, and the three-dimensional multiple native oyster attachments recorded at Newtownards Sailing Club represented the first documented live *O. edulis* reef formations in modern days.

Unfortunately, the history of the native oyster's demise continually repeats itself in Strangford Lough with numbers gradually decreasing over the past 15 years. However, the two consecutive high temperature summers in 2018 and 2019 offered the prospect of large multiple larval spawns from the remaining oysters in the Lough. As *O. edulis* offers a substantial suite of ecosystem services and is also subject to a UK Biodiversity Species Action Plan and a target species in carbon capture projects, it was thought appropriate by Ulster Wildlife Trust and DAERA to undertake a comprehensive population survey to ascertain its current status within the Lough. The survey would investigate population dynamics and compare the findings to baseline data from 2004, while also suggesting species augmentation and management measures.

Key Findings

The survey revealed a significant decrease in the overall total native oyster population since 2004. Intertidal sites continue to be harvested at a commercial level. The northern and eastern sites once considered prolific are now in danger of becoming biologically extinct. The less inaccessible island sites however, displayed high densities of oysters within highly fecund size classes and subtidal assemblages remained relatively unchanged.

- The total population of *O. edulis* in Strangford Lough currently stands at approximately 146,000 - a decrease of 814,000 oysters since 2004. The northern intertidal sites have shown little signs of recovery from the intense harvesting events of the mid-2000s. Fragmented low-density assemblages of small oysters remain but are unlikely to produce successful spawns due to age and distance between individuals and therefore a reduced Allee effect. The oyster assemblages at the island sites in contrast have increased significantly from approximately 1000 individuals in 2004 to >88,000 in 2021. The subtidal population remains relatively unchanged with expansion probably limited by the availability of siltation-free settlement substrate.

- Population dynamics of *O. edulis* in Strangford Lough have changed both geographically and biologically since 2004. The majority of large highly fecund oysters are now situated on the eastern island sites while the northern and eastern intertidal sites now accommodate small size cohorts of juvenile low fecundity oysters. Recruitment is still taking place at all sites. Native oyster mortality throughout the Lough's population is low at an average of 10%. This is extremely promising as it suggests a high degree of resilience to the parasitic *Bonamia ostreae* probably achieved over 20 years of genetic selection.

- The two most abundant *O. edulis* settlements in 2021 were recorded at Horse Island an intertidal site on the east shore and Skart Rock a central island site. Particle tracking models for *O. edulis* larvae over a spawning season were ran for both sites with the model output showing that a successful spawn had the potential to populate the majority of the Lough. However, the northern and north eastern sites which encompass the highest coverage of settlement substrate would be exposed to minimal larvae from Skart Rock and Horse Island. A review of the Smyth et al., (2016) particle dispersal model output would recommend the establishment of a larval source close to the original commercial stock of 1998 to supply the northern sites. It should be noted that since the initial survey in October 2021 the oyster assemblage at Horse Island no longer exists. Intense harvesting during March and April reduced the site density from 4.41/m^2 to 0.02/m^2.

- Harvesting of the native oyster population in Strangford Lough is intense with at least four to five groups working the lower shore on spring tides. The commercial value of *O.edulis* has increased significantly over the past five years with native oysters costing 80 pence per shell in 2018 now fetching >£3.00 per shell in 2021. In 2018 the harvesting of native oysters would have been considered a non-viable catch per unit effort. However, the recent threefold increase in market price may go some way to explaining the current indiscriminate nature of harvesting within the Lough. A list of immediate and long-term counter measures to tackle this problem are listed under Management Recommendations. However, it is suggested that an emergency bylaw to deal with the problem is introduced ASAP to protect the remaining population before the summer spawn. It seems bizarre that a Marine Conservation Zone does not possess the necessary legislation to protect a species which is categorised as one which should be conserved under UK and EU conservation recommendations.

The native oyster population in Strangford Lough is experiencing challenging times but it should be remembered that the species has shown considerable resilience to both disease and harvesting in the past. The Lough possess the two fundamental components required to rejuvenate a declining population; favourable hydrodynamics and sufficient quantities of natural shell material. With some pro-active measures it is envisaged that the native oyster could successfully recover from its present situation and once again Strangford Lough could become one of the species strongholds within the UK and Europe.

Ostrea edulis Species Profile

Common name:	European flat oyster / European native oyster / Native Oyster
Scientific name:	*Ostrea edulis*
Size:	up to approx.15 cm
Age:	up to 30 years; sexually mature at 3-4 years
Appearance:	Shape roundish to oval. Left / lower valve convex, right / upper valve almost flat and fitting inside the left valve to close it. Genus: Ostrea ´flat oysters` takes its name from its shape.
Habitat:	Estuaries and sea loughs as well as open coastal seas to ~50m depth. Primarily subtidal, colonizing mixed hard substrates, in particular shell material.
Range:	The native range is pan-European, including the northeast Atlantic from the south of Norway through to the Mediterranean Sea, as far as the Black Sea (See native range map below, data from Ocean Biogeographic Information System (OBIS)).
Status:	Rare throughout Europe due to overfishing, impacts of bottom towed gears, disease and pollution.
Legal status across UK:	**UK Biodiversity Action Plan Priority Species and habitat, UK-post 2010 Biodiversity Framework with its own Species Action Plan.** **Species of principal importance for the purpose of conservation of biodiversity, Natural Environment and Rural Communities Act 2006.** **Listed as a priority marine species under the Review of Marine Nature Conservation UK in 2007.** **Native oysters and native oyster beds are a "Species and Feature of Conservation Importance respectively (SOCI and FOCI) under Marine and Coastal Access Act.**
Legal status across Europe:	**At an international scale, the European flat oyster is included in the OSPAR List of Threatened and/or Declining Species and Habitats for the North-East Atlantic (Region II – Greater North Sea and Region III – Celtic Sea).** **It is also included in Ramsar as "shellfish reefs", and by some member states as "Reef" in the Habitats Directive.**

Geographical range of *Ostrea edulis* the native oyster. OBIS (2020) Ocean Biogeographic Information System. (Intergovernmental Oceanographic Commission of UNESCO. www.iobis.org).

Biology and Ecosystem Services

Ostrea edulis is recognised as a habitat-forming bivalve. It is a “protandrous hermaphrodite”, meaning the oyster starts life as male and may after several years change to female. Within one season the sex change may occur back-and-forth. A male oyster releases sperm into the water column, fertilising up to 1 million eggs in the pallial cavity of the female. Older oysters can spawn twice during one spawning season: once as a male and once as a female. Sperm cells are filtered out of the water phase by the females, and combined with egg cells in their shell cavity. The larvae are released from the female into the water after 8 to 10 days (depending on temperature), spending another 8 to 10 days in a pelagic phase before settling on a suitable substrate. The oysters preferentially settle on adults of their own species however, if these are not available, they will attach to an alternative calcium carbonate rich substrate. The metamorphosis from mobile larvae to settled spat can take up to two weeks. Because of the relatively brief mobile phase, dispersal of the native oyster occurs over relatively small distances, generally from 1 to 10 km. Once the planktonic phase has been completed, the oyster fuses itself to the underlying substrate via a cementation process (Fitzsimmons et al., 2019). When large aggregations of larvae settle out dense assemblages of interconnected oysters form and overtime these can create intricate reef structures. These oyster reefs provide food and habitat for many species and can serve as nursery grounds for numerous fish species (Gosling, 2003).

Oysters are filter feeders, and a single native oyster can filter up to 140 litres of seawater per day. Their filtering activity can improve water quality on local scales. This is not only because the oyster removes particles from the water, but also because they then deposit them on the sediment, where bacteria in the substrate can break down pollutants such as nitrates. This results in enhanced rates of denitrification, a process by which nitrites and nitrates are transformed into inert di-nitrogen gas.

By removing particles from the water column, the oysters can also increase light penetration to the sediment, and promote the recovery of valuable coastal marine plant species such as *Zostera marina*. The filter feeding drawdown of sediments together with the stabilizing effect of the reef, can also result in reefs acting as carbon sinks, although this ecosystem benefit is complicated. As the reef grows these particles and the associated carbon can become trapped. The shell material produced by the oyster contains carbon and may become buried and stored in the sediment, in some cases for thousands of years. Oyster respiration and growth involves the release of CO_2 and the short-term storage of organic carbon in the form of tissue. However, once the animal dies this is degraded. At the same time, shell production both releases and captures carbon.

As a result of the ecosystem services described above the native oyster in the UK and Ireland has become a target species for re-introduction and augmentation. Presently there are 21 projects and initiatives registered with the Zoological Society of London's Native Oyster Network with more being added annually.

Introduction

Historically shellfish were the most readily exploited food on the foreshore and were consumed in large quantities. References to the European "Native Oyster" *Ostrea edulis* and its consumption along the shores of the northern Irish sea loughs abound the archives of libraries throughout the UK and Ireland. Archaeologists working in Northern Ireland have unearthed oyster middens which can be dated as far back as the Mesolithic times and up to the post-Medieval period, with *O. edulis* being a major component of the shell debris (Yonge, 1960; Mc Erlean et al., 2002; Laing et al., 2005). Historical accounts relating to the native oyster suggest that its exploitation was carried out in a relatively sustainable manner from the 1100s to the early 1700s. However, by the mid-1700s native oyster fisheries throughout their natural range were reporting dramatic declines in landings and recruitment (Pazó et al., 1987; Beck et al., 2009; Pogoda, 2019). In the 19th Century the decline in oyster numbers became a major concern for fishery managers and was attributed to unsustainable fishing practices and unregulated harvesting (Went, 1962; Heral, 1990; Mc Erlean et al., 2002). Fishery deterioration in combination with reduction in oyster numbers was recorded at all the major oyster producing areas, with Strangford Lough being no exception.

Strangford Lough once had an extremely prolific *O. edulis* fishery, the Montgomery Records of 1683 states that, "The beds of Strangford are dredged of oysters in the deep water as well as being gathered on the Lough's foreshore in great numbers" (Mongomery, 1683). Quinn, in 1732, reported that the oysters were good for eating both in summer and winter. Harris, in 1744, stated that the oyster beds of Strangford were being commercially exploited by more than 20 small boats (Magennis et al., 1983). Lewis (1802) mentions Ringhaddy Sound as a notable location for harvesting and Lieutenant Henry Tucker in 1833 recorded that he found beds of oysters in 2.5-5m of water being dredged by more than 20 boats (Day and Mc Williams, 1991).

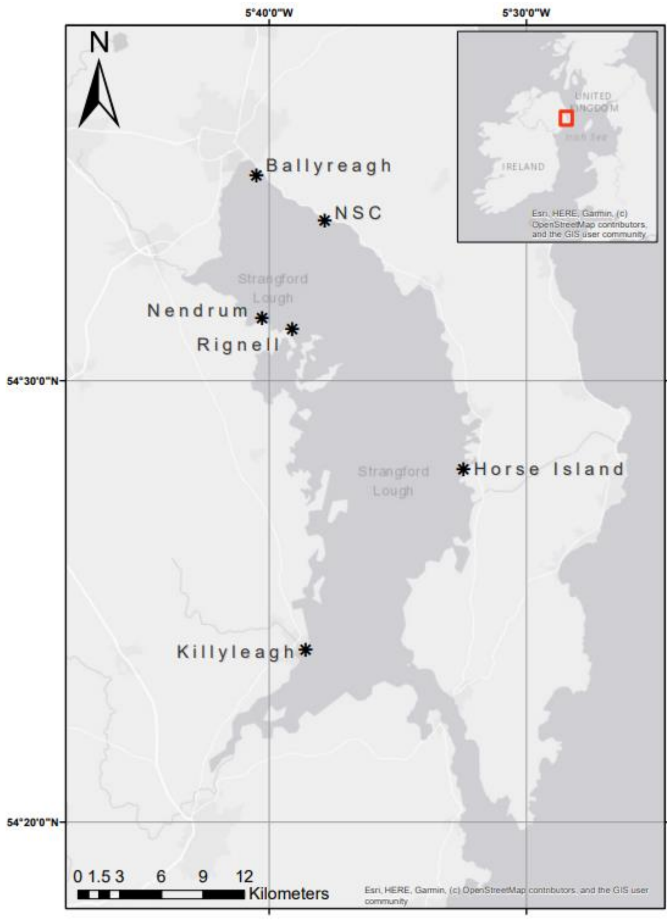


Figure 1. Historical and present-day native oyster sites of significance in Strangford Lough: Killyleagh the landing and shipping port for native oyster exports of the 1800s. Nendrum and Rignell location of 1998 commercial stock which initiated the rejuvenation of the Lough's native oyster population. Ballyreagh highest recorded oyster population of >300,000 oysters 2004, reduced to <500 in 2021. NSC (Newtownards Sailing Club) first documented live *O.edulis* reef formations recorded in UK and Europe 2010, no longer present due to harvesting. Horse Island highest density *O. edulis* site 2021, lowest density *O. edulis* site 2022.

However, oyster numbers declined rapidly and an Irish-wide official inquiry was conducted in 1877 by the Inspector of Irish Fisheries, Mr. J. A. Blake. On account of the great reduction (90%) over the previous fifty-year period it was decided to shorten the open season by a month and to prohibit the taking of juvenile oysters (Went, 1962). These methods seemed to have had little effect, for by the late 1800s the oyster beds had all but disappeared. Went (1962) reports that commercial oyster fishing was no longer profitable and had ceased before 1903.

The removal of oysters from Strangford was so complete in the 1800s that no significant oyster stocks were reported in the Lough between the 1900s and the 1970s. However, small assemblages of *O. edulis* must have remained in the more inaccessible parts of the lough as local fishermen still caught the occasional large solitary specimen (Williams, 1954). Aquaculture trials in the 1970s (Briggs, 1978) demonstrated favourable growth of both the Pacific oyster *Crassostrea gigas* and *O. edulis* which provided an impetus for the development of oyster culture within the Lough (Kennedy and Roberts, 1999). Although most of the resulting aquaculture concentrated on *C. gigas* production, commercial stocks of *O. edulis* were also maintained in the Lough. Nunn (1994) provided the first viable reports of small assemblages of *O. edulis* at a number of sites these oyster settlements were attributed to spawning activity from aquaculture stocks (Kennedy and Roberts, 2006).

In 1998 Strangford Lough held an estimated *O. edulis* aquaculture stock of approximately 100,000 individuals (Kennedy and Roberts, 1999). In a survey conducted in 1998-99 Kennedy and Roberts (1999) estimated the wild standing stock of native oysters at 2000 to 3000. By 2002, Smyth et al., (2009) estimated the wild stock at approximately 1 million and by 2003 the population had increased to > 1.2 million, with all sites located in the northern basin. However, after an initial increase, the estimated stock declined to approximately 900,000 by 2004 and to < 600,000 by 2005. The brood stock source for this unexpected rise in oyster density was always a point for debate. However, Smyth et al*.,* (2016) ran a particle tracking model for an *O. edulis* pelagic larval phase using the 1998 commercial stock at Ardmillan Bay as the larval source. The model output matched all the newly settled native oyster sites recorded between 2002 and 2005 confirming that a spawning event from the 100,000 oysters at Ardmillan Bay in 1998 was responsible for the rejuvenation of the species (Smyth et al., 2016).

Unregulated harvesting poses a major threat to *O. edulis* stocks that are recovering naturally or as a result of human intervention (Spärck, 1951, Millar, 1968, Roberts et al., 2004, Smith et al., 2006). During the 2002 to 2005 surveys shellfish gathers were encountered on a regular basis. The dramatic decline over a three-year period of the newly restored oyster population mirrored the excessive exploitation of the 1800s. Indeed, subsequent surveys have shown small increases in oyster numbers until they reach a commercial size, however, this is followed with an almost total removal from sites.

In an attempt to establish the current species status of the native oyster within Strangford Lough a comparative population survey using 2004 data as a baseline was undertaken encompassing the following aims:

Aims

- Ascertain the population status of *Ostrea edulis* in Strangford Lough
- Establish the population dynamics of *O. edulis* including mortality
- Provide particle tracking models for *O. edulis* larvae from high density sites
- Suggest species management protocols to create a self-sustaining *O. edulis* population

Current status of *O. edulis* in Strangford Lough 2021-22

Site Selection

In order to obtain comparable data for population dynamics and density modelling, site locations were selected from the 2002 to 2003 survey (Smyth, 2008). The survey consisted of 24 intertidal onshore sites, 14 intertidal island sites (Figures 2-7) and eight subtidal sites (Figures 8 and 9). Sites were categorised as being onshore if they were accessible during low tide, island sites could only be accessed by boat and subtidal could only be surveyed using SCUBA. The allocations of North, East and West were applied to an area based on the requirements of the Gunderson model and matched those previously used in Kennedy (1999) and Smyth (2008).

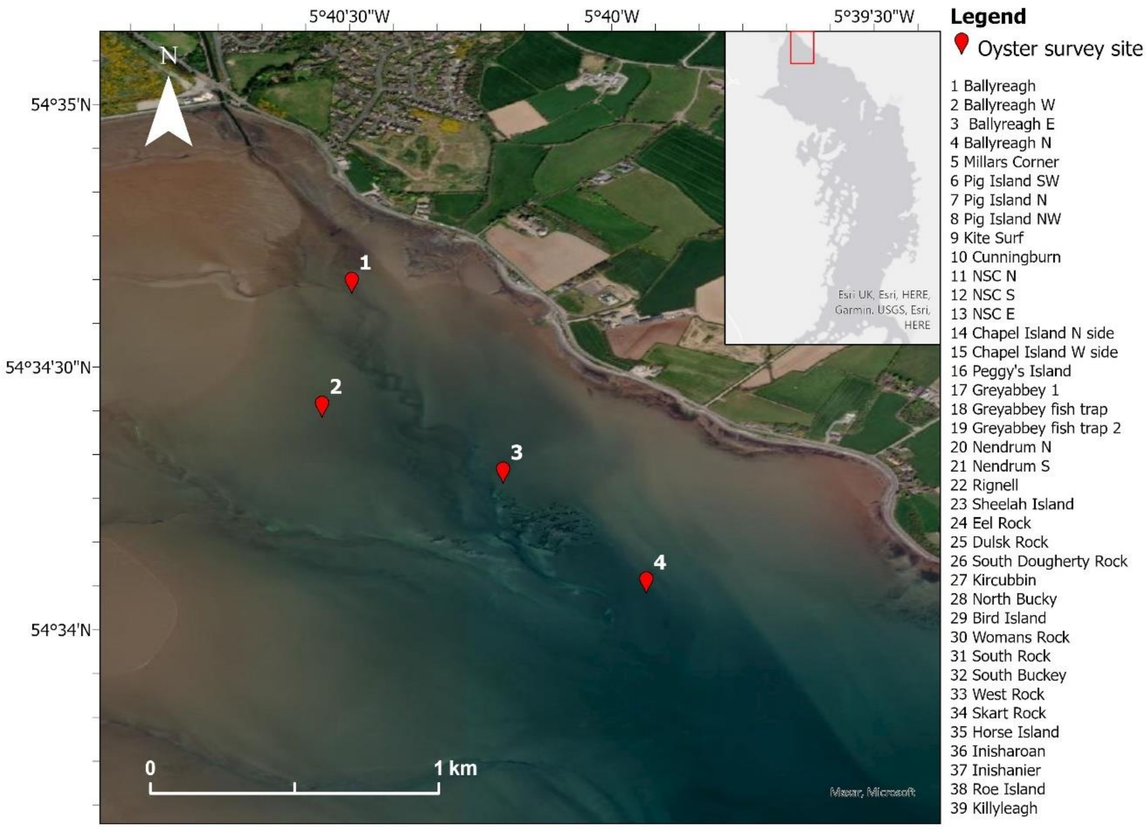


Figure 2. North intertidal onshore survey sites 1-4. The allocation of North is the regional categorisation as used in the Gunderson 1998 population model the same attains to West and East in figures 4 - 6. (Kennedy, 1999; Smyth, 2008).

Figure 3. North onshore intertidal sites 5-13. Pig Island 6,7,8 is categorised as onshore.

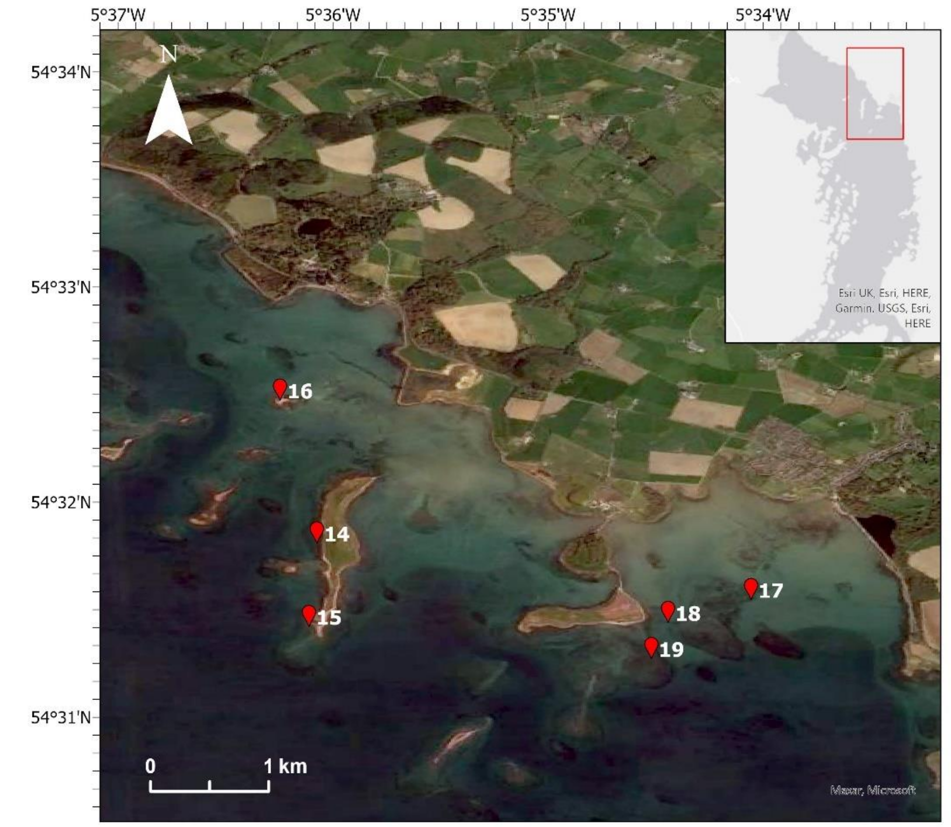


Figure 4. North onshore intertidal 14-19 all accessible by foot at low tide.

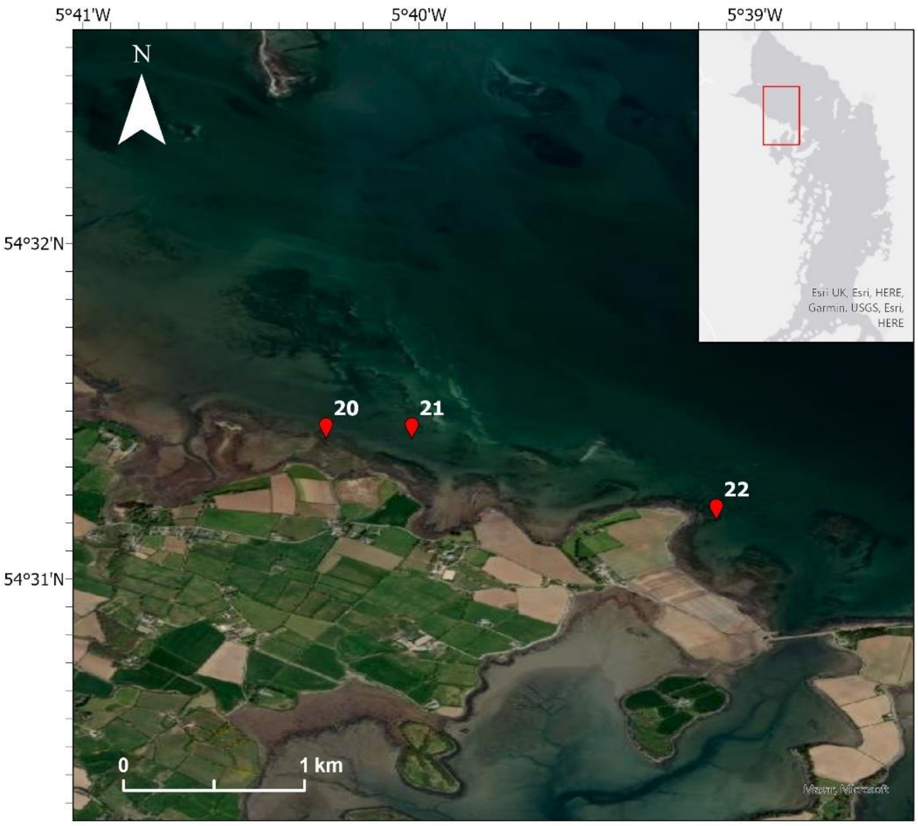


Figure 5. Western onshore intertidal sites 20-22.

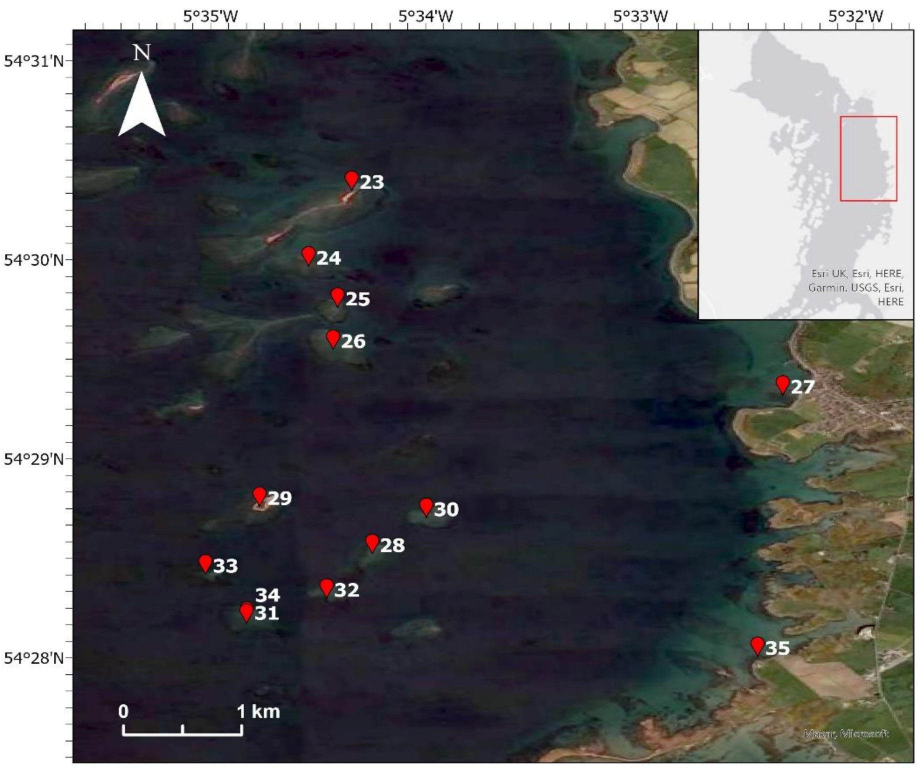


Figure 6. Eastern intertidal island sites 23-35, with the exception of 27 and 35 which were onshore.

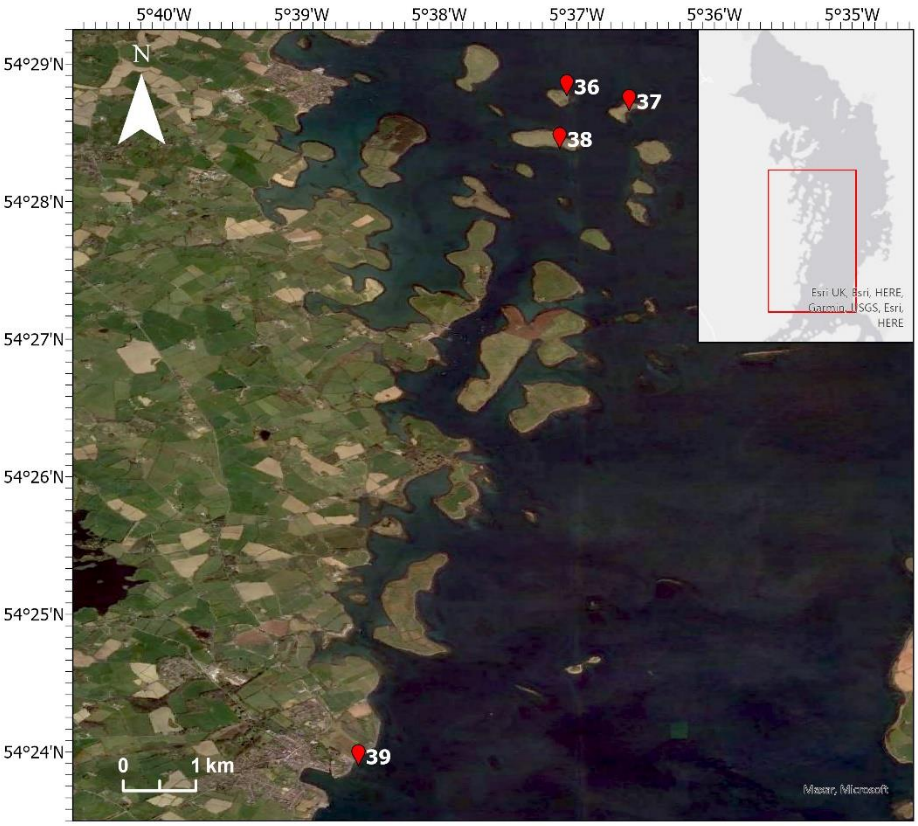


Figure 7. Western intertidal island sites 36, 37 and 38 and 39 onshore.

Methods

Survey Techniques

Surveys were undertaken at low tides of < 0.5m below chart datum. At each site oyster densities were established using counts in replicated quadrats and in timed searches. Quadrat surveys followed an 80m transect recording oysters in a 0.25m^2 quadrat every 5m on either side of the transect line. At sites where the terrain could not facilitate transect line surveys a timed search methodology was employed. This involved recording oysters in two 10 min searches in a site-specific plot size equal to an 80m transect survey. Density estimates using both techniques showed a highly significant positive relationship (r2 = 0.999; p < 0.0001).

During the surveys, substratum composition was recorded for each location. Digital stills of transect substratum were taken to allow the relative percentage coverage of different substrata to be determined. To establish the population dynamics of *O.edulis* live oysters were measured to 0.25cm *in-situ* at each site using a Vernier© calliper. The recording of *in-situ* subtidal shell length during SCUBA surveys was not possible due to the restrictions imposed by dive time. Oysters were therefore collected and measurements recorded onboard the survey vessel. The oysters were then returned as close as possible to the site of collection. Intertidal and subtidal mortality counts were undertaken in conjunction with live oyster recording, with mortality being expressed as a percentage of the total live count.

Figure 8. Digital still of grided 0.25m^{2}quadrat for substrate composition and measuring *O.edulis* from umbo to leading edge using vernier callipers for population dynamics.

In-situ Site Density

Site density was recorded for both quadrat/transect and timed search methodologies in n. number of oysters per m^2. Data was then converted into n. per 100m length of shore so that a direct comparison could be made between the current *O. edulis* densities and those presented in previous years.

Population Modelling

A Gunderson population model was used to estimate the abundance of oysters at a site, based on available area of suitable substrate at each site. This modelling approach has proved extremely accurate when assessing sessile or regionally limited fishery stocks (Kennedy and Roberts, 1999; Smyth et al., 2009). For each site, the proportion of total area accommodating the appropriate settlement substrate was determined by examining biotope classifications (Phase 3 EUNIS biotope coding). This allows for application of a correction factor, restricting abundance estimates to only the area with each survey site that is suitable for the settlement of oysters.

Gunderson model

The total number of potential *O. edulis* was estimated using the following formula which was adapted from Gunderson (1993):

$$P = \sum_{i=1}^{h} \left(Ri.\ F/a \right) C\,i$$

Where; P= Total population resident in full survey area.

Ri= Area of region in m^2.

a= Area sampled within a single sampling unit.

F= Correction factor estimating substratum types.

Ci= Mean number of oysters observed per sampling unit in the region i based on, n samples.

h= Number of regions composing the survey.

Here, the total population resident in the entire survey area, ‘P’, is determined using an estimate of the area of each survey region in m^2. The surface area, ‘Ri’, for the regions are estimated using scaled images of Strangford Lough from Global Lab image analysis software (Table 3). A proportionally weighted correction factor, ‘F’, is then applied to ‘Ri’ to account for the amount of suitable oyster settlement substratum present in the region. This factor was derived from survey results (Kennedy and Robert’s 1999; Smyth et al., 2009). Value ‘a’ is a constant which refers to the area sampled within a single sampling unit (9m). ‘Ci’ refers to the mean number of oysters observed per sampling unit in region ‘i’ based on ‘n’ samples.

Table 1. Dimensions of survey regions, surface area and allocated substratum correction factor (c.f.) (Kennedy, 1999; Smyth, 2008).

Region	**Intertidal area m^{-2} ($x10^6$)**	**Subtidal area m^{-2} ($x10^6$)**	**Total area m^{-2} ($x10^6$)**
1.North	19.644 c.f. 0.056	26.816 c.f .0.234	46.460
2.East	4.509 c.f. 0.0236	32.318c.f .0.236	36.828
3.West	5.438 c.f. 0.027	9.789c.f. 0.019	15.227
Total	29.592	68.954	98.516

Model outputs for population estimates will be expressed regionally and as an overall total.

Results

Survey results for non-modelled *in-situ* oyster density and mortality will be displayed on an individual site-specific profile. A modelled oyster population for both regional and total Lough areas will be presented as a table with accompanying graphical comparison of previous years population estimates.

Site 1.

Ballyreagh; 54.57733 -5.674925 northern site which had the highest oyster density of 2004.

Substrate muddy/sandy mix with *Mytilus edulis* shell.

2021 oyster survey density 0.03/m^2, mortality <10%

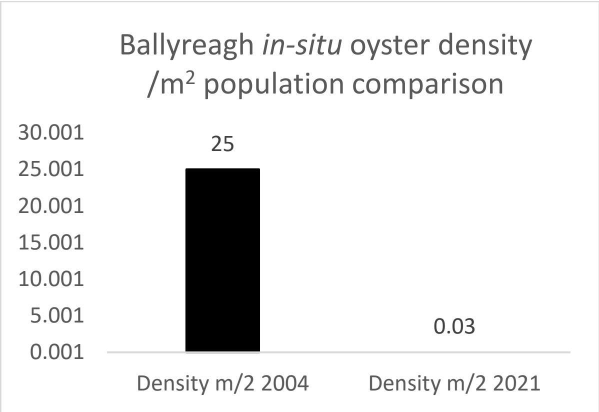


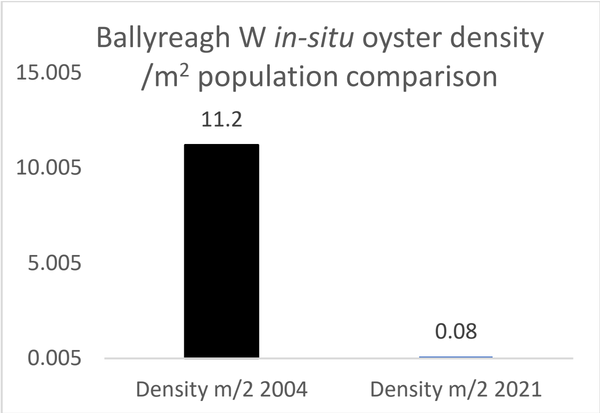
Figure 9. Shell coverage at Ballyreagh which accommodated the highest density of native oysters recorded post-1998, currently one of the lowest density sites in Strangford Lough 2021.

Site 2.

Ballyreagh W; 54.5734 -5.675869 allocated as a northerly regional site.

Substrate muddy/sand with mixed shell predominantly *Cerastoderma edule* and *Mytilus edulis*

2021 oyster survey density 0.08 /m^2, mortality <5%

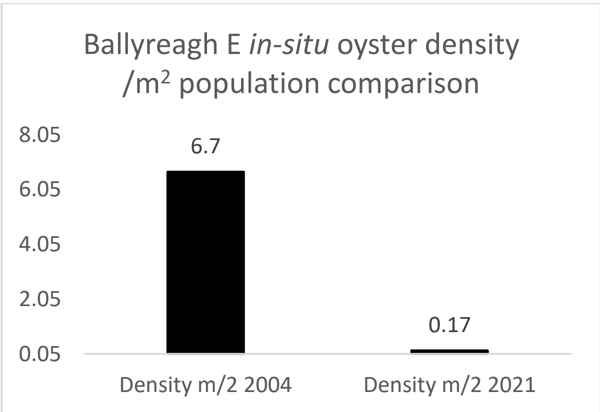


Site 3.

Ballyreagh E; 54.571311 -5.670118 allocated as a northerly regional site.

Substrate mud/shell mix predominantly *M. edulis*

2021 oyster survey density 0.17/m^2, mortality 8-10%

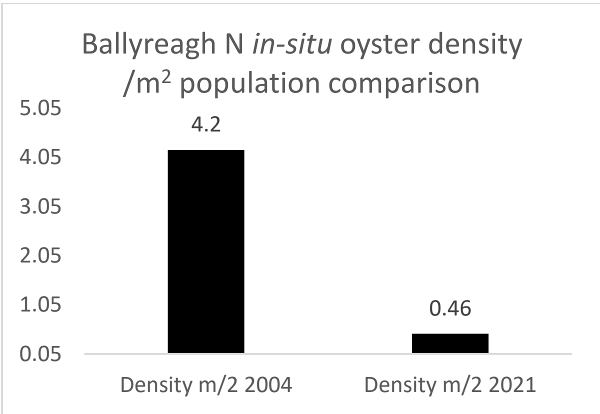


Site 4.

Ballyreagh N; 54.567828 -5.665569 a northerly region, first documented non-historical site 2002.

Substrate sandy/mud with mixed shell, shell types included *C. edule, M. edulis, O. edulis Littorina littorea and Ensis ensis*.

2021 oyster survey density 0.46 /m^2, mortality ≈10%

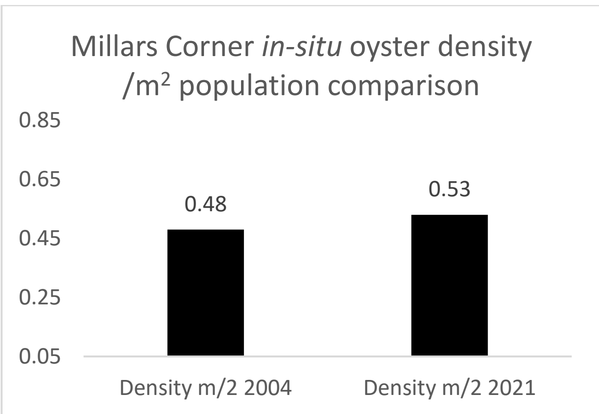


Site 5.

Millar's Corner; 54.561122 -5.635571 a northern site regularly visited by shellfish harvesters.

Substrate sandy/shell and stone mix, shell types included *C. edule, M. edulis, O. edulis L. littorea*.

2021 oyster survey density 0.53/m^2, mortality 8-10%

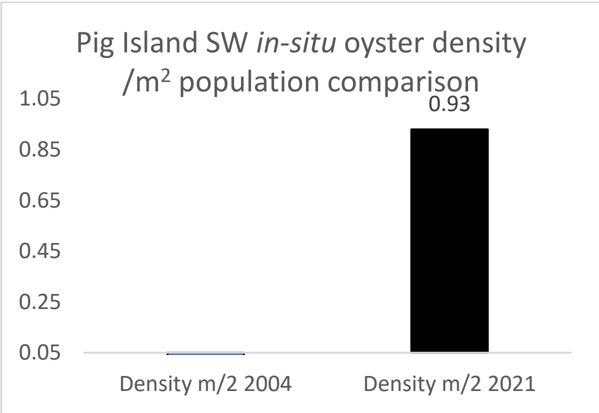


Site 6.

Pig Island SW; 54.554882 -5.619255 a northern site no oyster settlements recorded in 2004.

Substrate sandy/mud with mixed shell.

2021 oyster survey density 0.93/m^2, mortality ≈10%.

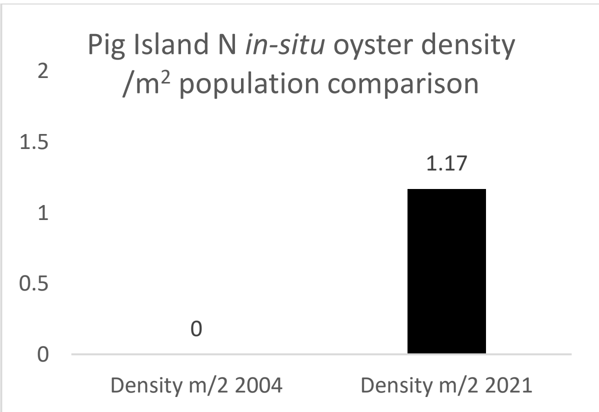


Site 7.

Pig Island N; 54.555492 -5.620274 a northern site no oyster settlements recorded in 2004.

Substrate sandy/mud with mixed shell and cobble.

2021 oyster survey density 1.17/m^2, mortality ≈12%.

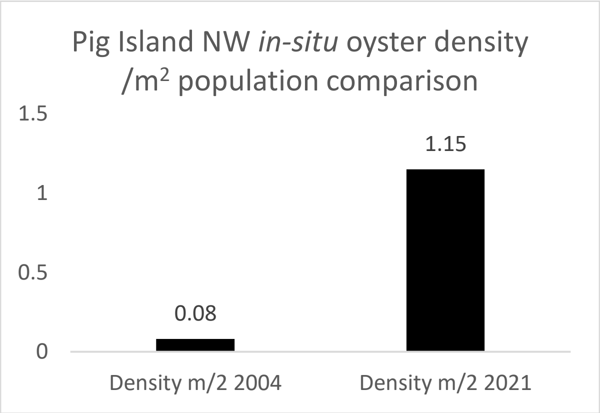


Site 8.

Pig Island NW; 54.554646 -5.620596 a northern site.

Substrate sandy/mud with mixed shell and cobble.

2021 oyster survey density 1.15/m^2, mortality ≈10%.

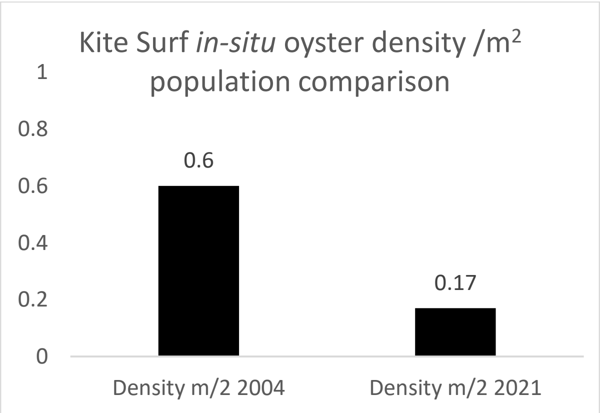


Site 9.

Kite Surf; 54.562304 -5.639949 a northern site, reports of intense gathering during November.

Substrate sandy/mud with mixed shell predominantly *M. edulis* and cobble.

2021 oyster survey density 0.17/m^2, mortality 10-15%.

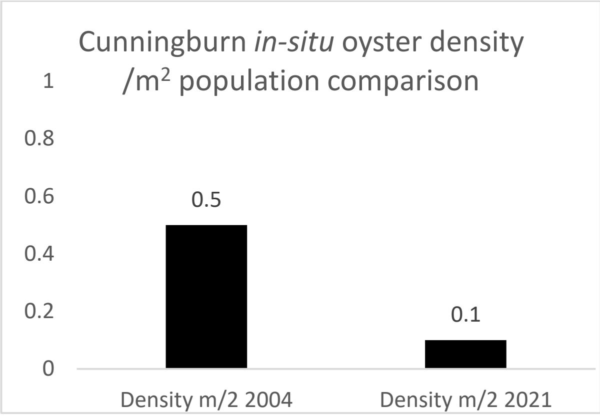


Site 10.

Cunningburn; 54.561669 -5.632417 a northern site, regularly visited by harvesters.

Substrate sandy/mud with mixed shell predominantly *M. edulis*

2021 oyster survey density 0.1/m^2, mortality 15%.

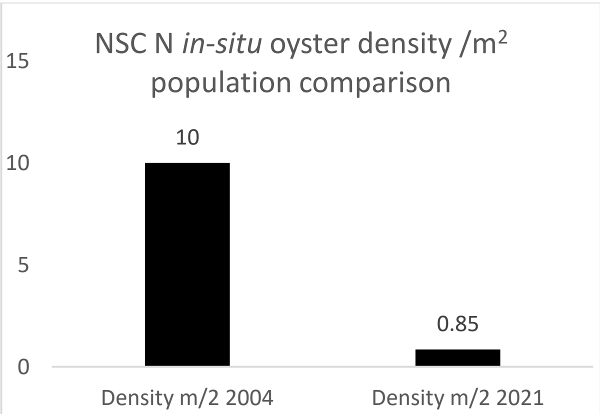


Site 11.

NSC N; 54.560338 -5.6307 a northern site, harvesting witnessed November and December

Substrate sandy/mud with mixed shell predominantly *M. edulis*

2021 oyster survey density 0.85/m^2, mortality ≈12%.



Site 12.

NSC S; 54.558721 -5.622945 a northern site, harvesting reported in October and December.

Substrate sandy/mud with mixed shell, predominantly *M. edulis*.

2021 oyster survey density 0.95/m^2, mortality ≈16%.

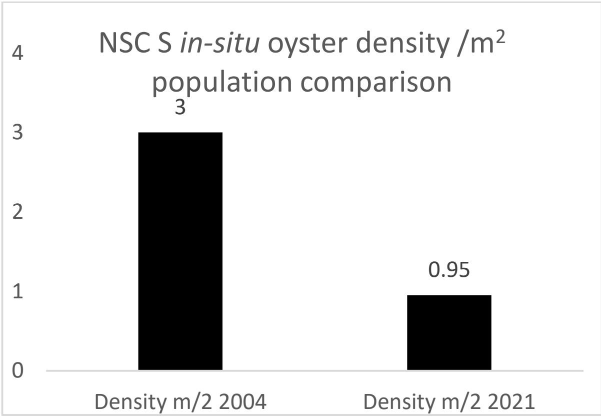


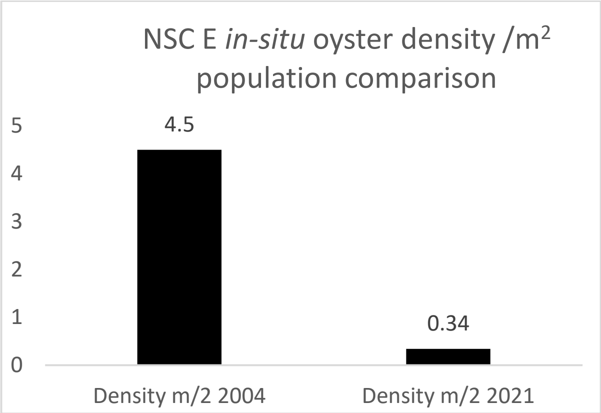
Figure 10. Intertidal pools created by mussel banks at NSC, site of the first documented *O. edulis* reef formations within Europe and the UK (Kregting et al., 2020).

Site 13.

NSC E; 54.558994 -5.629769 a northerly site, harvesting witnessed November and December.

Substrate sandy/mud with mixed shell, cobble and pebble.

2021 oyster survey density 0.34/m^2, mortality ≈16%.

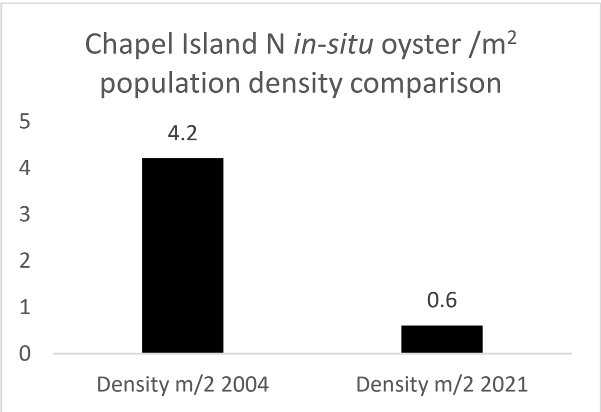


Site 14.

Chapel Island N side; 54.530142 -5.601248 a northerly site, harvesting reported in previous years.

Substrate sandy/mud with mixed shell and pebble.

2021 oyster survey density 0.6/m^2, mortality ≈15%.

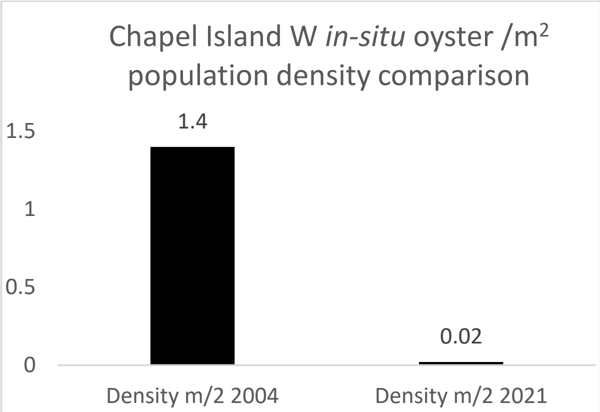


Site 15.

Chapel Island W side; 54.523686 -5.60186 a northerly site, harvesting reported in previous years.

Substrate sand/mixed shell and pebble.

2021 oyster survey density 0.02/m^2, mortality ≈10%.

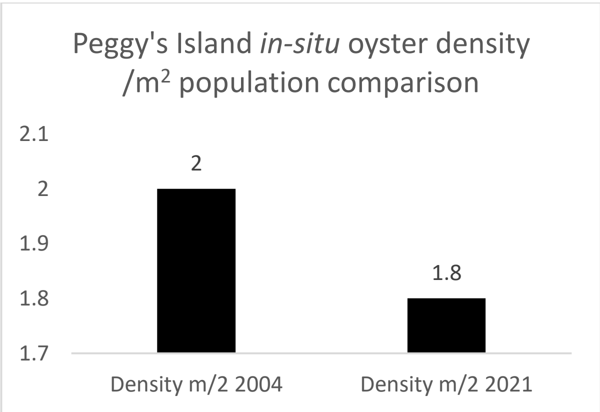


Site 16.

Peggy's Island; 54.541213 -5.604106 a northerly site.

Substrate sand/mixed shell.

2021 oyster survey density 1.8/m^2, mortality 8%.

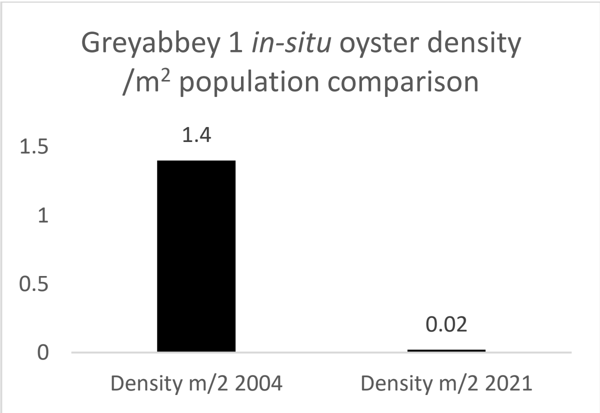


Site 17.

Greyabbey 1; 54.52576 -5.567595 northerly site, intense Littorinid harvesting in previous years.

Substrate sand/mixed shell and cobble.

2021 oyster survey density 0.02/m^2, mortality 15%.

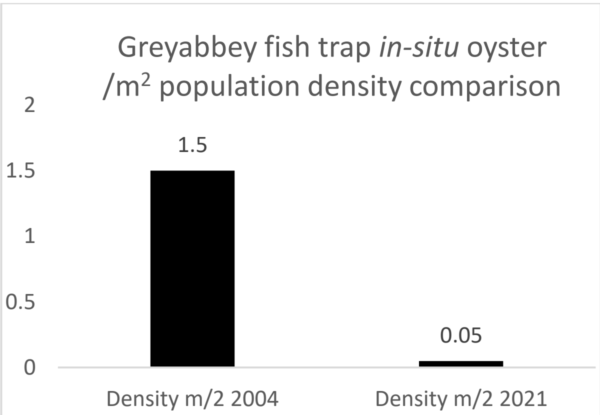


Site 18.

Greyabbey fish trap; 54.523991 -5.574032 northern site, harvested in previous years.

Substrate sand/mixed shell predominantly *M. edulis*.

2021 oyster survey density 0.05/m^2, mortality 18-20%.

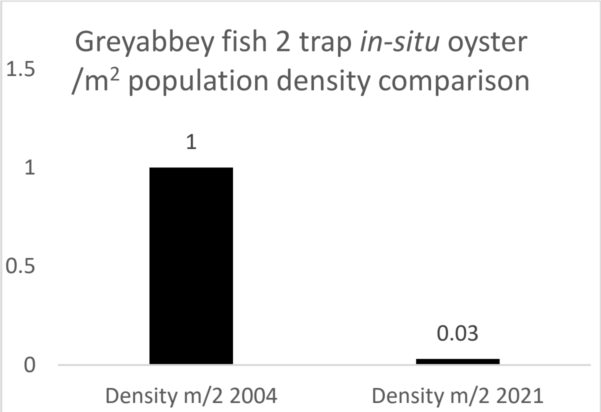


Site 19.

Greyabbey fish trap 2; 54.521198 -5.575322 northern site, harvested in previous years.

Substrate sand/mixed shell.

2021 oyster survey density 0.03/m^2, mortality 20%.

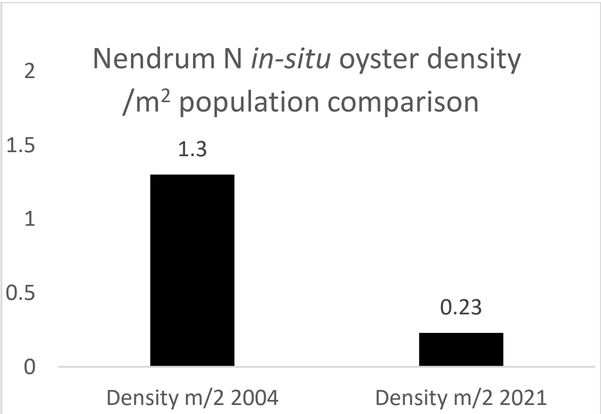


Site 20.

Nendrum N; 54.52277 -5.66113 a western site.

Substrate sand/mixed shell.

2021 oyster survey density 0.23/m^2, mortality 8%.

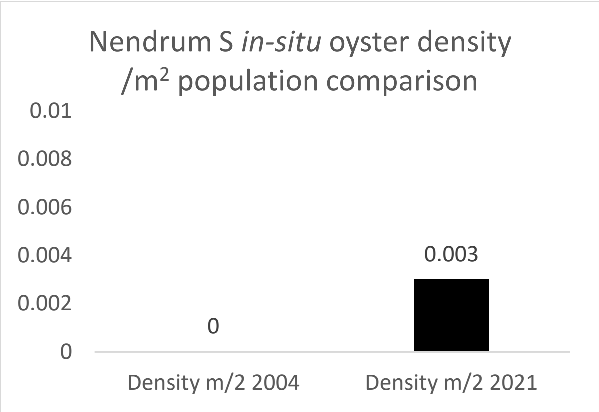


Site 21.

Nendrum S; 54.523615 -5.667013, western site.

Substrate sand/mixed shell.

2021 oyster survey density 0.003/m^2.

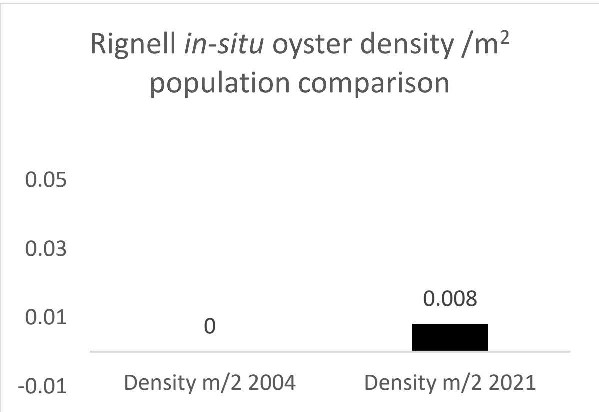


Site 22.

Rignell; 54.51958 -5.651911, western site.

Substrate sandy/mud with mixed shell.

2021 oyster survey density 0.008/m^2.



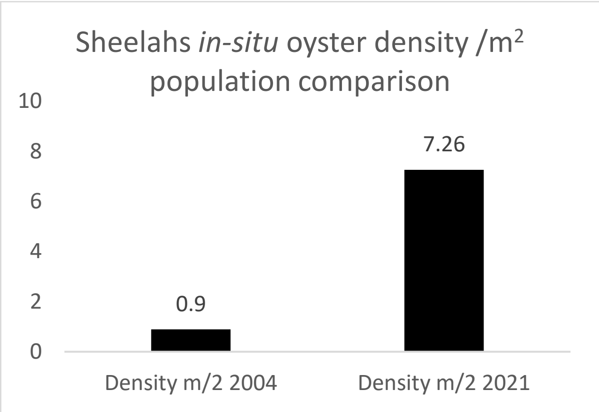
Site 23.

Sheelahs; 54.50578 -5.572396, eastern island site, previous years experienced intense harvesting. Gathering witnessed in September.

Significant assemblages of mature (>40) and Juvenile (<2yr) *Crassostrea gigas*.

Substrate sand/mixed shell and cobble.

2021 oyster survey density 7.26 /m^2, mortality 10%.

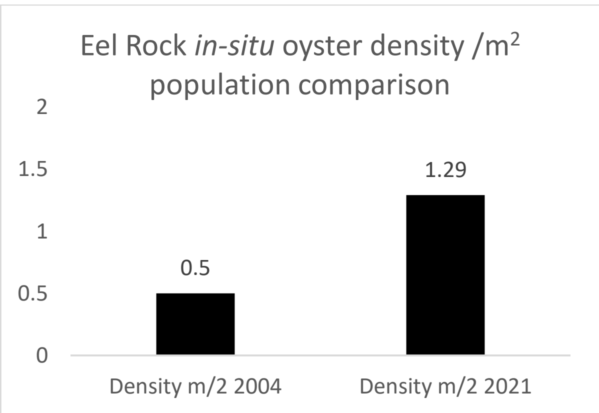


Site 24.

Eel Rock; 54.499448 -5.575743, eastern island site, harvested in previous years.

Substrate sand/mixed shell and cobble.

2021 oyster survey density 1.29 /m^2, mortality 5%.

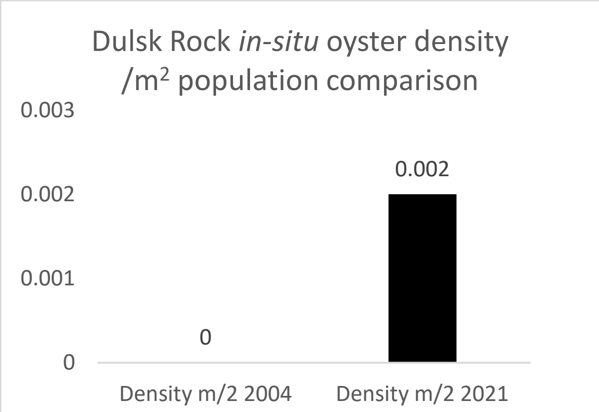


Site 25.

Dulsk Rock; 54.46002 -5.57349, eastern island site.

Substrate sand/mixed shell and cobble.

2021 oyster survey density 0.002 /m^2.



Site 26.

South Dougherty Rock; 54.49393 -5.5743, eastern site, harvested in previous years.

Juvenile (<2yr) *Crassostrea gigas*.

Substrate sand/mixed shell and cobble.

2021 oyster survey density 4.34/m^2, mortality 10%.

Majority of *O. edulis* between 80-120mm >5 years old, brood stock oysters.

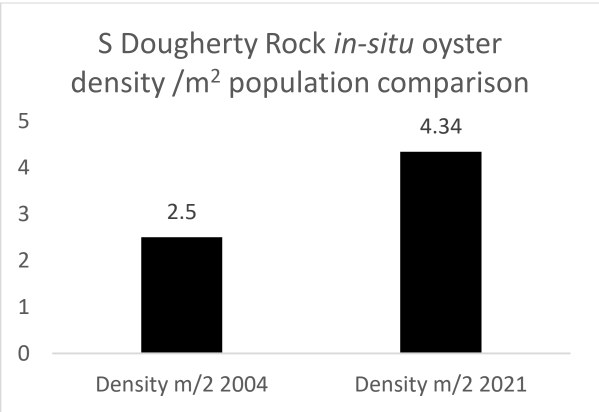


Figure 11. Juvenile *Crassostrea gigas*(<2yr) are settled on the majority of island sites.

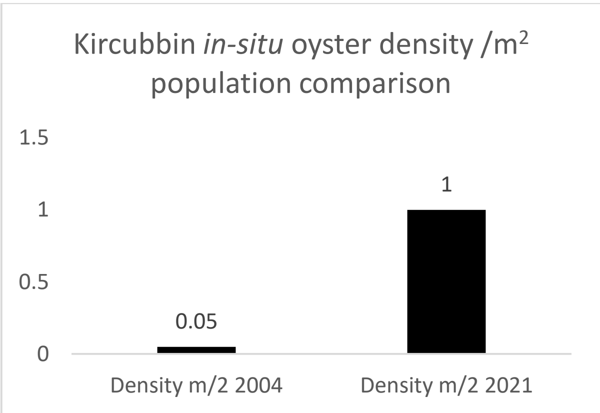
Site 27.

Kircubbin; 54.488644 -5.538985, eastern intertidal site.

Juvenile (<2yr) *Crassostrea gigas* <60mm.

Substrate sand/mud and mixed shell.

2021 oyster survey density 1.0 /m^2 mortality 10-15%.



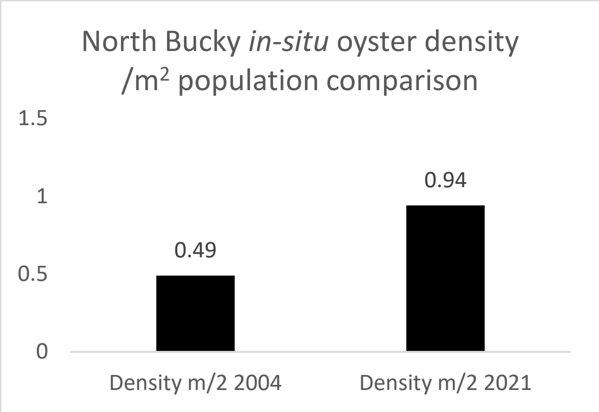
Site 28.

North Bucky; 54.47567 -5.57023, eastern site harvested in previous years.

Juvenile (<2yr) *Crassostrea gigas* <60mm.

Substrate sand/mud and mixed shell.

2021 oyster survey density 0.94 /m^2 mortality 10%.



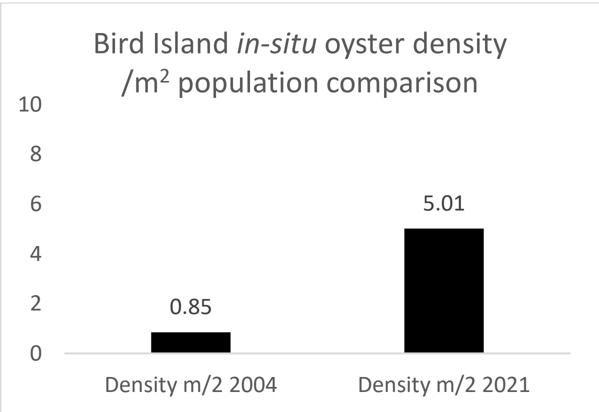
Site 29.

Bird Island; 54.48029 -5.57895, eastern island, harvested in previous years.

Adult *C. gigas* approx. 4-6yrs.

Substrate sand/mud and mixed shell.

2021 oyster survey density 5.01 /m^2 mortality < 10%.



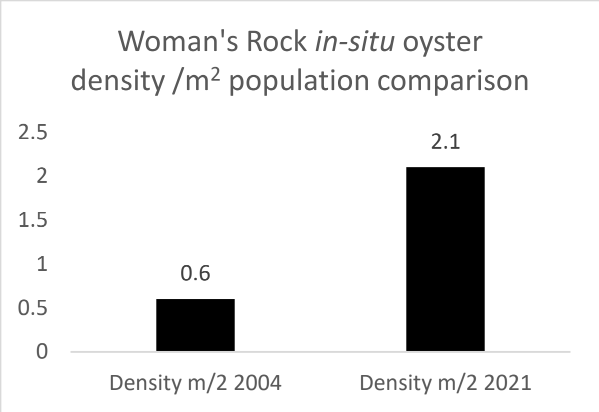
Site 30.

Woman’s Rock; 54.47913 -5.56575, eastern island, harvested in previous years.

Harvesting witnessed November.

Substrate sand/mud and mixed shell.

2021 oyster survey density 2.1 /m^2 mortality < 10%.



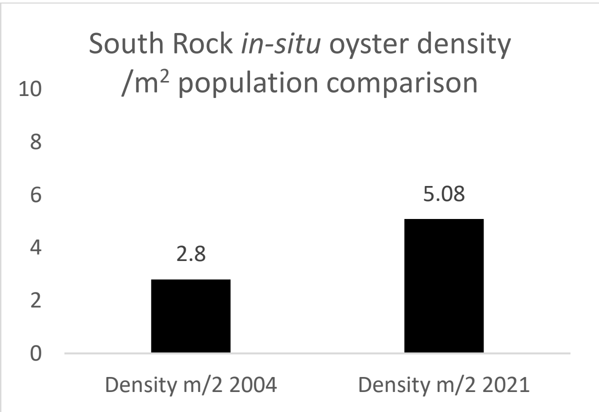
Site 31.

South Rock; 54.47072 -5.5803, eastern island, harvested in previous years.

Substrate sand/mud and mixed shell.

2021 oyster survey density 5.08 /m^2 mortality 8%

Majority of *O. edulis* between 80-120mm >5 years old, brood stock oysters.



Site 32.

South Buckey; 54.47221 -5.5741, eastern island, harvested in previous years.

Significant numbers of *C. gigas* 4-6yrs age on the western shore of South Buckey.

Substrate sand/mud and mixed shell.

2021 oyster survey density 0.9 /m^2 mortality 10%.

Majority of *O. edulis* between 80-120mm >5 years old, brood stock oysters.

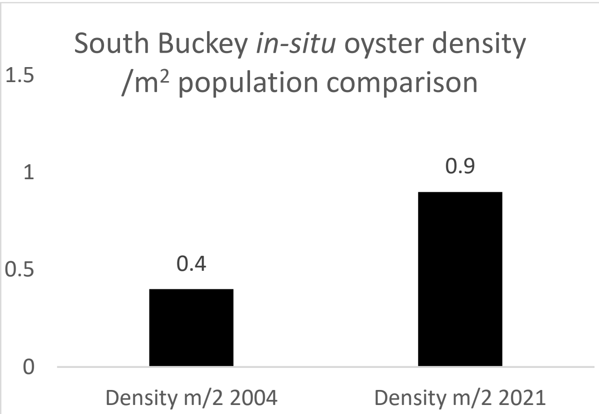


Figure 12. *C. gigas* 4-6yrs age on the western shore of South Buckey.

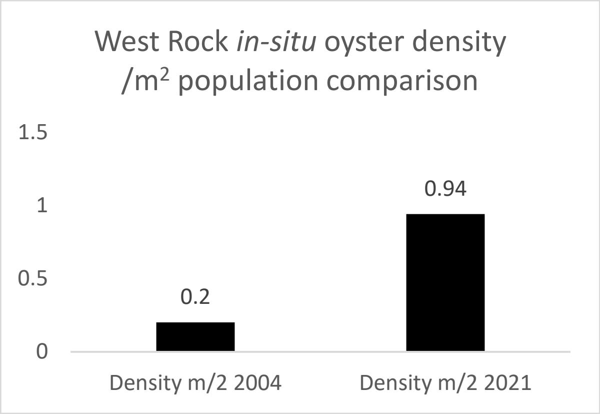
Site 33.

West Rock; 54.473658 -5.58373, eastern island, harvested in previous years.

Substrate sand/mud and mixed shell.

2021 oyster survey density 0.94 /m^2 mortality 10%.

Majority of *O. edulis* between 80-120mm >5 years old, brood stock oysters.



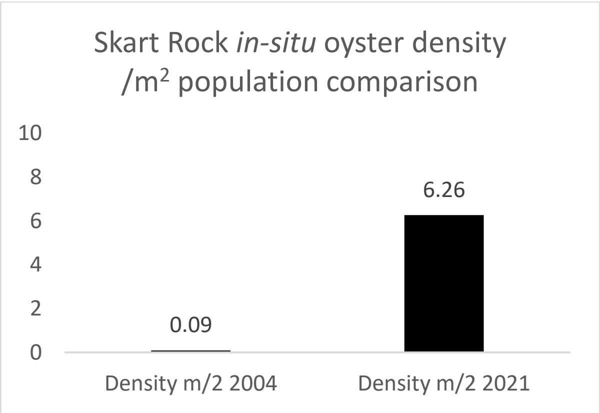
Site 34.

Skart Rock; 54.469545 -5. 580546, eastern island, harvested in previous years.

Substrate sand/mud and mixed shell.

2021 oyster survey density 6.26 /m^2 mortality 10%.

Majority of *O. edulis* between 80-120mm >5 years old, brood stock oysters.



Site 35.

Horse Island; 54.466762 -5.540934, eastern intertidal site, harvested in previous years.

Harvesting witnessed on three separate occasions in December 2021. **Harvesters witnessed on the 29/03/2022 in possession of an estimated 1,500-2,000 native oysters and two sacks of winkles.**

A follow-up survey undertaken on the 30/03/2022 recorded the almost total removal of the entire native oyster assemblage of Horse Island. This is reflected in the three-bar histogram below.

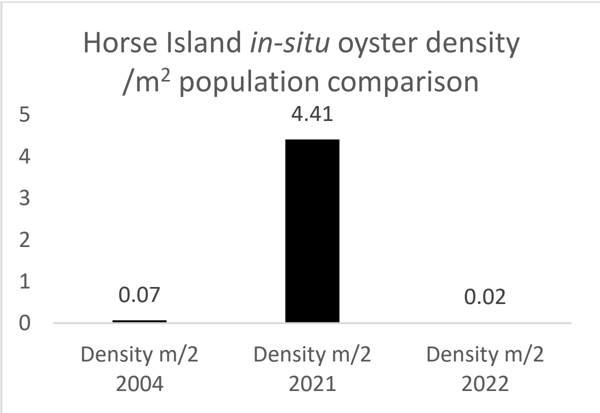


Figure 13. Harvesters returning to Horse Island carpark 29/03/2022 with an estimated 1,500 to 2,000 native oysters.

Site 36.

Inisharoan; 54.479443 -5.617885, western island site.

Substrate boulder/cobble with mixed shell

No native oyster assemblages recorded in 2004 or in 2021.

Site 37.

Inishanier; 54.477648 -5.610332, western island site.

Substrate boulder/cobble with mixed shell

No native oyster assemblages recorded in 2004 or in 2021.

Site 38.

Roe Island; 54.47306 -5.618744, western island site.

Substrate boulder/cobble with mixed shell

No native oyster assemblages recorded in 2004 or in 2021.

Site 39.

Killyleagh; 54.398293 -5.580546, western intertidal site.

Substrate, sand and cobble with mixed shell

No native oyster assemblages recorded in 2004 or in 2021.

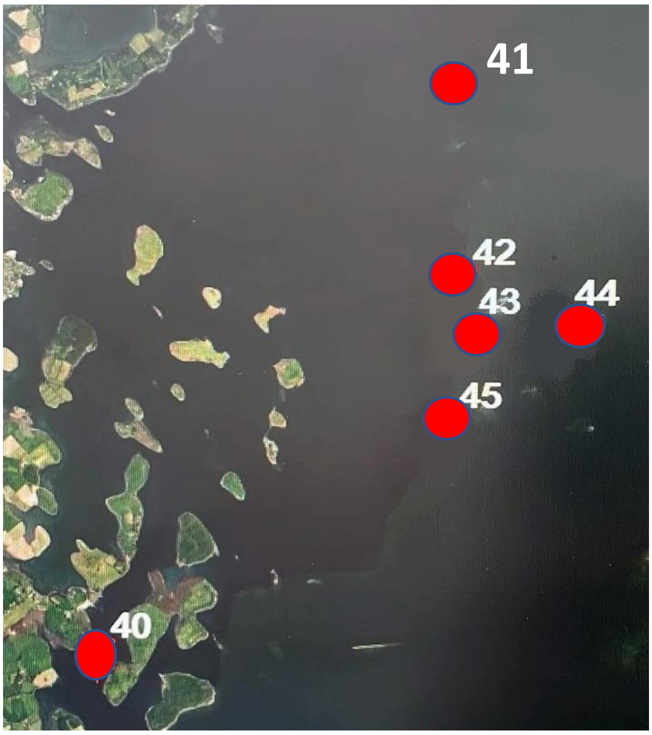


Figure 14. Subtidal dive surveys were contained within the boundary of the red marker.

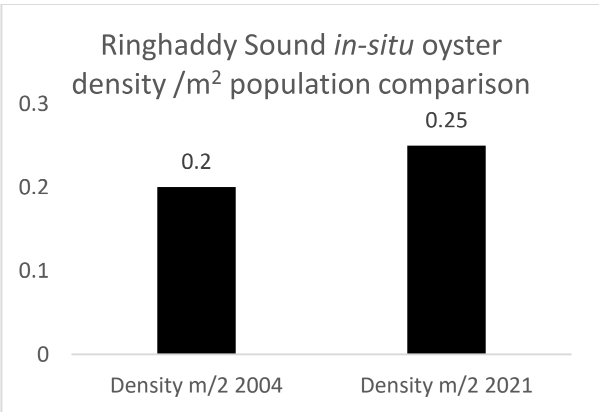
Site 40.

Ringhaddy Sound; 54.445211 -5.632330, western subtidal site, history of oyster stocks dating back to the 1600s.

Substrate, mud with mixed shell.

2021 oyster survey density 0.25 /m^2 mortality ≈10%.

Majority of *O. edulis* between 80-120mm >5 years old, brood stock oysters.



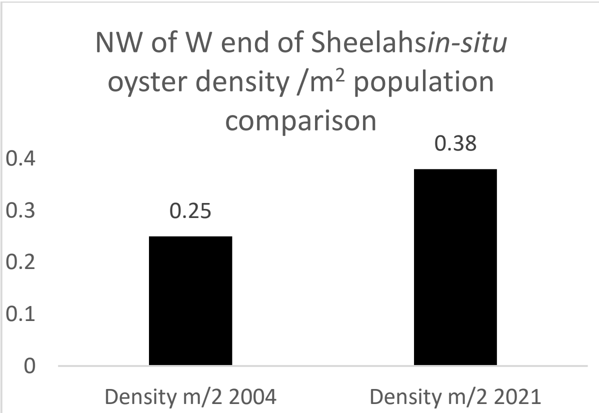
Site 41.

NW of W end of Sheelahs; 54.504279 -5.584930, central subtidal site.

Substrate, mud with mixed shell.

2021 oyster survey density 0.38 /m^2 mortality ≈10%.

Majority of *O. edulis* between 80-120mm >5 years old, brood stock oysters.

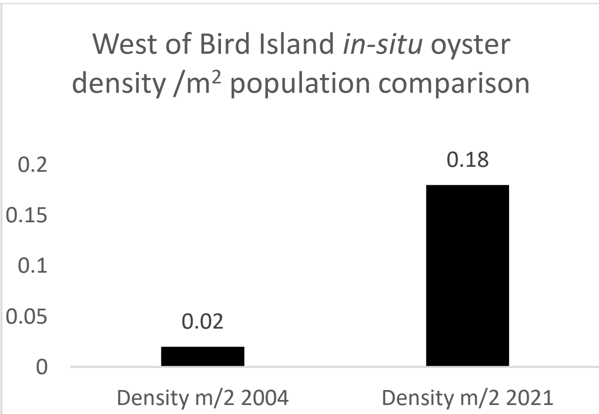


Site 42.

West of Bird Island; 54.480786 -5.583428, eastern subtidal site.

Substrate, mud with mixed shell.

2021 oyster survey density 0.18 /m^2 mortality ≈10%.

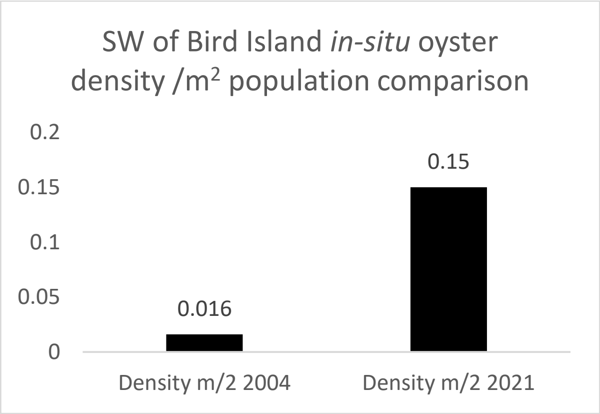


Site 43.

SW of Bird Island; 54.476 -5.583686, eastern subtidal site.

Substrate, mud/sand with mixed shell.

2021 oyster survey density 0.15 /m^2 mortality ≈10%.

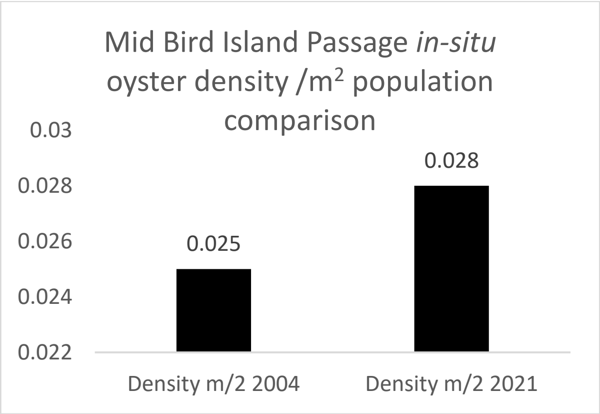


Site 44.

Mid Bird Island Passage; 54.477433 -5.570811, eastern subtidal site

Substrate, mud with mixed shell.

2021 oyster survey density 0.028 /m^2 mortality ≈10%.

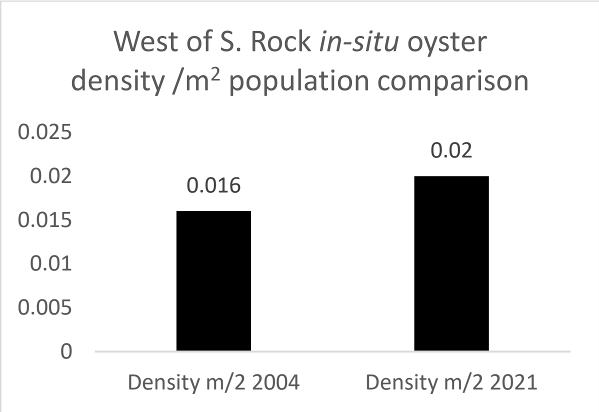


Site 45.

West of S Rock; 54.467957 -5.585574, eastern subtidal site.

Substrate, mud/sand with mixed shell.

2021 oyster survey density 0.02 /m^2 mortality ≈10%.



In-situ O. edulis site densities 2021

Intertidal:

The *in-situ* transect densities were compared with data from 2004. Native oyster numbers in 2004 were showing a decline from peak densities in 2003 (Smyth et al., 2009) and therefore considered a good match, as sites from both survey dates would have been exposed to harvesting pressure.

In 2021 a total of 24 intertidal sites were surveyed (Figures 2-7) 16 of these showed a decline in oyster density since 2004. The sites can all be considered as easy access with sporadic bouts of oyster harvesting being witnessed over the 17 years. The declines cannot be attributed to disease as dead oysters within the intertidal population were recorded at ≈10%. If *Bonamia ostreae* had been a factor in the intertidal population mortalities, the mortality rate would have been considerably higher. At the time of writing seven sites did experience an increase in oyster density with the exception of Kircubbin; none of the sites could be considered regular harvesting sites. However, *in-situ* oyster numbers may have changed as these sites as surveying took place in mid-September 2021. Intertidal shellfish gathering in Strangford Lough was intense between February and April 2022 and these sites may have been targeted. The western intertidal site of Killyleagh remained unchanged since 2004 with no oyster assemblages recorded in 2021.

Island:

In 2021, fourteen island sites were surveyed. Eleven sites experienced a significant increase in oyster densities with the others remaining unchanged. The data revealed densities and oyster sizes at the eastern island sites (Figure 6) which can be considered as a larval supplying brood stock.

Mortality within the native oyster island population remained low with site percentages ≈10%. This continuity in low mortality throughout the Loughs *O. edulis* assemblages suggests that after more than 20 years of genetic selection the resident native oysters have developed a degree of resilience to the parasitic *Bonamia ostreae.*

In 2004 intense harvesting was witnessed throughout the island sites. The present data suggests that harvesting has been limited over the last 17 years and on some islands absent as assemblages of oysters of >110mm in shell length (an approximate age of 8-12 years) were found at a number of sites.

Subtidal:

The 2021, subtidal survey encompassed a total of six sites, all revealed an increase in oyster densities. However, densities are particularly low with the highest being 0.25 /m^2 recorded at Ringhaddy Sound. Substrate type at all sites had a high mud percentage which could explain the unchanged densities over the 17 years. A substrate type with a high mud content can be a considerable limiting factor in oyster larval settlement. Siltation from substrate disturbance can cover shell surfaces and thereby reduce the availability of suitable larval attachment material. Subtidal oyster densities within the lough could be considerably increased through the deployment of natural shell cultch using protocols which are currently being practiced by other native oyster restoration projects in the UK and Ireland (Pogoda et al., 2019; Smyth, 2020).

Gunderson Population Model Output 2021

In-situ 2021 native oyster site densities /m^2 were subjected to the Gunderson (1993) population model which estimates total oyster densities based on available substrate suitable for larval settlement.

Table 2. Intertidal Gunderson population model estimates, 2004 and 2021 for total available substrate coverage in the northern basin of Strangford Lough.

Basin	*Intertidal area m^{-2} ($x10^6$)*	*Substratum Correction factor**	*Area suitable for settlement m^{-2} ($x10^6$)**	*Standing stock Oysters+ ($x10^3$) 2004*	*Standing stock Oysters+ ($x10^3$) 2021*
North	29, 591	Region 1 (0. 056)	11. 000	964.0	58.212
		Region 2 (0. 236)	1. 064	1.0	88.242
		Region 3 (0. 027)	0. 146	0.5	0.35
Total			**12. 21**	**964. 6**	**146.804**

Table 3. Subtidal Gunderson population model estimates, 2004 and 2021 for total available substrate coverage in the northern basin of Strangford Lough.

Basin	*subtidal m^{-2} (x 10^6)*	*Substratum Correction Factor**	*Area suitable for settlement m^{-2} ($x10^6$)**	*Standing stock Oysters+ ($x10^3$) 2003-2004*	*Standing stock Oysters+ ($x10^3$) 2021-2022*
North	26. 816	Region 1 (0. 234)	6. 274	0. 4	0
		Region 2 (0. 236)	7. 627	0. 2	1.363
		Region 3 (0. 019)	0. 185	0. 6	0.008
Total			**14. 086**	**1. 2**	**1.371**

Native oyster *Ostrea edulis* Population Dynamics 2021

Ostrea edulis population dynamics were based on *in-situ* size density data which was categorised into five cohorts which could be approximated into age classes as per Walne (1974) and Richardson et al., (1993). Individual site locations were divided into survey specific regions; intertidal, Island and subtidal. All *in-situ* data were pooled and assigned a size cohort in mm; 1-30, 31-60, 61-90, 91-120 and 121-150 specific to each region.

Walne (1974) successfully identified the larval output from brooding native oysters based on size. The determination of age within native oyster populations can be used to predict spawning output and the overall potential for population growth.

Table 4. Number of larvae produced per *O. edulis* in relation to approximate age and size (Walne, 1974).

Age (Years)	***Mean shell diameter (mm)***	***Number of larvae***
1	40	100,000
2	60	540,000
3	70	840,000
4	80	1,100,000
7	90	1,500,000

However, the presence of oysters of > 80mm will not guarantee high fecundity and large spawning events. The density of oysters and proximity of fecund adults are the governing factors in spawning success (Guy et al., 2019). Guy et al., (2019) showed that oysters with a nearest neighbour ≤1.5 m were found to brood significantly more larvae than individuals with nearest neighbours ≥1.5 m. This is of particular relevance in 2021 as native oyster stocks which remain at harvested sites will be extremely fragmented and unlikely to spawn successfully.

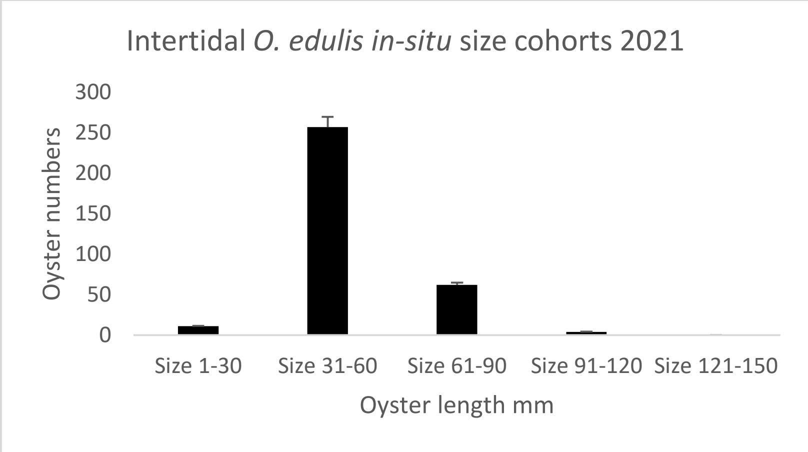


Figure 14. Intertidal sites *in-situ* native oyster size densities per cohort.

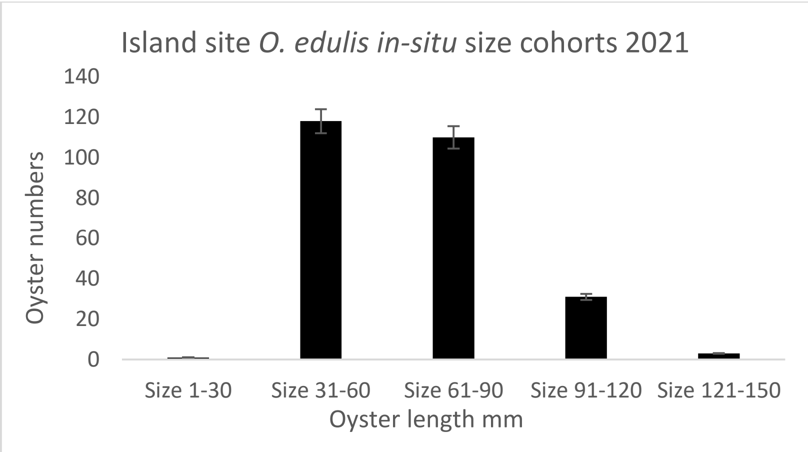


Figure 15. Island sites *in-situ* native oyster size densities per cohort.

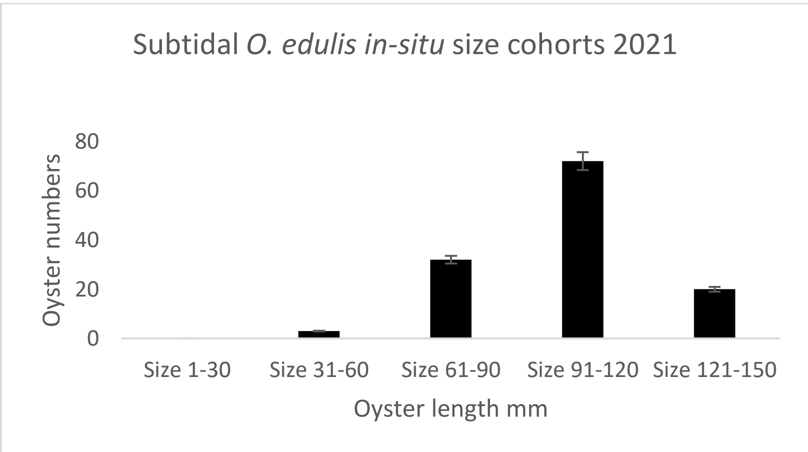


Figure 16. Subtidal sites *in-situ* native oyster size densities per cohort.

Discussion

Intertidal:

The 2021 intertidal population of native oysters in Strangford Lough can be considered in a state of poor conservational health with a high likelihood of being categorised as biologically non-functional. The oyster assemblages are dominated with oysters ranging between 31-60mm in size, approximately year 1-2 with a low potential larval output (Table 4).

The fecundity of these intertidal sites is further reduced when we consider that the average *in-situ* densities have dropped from 3.36/m^2 in 2004 to 0.44/m^2 in 2021. Fragmentation of oyster densities /m^2 to this degree do not correspond to successful spawning and settlement (Guy et al. 2019).

Island:

In contrast the *O.edulis* island population of 2021 (2.63/m^2), has shown a marked increase in densities since 2004 (0.72/m^2). The Gunderson (1993) model estimated a growth in the *O. edulis* island population from approximately 1000 individuals in 2004 to >88,000 in 2021 (Table 2). The island population is predominantly made up of oysters in the 4–7-year age categories. Oysters of this size can produce maximal larval outputs under suitable conditions. The fecundity of the island oysters has the potential to be high as the density /m^2 will be considerably closer than that found on the more expansive areas of the intertidal. Indeed, it would appear that the island populations are currently acting as a brood stock source for the entirety of Strangford Lough.

However, these sites remain vulnerable to harvesting. It is only changes to the community make-up of those involved in unregulated harvesting and the difficulty in accessing these sites which has probably protected the island oysters.

Subtidal:

The 2021 subtidal population contained the highest density of oysters of >7 years of age (Av. Density 2004: 0.09 2021: 017) hese assemblages were composed of the most fecund individuals in the Lough. However, the oysters were very fragmented and the lack of suitable silt-free settlement material will always limit successful larval settlements. Indeed, it is these limiting parameters which have probably led to the relatively unchanged densities and sizes at the subtidal sites over the past 17 years (Table 3). If substrate type was improved through the laying of cultch a more biologically functional subtidal population could feasible.

Modelling native oyster larval output for key sites Strangford Lough 2021

The establishment and successful longevity of oyster habitats within the Ostreidae family is governed by a number of parameters however, the most influential are undoubtedly density of brooding oysters and sufficient coverage of suitable settlement material (Dayton et al., 1995; Peterson et al., 2003; Smyth et al., 2016; Smyth et al., 2018). A comprehensive understanding of the hydrodynamics of a region is vital to comprehend the dynamics of the oyster post-spawning larval dispersal, the pelagic phase and the final settlement (Lipcius and Ralph, 2011). Smyth et al., (2016) constructed an in-depth particle tracking model specific to *O. edulis* larvae for high density native oyster settlements in the north of Lough.

The present research revealed that the geographical and population dynamics of oyster settlements in the Lough has drastically changed over the 17-years since the last survey. The northern sites can no longer be considered as larval sources as densities are now too low and oyster sizes too small. The 2021 survey however did document two new sites which could be considered as larval sources, Skart Rock and Horse Island. Both of these sites had high densities of mature oysters in close proximity to one another. In an attempt to understand the settlement coverage of a spawning event from these two sites the Smyth et al. (2016) model was ran for Skart Rock and Horse Island.

Methodology

Simulation of O. edulis larval dispersal

In order to simulate the dispersal of *O. edulis* larvae a particle tracking module was coupled to the Kregting and Elsäßer (2014) Strangford Lough hydrodynamic model using MIKE 21 modelling software (DHI Water and Environment software package; (www.dhisoftware.com)).

In brief, the model determined the current by solving a depth integrated incompressible Reynolds averaged Navier–Stokes equation. The model was calibrated using tidal elevation data from seven sites and current speed data from four sites throughout Strangford Lough. To quantify the performance of the model compared to observed data (validation of the model), several quantitative metrics were used to capture different aspects of model performance: modelling efficiency, skill, root mean square and bias (Stow et al., 2009; Dias and Lopes, 2006). The results showed an excellent agreement between modelled and observed tidal elevation and good to excellent agreement between modelled and observed current data (Kregting and Elsäßer, 2014). A high degree of confidence in the performance of the numerical model could therefore be placed into predicting the larval dispersal of *O. edulis* for the purposes of this study.

The tidal flows were simulated from June to August when peaks in spawning of *O. edulis* in Strangford Lough have been reported (Kennedy and Roberts, 1999). In order to reduce the computational time for different particle tracking simulation over these periods, the depth averaged velocity results (u and v velocity) and the bed friction velocity of the hydrodynamic simulations were saved as decoupled output files.

Particle dispersal modelling was used to examine:

The larval flow of newly recorded brood stock sources in 2021 at Horse Island and Skart Rock. Particles were released where populations showed the greatest densities. Because the exact timing of the spawning of *O. edulis* was not known, 200 particles were released every 5 min

throughout the four-month summer period (June to September) when peak spawning events are most likely to occur. This resulted in a total of 57,600 particles released per day.
There are two mechanisms directly affecting the transport of particles in the marine environment: advection and dispersion. Advection describes the transport of particles by mean water flow and dispersion is influenced by diffusive processes both molecular and turbulent of which turbulence is the main driver in diffusive processes in natural waters. Therefore, the movement of larvae in the horizontal and vertical dimensions was simulated by applying a random walk procedure using the Langevin equation (Pope, 2000) which simulates both dispersion and advection with zero sinking velocities assumed. Although the hydrodynamic model derives only depth averaged velocities, the particle tracking model uses the bed friction velocity from the hydrodynamic model to derive a logarithmic bed profile to estimate the change in velocity with depth. In view of the lough being well mixed, the logarithmic velocity profile was deemed appropriate.

The lough is known to have intricate flow patterns with considerable eddying around the various pladdies and islands (Kregting and Elsäßer, 2014) with elevated turbulence intensity as a result of the high inflow velocities close to the entrance and the complex bathymetric features. A scaled eddy viscosity formulation was used for horizontal dispersion of the particles with a dispersion coefficient of 1.1 similar to that used in the hydrodynamic model (Kregting and Elsäßer, 2014).

Particles were released 0.1m above the substrate in the shallow subtidal regions, simulating the height of the wild oyster populations in the lough. Larvae released into the water column remain as free swimming planktotrophic stage between 7 and 15 days before settlement. Therefore, 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/m^2. Wind drift was taken into account in the particle tracking models. Wind forcing in the model was user specified varying in time using the input parameters speed and direction with data obtained from the ERA-Interim project supplied by the European Centre for Medium-Range Weather Forecasts (Dee et al., 2011) for the June–September period in 1995, 1998 and

2001. There is also a nearby weather station at Orlock Point (54.667°N, 5.583°WWGS84) on the shore of Belfast Lough. However, in this instance for the simulations the data was found to be incomplete for some of the years and is also biased with higher wind speeds from the north due to the exposure of the weather station at the shore and its elevation. A parabolic drift profile (Al-Rabeh, 1994) was derived with the drift direction taking into account relevant Coriolis forcing. Time series analysis was used at the sites of interest.

Output 2021 particle dispersal model

Horse Island: NO LONGER RELEVANT AS OYSTERS REMOVED BY HARVESTERS MARCH 2022

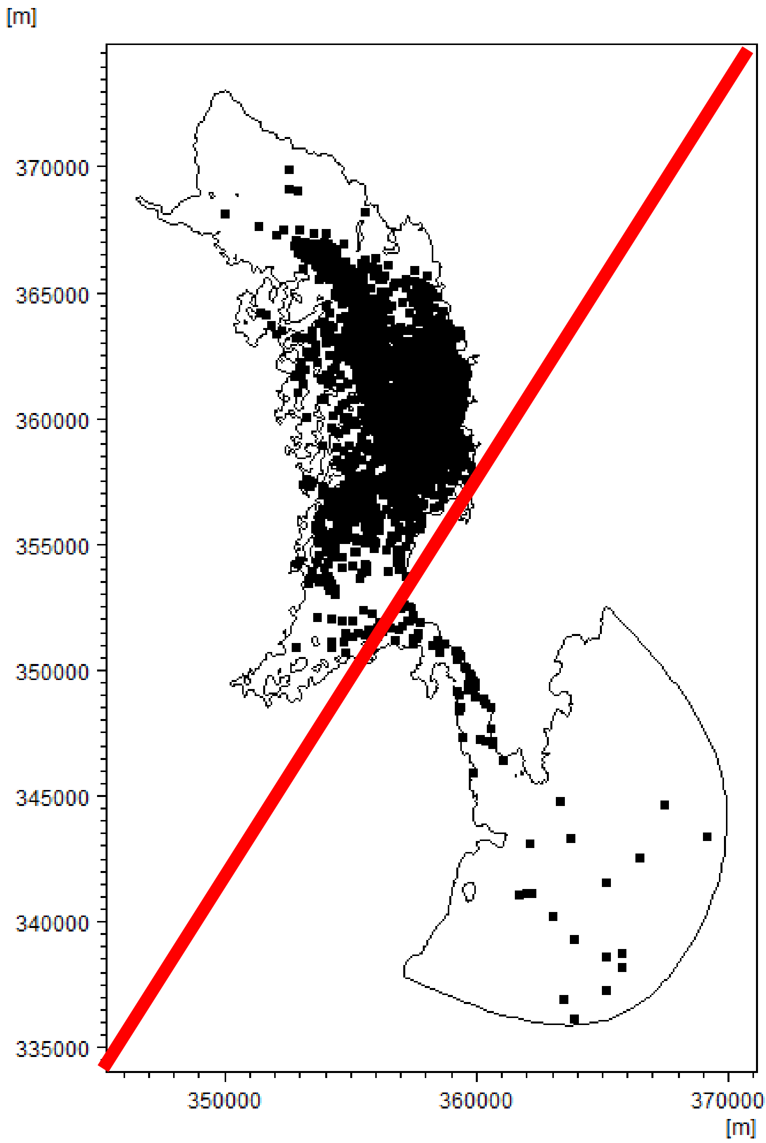


Figure 17. Particle tracking model output specific to *O. edulis* larvae released from the lower intertidal at Horse Island.

Skart Rock

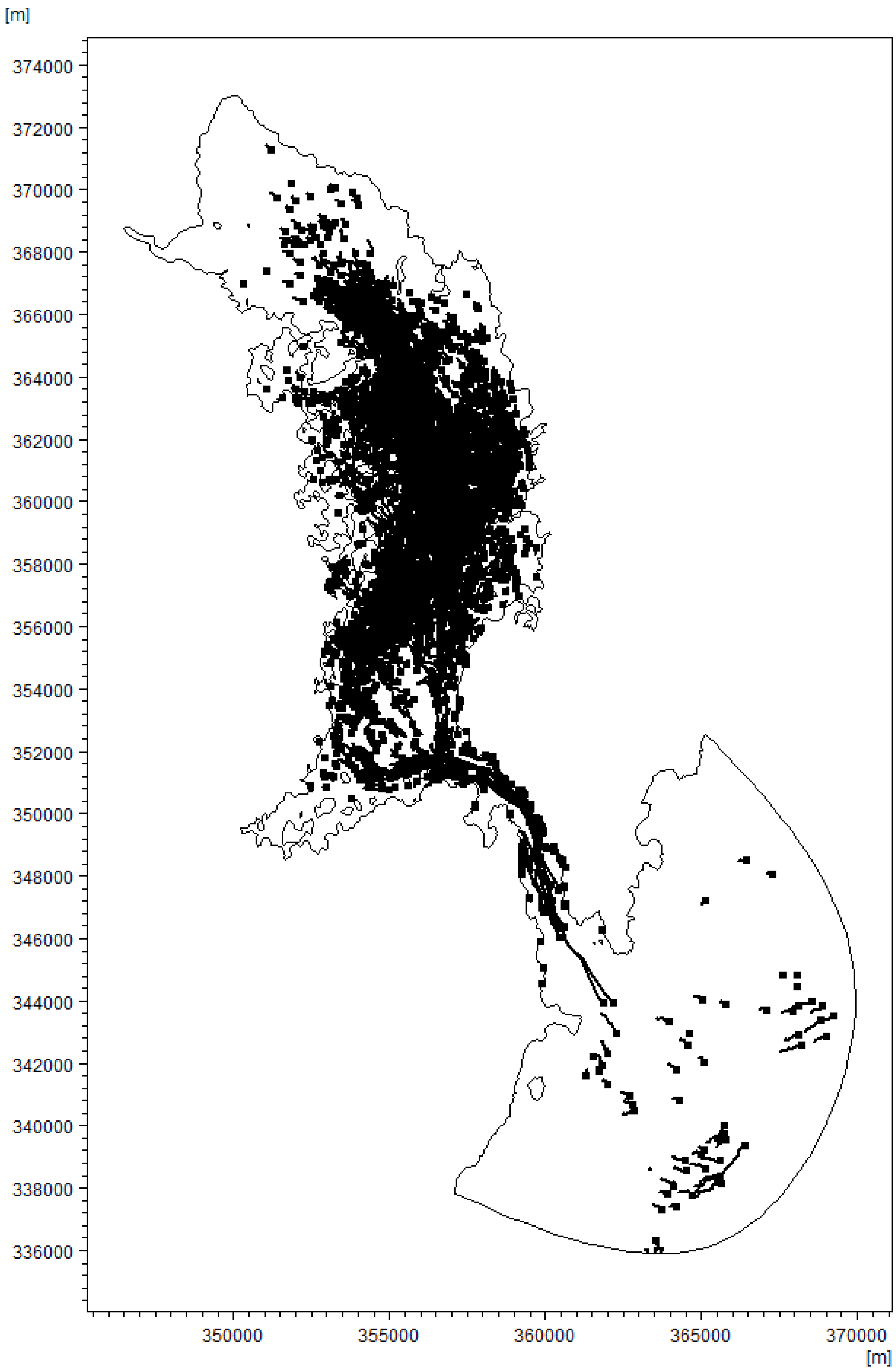


Figure 18. Particle tracking model output specific to *O. edulis* larvae released from the lower intertidal at Skart Rock.

Northern sites 2003-2004

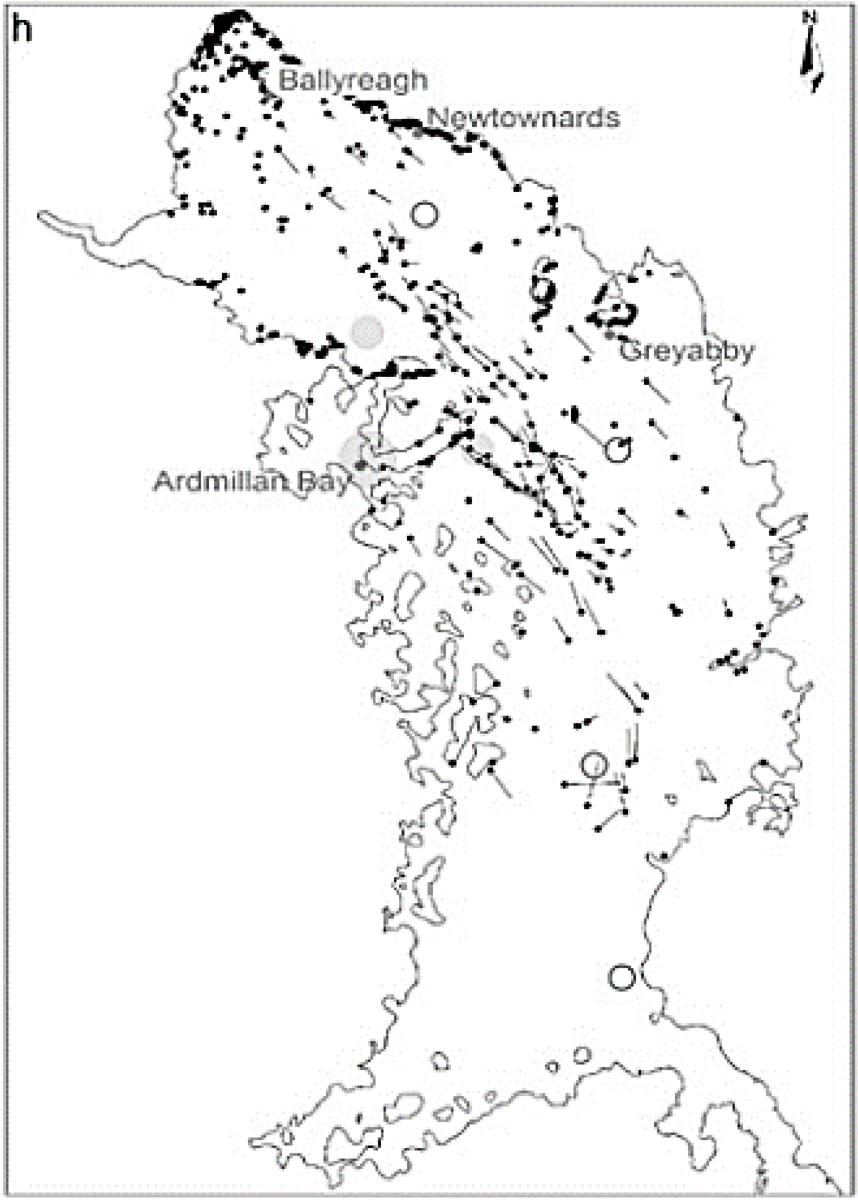


Figure 19. Particle dispersal model output for *O. edulis* larvae releases from northern sites four years post spawning event of the 1998 Ardmillan commercial stock.

Discussion

The 2021 modelling output for the newly recorded high-density oyster assemblages at Skart Rock and Horse Island revealed, *O. edulis* larval dispersal patterns that could reach the majority of sites within the Lough which have suitable settlement substrate (Figures 17 and 18). However, the most northerly sites at Ballyreagh which once accommodated the highest native oyster numbers in the Lough would be outside the initial pelagic phase of a spawn (Smyth et al., 2009). Nonetheless, if the hypothetical oyster settlements from Skart Rock and Horse Island were allowed to develop over a period of 5-10 years the northerly sites could once again become self-sustaining entities. The Smyth et al. (2016) model showed the hydrodynamic regimen for the north of the Lough could accommodate self-sustaining oyster sites at Ballyreagh, Newtownards Sailing Club and Greyabbey once a viable spawning assemblage was functional (Figure 19).

Unfortunately, the impact of harvesting on a recovering oyster population was witnessed during a follow-up survey of Horse Island. The site was first surveyed in early October 2021 in a follow-up survey in early April 2022 it was discovered that most of the standing stock had been removed and two harvesters were witnessed caring an estimated 1,500-2,000 oysters of the shore. The harvesting at this site negated the possibility of the Horse Island oyster assemblages making any contribution to future larval numbers. Indeed, the removal of oysters from the site was so comprehensive that it is unlikely that recovery will take place over the next 10 years. The native oyster settlements at Ballyreagh experienced a similar total removal in 2005 and the site has yet to show any significant signs of recovery some 17 years after the event.

Unregulated Harvesting

The unsustainable exploitation of the native oyster has been an issue throughout its geographical range since the 1700s. In the mid-1800s, harvesting was so intense that many sites which were regarded as prolific remain absent of *O. edulis* more than 200 years after the event (Thurstan et al. 2013; Smyth et al. 2017; Pogoda et al. 2019; Smyth et al., 2020). This was the situation for the native oyster in Strangford Lough for >100 years, until an inadvertent restoration from a spawning commercial stock in 1998 (Kennedy and Roberts 2006). This recovery in oyster numbers seen the Lough's population rise from a few 1,000 to > 1.2 million over five years (Smyth et al. 2009). However, as a result of intense shellfish gathering the population decreased to ≈500,000 in less than three years (Smyth et al.2020).

The 2021 survey witnessed several harvesting incidents between October 2021 and March 2022. All with the exception of one focused on easy access sites along the eastern shore. The harvesting can only be described as industrial in nature with full mesh sacks of various shellfish species lined up along the low intertidal for removal by additional team members in refrigerated vans. The events at Horse Island demonstrating the scale of harvesting whereby oyster density /m^2 dropped from 4.41 in October to 0.02 in March.

The 2021 Gunderson (1993) model of Strangford Lough's *O. edulis* population revealed the extent of decline since 2004 with a drop from 964,000 to 146,000 in 2021. Population dynamics surveys for 2021 showed intertidal sites to be dominated by small size cohorts of minimal fecundity oysters which had settled in fragmented low-density assemblages. In contrast, the less easily accessed island populations displayed relatively little harvesting impact with more densely settled highly fecund oysters recorded. However, as *O. edulis* prices rise the island populations will become extremely vulnerable and it should be noted that harvesting was witnessed at the Sheelahs in November but not on a commercial scale.

In Strangford in the 2010s it was thought that native oysters had reached such low numbers that the "Catch Per Unit Effort" (CPUE) made them no longer economically viable. However, this is no longer the case, as an upsurge in restoration projects throughout Europe has created an increase in demand which in-turn has seen the retail price of an individual native oyster rise from 80 pence in 2018, to > £3.00 in 2021. This increase in market demand has led to a resurgence in native oyster harvesting UK wide and may go some way to explain the current situation in Strangford Lough.

In the early 2000s the late Dr. Dai Roberts highlighted the impact of intense harvesting of native oysters and other shellfish in Strangford Lough to habitat managers, NGO's and conservation charities. Unfortunately, either through a lack of understanding or insufficient powers to manage the problem the situation remains unchanged some 20 years later.

The effects of harvesting have more impact than on merely native oyster and littorinid numbers. While analysing past and present substrate images during the survey a visible decrease in species richness and diversity was apparent at several sites: The rocky intertidal reef at the lower fish trap at Greyabbey, the northerly point at Chapel Island, the northerly site Newtownards Sailing Club and the southerly Ballyreagh site.

At the present time the lower intertidal zone in Strangford Lough could benefit greatly from a period of respite from destructive activities. The introduction of shellfish gathering specific bylaws similar to those enforced by the East Lothian Council in Scotland and Southend-on-Sea Borough Council England could offer a stop-gap solution:

East Lothian Council

- Collecting of bivalve shellfish from unapproved areas for commercial purposes and placing them on the market for retail sale is an offence under Regulation (EC) 853/2004.
- Aberlady Bay Local Nature Reserve and John Muir Country Park which includes Tyninghame Bay are protected by local bylaws. These bylaws make the killing, taking or disturbing of any living animal in these areas an offence.
- The Scottish Outdoor Access Code also stipulates that the collection of fauna for commercial purposes requires the prior permission of the landowner.
- East Lothian Council regularly carries out surveillance at locations when reports of commercial harvesting of shellfish are received. When performing food hygiene inspections at local businesses, the environmental health team will always seek to ascertain where food has come from. This includes checking that shellfish have full traceability documentation.

(https://www.eastlothian.gov.uk/homepage/10450/gathering_bivalve_shellfish)

Southend-on-Sea City Council

- If shellfish are harvested from unclassified or prohibited beds or a batch of live shellfish is not accompanied by a valid registration document, food authorities are empowered to seize them and seek an order for their destruction through the Magistrates' Court. The shellfish gatherer will be liable to pay all reasonable expenses incurred by Southend-on-Sea City Council in the destruction and disposal of the seized shellfish.
- Further charges can also be brought against the shellfish gatherer. Any organised shellfish harvesting activities in Southend-on-Sea City must comply with the food hygiene regulations. Failure to comply with these regulations is a criminal offence and offenders on conviction are liable to an unlimited fine and/ or a 2 year imprisonment.

(https://www.southend.gov.uk/licences-permissions-trading-standards/food-safety/3)

Management Recommendations

If the remnants of the Strangford Lough *Ostrea edulis* population are to be preserved and augmented, as is suggested by the UK Native Oyster Biodiversity Action Plan (UKBAP, 2009) and OSPAR signatories' obligations (OSPAR Commission, 2009), pro-active protective measures need to be introduced immediately. The following recommendations are suggested measures which have been employed successfully in the other regions experiencing similar pressures on indigenous native oyster populations.

Immediate Protective Actions

1. **Translocation of vulnerable populations to safe havens.**
2. **Introduction of bylaws banning all shellfish gathering.**
3. **Installation of signage (dual language) warning that an offence is being committed in relation to said bylaw especially at areas where shellfish harvesters access sites.**
4. **Policing with FSA involvement at regularly harvested sites, particularly on low spring tides.**

Immediate Conservation Actions

1. **Establish a protected brood stock sanctuary that will supply larvae to suitable settlement sites using prevailing wind and hydrodynamic regimen.**

Private land (Bird Island) or National Trust land which is policed would offer some protection against harvesting. Alternatively, a bank of oyster nurseries similar to the Ulster Wildlife Hub at Bangor Marina could be established along the west coast at receptive sailing clubs with suitable pontoon set-ups, possibilities include: East Down Yacht Club, Down Cruising Club, Ringhaddy Club, Whiterock Sailing Club, Strangford Lough Yacht Club, Killyleagh Sailing Club, Quoile Yacht Club and the Private Pontoon Simmy Island.

Figure 20. UWT, hanging pontoon oyster nursey which could be employed in Strangford Lough to provide protected brood stock sanctuaries.

These sites would offer ideal protected locations from which the Lough's native oyster population could be restored. Larval releases would be dispersed by favourable prevailing wind and currents to repopulate the depleted eastern and northern sites.

2. **Establish long-term monitoring protocols for *in-situ* native oyster densities, spat settlement and biodiversity indices, suitable sites should include: Newtownards Sailing Club, Greyabbey, Horse Island, Skart Rock and Bird Island.**

Long-term Conservation Actions

1. **Development of a restoration hatchery facility similar to the NOAR project at Bangor University or the Langstone Harbour Native Oyster Hatchery at Portsmouth University.**

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The hatchery unit could produce spat on shell from indigenous native oysters to augment recovering sites in Strangford Lough or any of the other five sea loughs in Northern Ireland.

The hatchery would not need to be species specific and could be active in the culture of other threatened species. At present the most feasible facility with a necessary through-flow set-up is located at the QUB Marine Laboratory Portaferry.

Point of contact: Dr. Louise Kregting, l.kregting@qub.ac.uk

2. **Seed previously prolific *O.edulis* sites with spat on shell.** (This has proved to be extremely successful in the Nature Conservancy© restoration projects)
3. **Examine the possibility of establishing subtidal oyster populations within suitable hydrodynamic regimens which could supply larvae for the restoration of intertidal and subtidal sites.**
4. **Expansion of subtidal settlement sites through the deployment of shell cultch.**

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