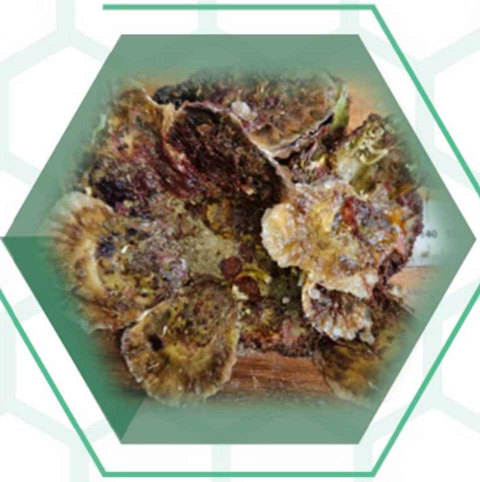
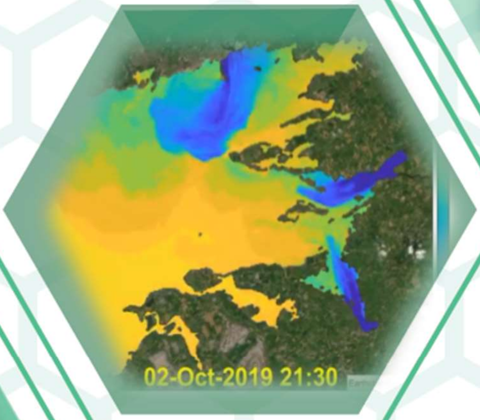
EMFF Operational Programme 2014-2020

Marine Biodiversity Scheme

Status and restoration of native oysters in Galway Bay 2018-2023





Around 700 million oysters were consumed in London in 1864. The UK landings fell from 40 million in 1920 to 3 million in the 1960s and never returned to former levels (Edwards, 1997).

Lead Partner: Marine Institute

Partners: Cuan Beo, Bord Iascaigh Mhara

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Contents

Summary

1. Native oysters are widely distributed in low densities in inner Galway Bay from Oranmore Bay in the north, south to Kinvara Bay and west to Auginish. The main stocks occur south and north east of Eddy Island.
2. Survey time series (2011-2023) shows regular recruitment but very high mortality rates in larger size classes. This mortality is not due to fishing. Mortality rates increased during the time series.
3. Pacific oysters are common in the Clarin/Dunkellin estuary having naturalised from previous extensive bottom culture of Pacific oysters in the estuary. However, the species is not common, outside of aquaculture sites, in the inner Bay.
4. Native oyster spat can be reliably produced in spatting ponds which provide stable and higher temperatures for spawning and larval settlement.
5. Spat produced in spatting ponds and re-laid on the seabed or held in enclosures attain an average shell height of about 40mm after 2 years. Mortality rates of these spat are very high in the first winter.
6. Spat settlement can be enhanced by providing bivalve shell material (cultch) for settlement. Small scale trials show that settlement occurs in all areas when this material is provided and indicates that substrate availability is limiting recruitment.
7. The success of large scale sub-tidal deployments of cultch depends on location and the type of cultch used. Scallop shell cultch deployed in a specific area resulted in settlement of 13.9million spat in 2021 and 5.9 million spat in 2022 and provides substrate for successive annual settlements given that it remains available at the sediment surface over time. Survival to 1 year was 45% and significantly higher than spat released from spatting ponds. Growth is seasonal and stops in winter.
8. *Bonamia ostrea* is present in oysters in Galway Bay. Prevalence varies annually and seasonally. Intensity of infections is usually less than 30%. Current understanding suggests that *Bonamia* infection is responsible for high mortality of larger size classes of oysters.
9. Oysters tolerate a broad range of temperatures and salinities but prolonged (days) exposures to reduced salinities, especially when temperatures are high, can be lethal or can reduce feeding rates. Modelled estimates of daily temperature and salinity in inner Galway Bay indicate that estuarine areas, that previously supported oyster stocks, are now high risk areas due to low salinity events. Low level mortality due to unsuitable combinations of temperature and salinity is predicted to occur periodically during the life span of a cohort of oysters
10. Habitat suitability assessment is key to successful oyster restoration.

Introduction

The status of native oyster populations in Galway Bay, and other areas in Ireland and Europe, has declined in recent decades. Since 2017, supported by the European Maritime and Fisheries Fund and the Irish Government, various projects have been undertaken to identify pathways to restoration. A number of projects to characterize the distribution and abundance of oysters in Galway Bay and post settlement growth and survival have been completed. Spat have been produced on shell (cultch) in spatting ponds for distribution to enclosures and to the seabed. Small and large scale trials to increase shell cover and spat fall in fishery order areas have been completed. Data on the prevalence and intensity of infection of oysters with the parasite *Bonamia ostrea* since the 1980s have been compiled and new data collected. The effects of temperature and salinity on oyster survival and feeding rates were estimated and used to identify areas of the Bay that posed high risk to oysters by combining results with a high resolution hydrodynamic model. These projects are described below.

Historical context

The history of oyster fishing and production in Galway Bay in the 19th and 20th century has been documented by Wilkins (2001). Peak production was in the 1840s-1860s but this resulted in depletion of stocks and was evidently unsustainable. The response to this was to remove open public access to many beds by privatizing them, mainly to local landowners and landlords, and giving rights to cultivate, relay and manage oysters in these areas (Figure 1). This was equivalent to the use of Several Orders in the UK. Poor management, however, largely continued and the status of privately owned beds did not fare any better than public beds. Interventions mainly consisted of moving oysters from one place to another to increase production in privately held beds rather than system wide limits on total outtakes. The taking of small oysters was widespread. Early attempts to enhance spat production in settlement ponds were driven by Ernest Holt at the Oyster Parcs at Auginish and at the research station at Ardfry. These were largely unsuccessful due to infrequent oyster spat settlement probably caused by low temperatures.

In the mid 20th century similar concessions were given in the form of fishery orders (under the 1959 Fisheries Act, Part XIV, Ch. 3). These were equivalent to UK regulating orders. Such an order was allocated to the Clarinbridge co-operative in the 1970s and following protracted social and political debate the once privately licensed St. George's bed was transferred to state ownership for use by the local communities in the early 1980s.

In recent decades the main change in the oyster landscape has been the introduction of Pacific oyster into aquaculture licensed sites. Pacific oyster spat are bought from hatcheries and deployed in bags on oyster trestles on the lower shore for ongrowing to market size. Pacific oysters were also ongrown on the seabed in the Clarinbridge fishery order area during the 1990s and early 2000s but this production has since ceased (Figure 2).

Recent context (NOW17)

Although oyster beds in Galway Bay have supported small fisheries in some recent years, the depleted status of the beds has been recognised since the 1980s. Little action or intervention has occurred since then that could identify how stocks could be rebuilt. This is the case for all oyster beds in Ireland other than the beds in inner Tralee Bay (Fenit). In the meantime, the oyster co-operatives, who have delegated responsibility to manage and maintain oyster beds, under extensive Aquaculture licences or Fishery Orders have not had income from production that would enable any re-investment into stock recovery measures.

In 2017, the oyster co-operatives held a workshop (NOW17) in Clarinbridge Co. Galway to discuss future initiatives for native oyster management. This workshop was facilitated and hosted by Cuan Beo (www.cuanbeo.com; Cuan Beo was also officially launched at the meeting), the Marine Institute (MI) and Bord Iascaigh Mhara (BIM) and the proceedings were published in NOW (2017). From that meeting the Irish Native Oyster Fisheries Forum (INOFF) was founded in 2018 and discussions around restoration of oysters began.

The key recommendations from NOW17 were:

1. To form a working group for native oyster fishermen and co-operatives in Ireland to promote and foster relationships and knowledge transfer between managers and stakeholders in Ireland’s oyster fisheries
2. Streamline the administration of the shellfish industry while maintaining the high standards of food safety and to develop sustainable fisheries management
    a. Aim for one single authority to allow a fisherman dredge native oysters instead of the six authorities they currently have to deal with.
    b. Aim for one single authority to allow Food Business Operators (FBOs) to purchase and sell native oysters instead of the four authorities they currently have to deal with.
3. Fisheries Co-ops should establish a strategic alliance with Irish FBO’s to add value to the native oyster here in Ireland to the benefit of the Irish economy.
4. Support should be given to Co-ops to individually review their current management / administrative structures so as to avail of future state support for development of those fisheries. This support should extend to the completion of Fisheries Management Plans. Co-op members are to work with BIMs’ Regional staff in bringing this forward. This is key to the relevance and success of all other recommendations.
5. The integration of aquaculture into each Fisheries Management Plan, depending on resources and the profile of the Fishery itself, should be investigated.
6. Research to identify a sustainable source of cultch (shell for spat settlement) on behalf of all oyster fisheries to look at the most cost effective source, treatment and storage requirements and the most effective methods of deployment or use.
7. Key state agencies involved in water quality issues, including the EPA and Irish Water, should continue to engage with stakeholders to identify priority shellfish growing areas for further investigation leading to improvements in wastewater treatment plant processes and water quality in shellfish growing waters.
8. Integrated catchment management to bring together scientific and local expertise in a way that will improve both understanding and appreciation of the importance of the contribution of rivers and freshwater inflow to the shellfish growing waters.

Since NOW17 a number of active oyster restoration interventions, research and management plans have been developed in Galway Bay. They are described in this report.

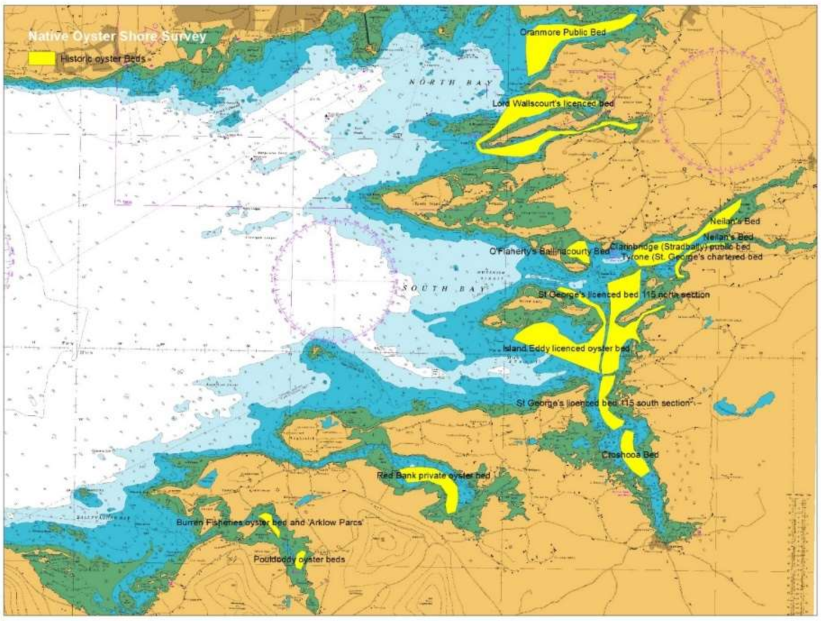

Figure 1. Distribution of private and public oyster beds in the mid 19th century in south east Galway Bay (reproduced from Wilkins 2001).

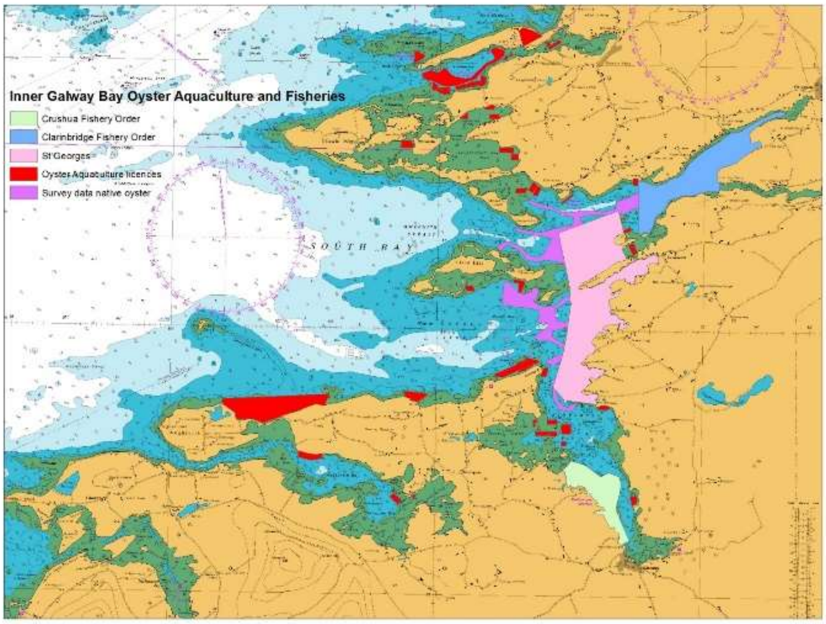

Figure 2. The distribution of native oyster public and fishery order areas, and oyster and mussel aquaculture sites or applications in recent years in south east Galway Bay.

Considerations for oyster restoration

Some key considerations need to be addressed and defined to inform the protocol and methods that could be used to recover oyster populations (Preston *et al*. 2020). These include:

1. Clear objectives as to the scale and ambition of the project
2. The legal framework and operational constraints that need to be considered
3. Identifying the causes of population decline and whether these causes persist or can be mitigated
4. Information on current status of oyster stocks at the proposed restoration site. The status will largely define the approach to re-building stocks. The approach at sites where spawning stocks no longer exist will be very different to sites which have spawning stocks
5. Sites that previously held oyster stocks are likely to be more suitable than areas that did not. At least they are proven suitable habitats, provided significant changes have not occurred
6. Identifying the constraints to population recovery is important
    a. Is spawning stock present and at densities that enable high rates of fertilization?
    b. Is the spawning stock located in areas which will enable high larval retention in the system?
    c. Is water temperature high enough to enable gametogenesis, larval production and settlement annually? If not, then recruitment will be infrequent
    d. Is there an abundance of clean shell material available for spat settlement in areas where larvae are distributed?
    e. Is the balance of growth and mortality of a cohort of oysters such that biomass is expected to increase?

In Galway Bay and other oyster sites on the west coast of Ireland, spawning stocks still exist and spawning occurs frequently if not annually. This is not to say that larval supply is not an issue and that recruitment is not limited by low spawning stocks. Re-building and maintaining high density of spawning stock in suitable locations is still necessary. Spat settlement may be less frequent in some sites if summer temperatures do not exceed 17°C and the rate of recovery of populations will be slower in such areas. Seabed substrate, in the form of clean shell, for larval settlement seems to be a significant bottleneck in Galway Bay and other oyster sites. Siltation from land run off, including the effects of high rainfall events or increased flows caused by upstream drainage projects, and decline in availability of surface shell material due to reduced productivity of oyster over the last 40 years are seen as significant impacts on oyster ground. Adult oyster beds are likely to be the optimum surface for oyster spat settlement and as adult stocks decline a negative feedback loop to spat settlement may be established. Nevertheless, as evidenced in this report, spat settlement and the abundance of juvenile oysters is significant in some areas but mortality rates after a given size is reached is extremely high. The current understanding is that this is mainly caused by the parasite *Bonamia ostrea* which was introduced to Galway Bay, and many other sites in Ireland during the late 1980s. This is a major constraint to restoration. Nevertheless, recent studies have shown increased tolerance or resilience to *Bonamia* infection and that this has a genetic and heritable basis (Vera *et al*. 2019, Sambada *et al*. 2022). Selective breeding or introduction of resilient stocks into *Bonamia* infected areas, therefore, offers potential.

In this report a number of projects investigating issues relevant to oyster restoration identified above in Galway Bay are presented. The reports include:

1. Intertidal surveys to identify the distribution of native oysters and other bivalve molluscs in intertidal areas of the Bay
2. Estimates of residual stocks of Pacific oysters in the Clarin/Dunkellin estuary
3. A compilation of survey data for native oysters providing information on distribution, biomass and mortality rates between 2011-2023
4. Spat settlement indices at sentinel sites in 2018 and 2019
5. Growth and survival of known age juvenile oysters
6. Spat settlement on large scale cultch deployments 2018-2023
7. *Bonamia* monitoring data compiled from the 1980s and including new data
8. Effects of temperature and salinity on survival and feeding of oysters and habitat suitability assessment

1. The distribution of native oyster (*Ostrea edulis*) and other bivalves in intertidal habitats in inner Galway Bay in 2018

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Introduction

During autumn and winter of 2018 a broadscale survey in intertidal habitats was completed to describe the distribution and abundance of native oysters, Pacific oysters, mussels, saddle oysters and periwinkle in the area. The results were used to scope further sub-tidal surveys to obtain a synoptic map of the distribution and abundance of native oysters in the Bay to inform restoration efforts. The presence of native oyster in the intertidal zone may indicate that oysters are also present sub-tidally in these areas as native oyster is primarily a sub-tidal species. Small patches of oyster may generate some larval production locally and if these patches are common and widespread, significant larval production may be occurring in areas outside of the main stock distribution areas.

Methods

The survey was completed in 2018 by teams of fishermen, and oyster and mussel farmers. This project took a 'citizen science' approach and facilitated data and image acquisition on mobile phone forms which were provided to the surveyors. Data were submitted using phone forms, in near real time, to a database at the MI. Data for over 3000 1m^2 quadrats along 84km of shore line were submitted. Local knowledge of oyster fishermen, oyster farmers and informed local people was used to identify stretches of coastline to include in the survey. Such areas were to include any habitat on which native oyster could occur and, therefore, excluded some of the estuarine soft sediment habitats where oysters cannot readily survive and also open exposed cobble shorelines where the shoreline is too dynamic to allow oyster settlement.

The areas to include in the survey were mapped, using GIS in real time, at meetings of local fishermen and oyster farmers. The survey area was divided into longshore transects and allocated to survey teams. The total transect length was 84km (not including any parallel transects at different vertical levels on the same shoreline)

The survey design approximated to a concurrent two phase survey with a random stratified approach in the second phase. Surveyors had prior knowledge of areas where oysters were present and were asked to focus on such areas in phase 1 in order to record all known positive occurrences. The surveys then extended from these areas along transects on the shore two hours before and after low water during spring tides. On some shores, two parallel transects were covered. The lower shore transect corresponded to the lowest level on the shore accessible around low water on the day of sampling and the transect parallel to it covered an area about 10m upshore of it. Surveyors walked the transects and at approximately 50m intervals a 1m^2 area was randomly chosen and all oysters, mussels and periwinkles within a 1m^2 quadrat, placed on the shore, were counted (Figure 3). The majority of sampling was completed during spring tides in September and October 2018 (74% of samples) which allowed access to the lower shore close to chart datum depth.

Although the majority of surveyors had significant knowledge of the shore line, species guides were provided, particularly on the identification of *Fucus* species and *Laminaria*. These species occupy specific vertical zones on the shore and could be used by surveyors to choose a particular shore level to sample. These guides were laminated and distributed to survey teams. Also a workshop was held on the identification of native oysters, especially spat, which could be confused with saddle oyster or Pacific oysters. However, native oysters encountered during the survey were not spat and were generally over 20mm in size and easily identifiable.

All data were submitted using a purpose designed mobile phone form using the Fulcrum app (https://www.fulcrumapp.com/).

The following information was recorded on the form

- The GPS location at which the sample was taken was automatically logged and transmitted with each phone form record. The precision of the GPS log may have varied between phones used by survey teams but was sufficient to record position at the shore level indicated by the species of seaweed present. The data successfully mapped onto the correct shore level in GIS
- Date and time (at which the record was submitted)
- Photograph of team members (for the purpose of estimating survey time and payment for each survey team)
- The zone of the shore was indicated by identifying the species of *Fucus* brown seaweeds immediately around the quadrat
- A photograph of the shore area inside the quadrat
- An estimate of ground cover type (rock, sediment, seaweed) within the area of the quadrat
- Presence or absence of oysters
- If oysters were present a second photograph zoomed to 0.25m^2 of the 1m^2 quadrat was taken in order to confirm identification of recorded oysters
- The number of native oysters, Pacific oysters (*Magallana gigas*), saddle oysters (*Anomia*), mussel (*Mytilus*) and perwinkle (*Littorina*) were recorded

Completed forms were submitted by surveyors in real time or later on the same day when mobile phone reception allowed remote synchronisation with the Fulcrum database. Spatial coverage and progress of the survey was monitored by MI using the Fulcrum map display. Transects were re-allocated to teams where required and depending on availability of teams on suitable tides.

Survey transects and quadrat samples were grouped to 7 locations and summary statistics on prevalence (% of quadrats with oysters or other species) and density of oysters prepared for each location (Figure 4).

Figure 3. Intertidal transects for survey of native oyster in Galway Bay in 2018. Transects were allocated to 6 teams of surveyors using the numeric coding on the map. The total transect length is 84km.

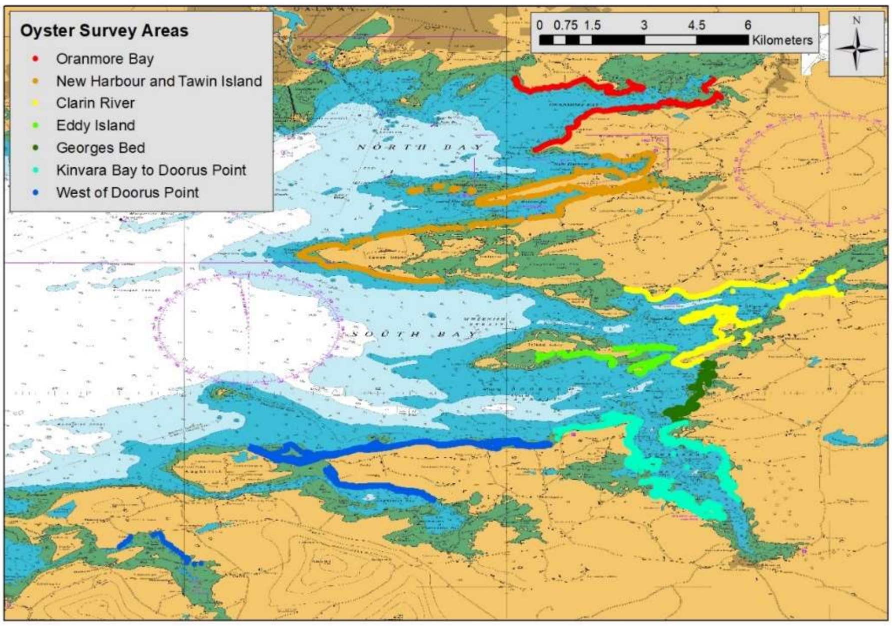

Figure 4. Shoreline transects aggregated to 7 locations.

Results

Species counts for 3027 quadrats were obtained along approximately 84km of intertidal transect.

Native oysters

The prevalence or % of quadrats with oysters, varied from 28% in the Clarin River, 14% in Oranmore Bay, 11% at Tawin and less than 10% in other areas (Table 1, maps in Annex I). Densities were generally less than 0.5 oysters.m^{-2} but where oysters were present, average density varied from 4.2 oysters.m^{-2} at Tawin, 3.6 oysters.m^{-2} in Oranmore Bay and between 1-2 oysters.m^{-2} in other areas.

Table 1. Prevalence (% positive records) and density of oysters in different areas of the south east Galway Bay during summer-autumn of 2018.

	N (quadrats)	Absent	Present	Prevalence	
Clarin River	660	472	188	28.5%	
Eddy Island	157	154	3	1.9%	
Kinvara Bay to Doorus	685	632	53	7.7%	
New Harbour_Tawin Island	543	484	59	10.9%	
Oranmore Bay	264	226	38	14.4%	
St. Georges Bed	200	183	17	8.5%	
West of Doorus	518	469	49	9.5%	
		Density (all quadrats)		**Density (>0)**	
	N (oysters)	**Average**	**St.Dev**	**Average**	**St.Dev**
Clarin River	442	0.67	1.65	2.35	2.38
Eddy Island	3	0.02	0.14	1.00	0.00
Kinvara Bay to Doorus	90	0.13	0.52	1.70	0.95
New Harbour_Tawin Island	250	0.46	1.83	4.24	3.89
Oranmore Bay	137	0.52	2.11	3.61	4.48
St. Georges Bed	36	0.18	0.66	2.12	1.05
West of Doorus	84	0.16	0.59	1.71	1.00

Periwinkle

The prevalence of periwinkle varied from 60-70% in the Clarin River, Eddy Is and Tawin, 55% at St. Georges, 48% in Oranmore Bay and much lower In Kinvara and west of Doorus (Table 2Table 2). Densities were highest in the Clarin River estuary at 5.7 periwinkle.m^{-2} and generally 1-3 periwinkle.m^{-2} in other areas. Including only quadrats where periwinkle were present densities generally ranged from 4-8 periwinkle.m^{-2}.

Table 2. Prevalence (% positive records) and density of periwinkle in different areas of the south east Galway Bay during summer-autumn of 2018.

	N (quadrats)	Absent	Present	Prevalence	
Clarin River	660	206	454	68.8%	
Eddy Island	157	62	95	60.5%	
Kinvara Bay to Doorus	685	527	158	23.1%	
New Harbour_Tawin Island	543	213	330	60.8%	
Oranmore Bay	264	137	127	48.1%	
St. Georges Bed	200	89	111	55.5%	
West of Doorus	518	435	83	16.0%	
		Density (all quadrats)		**Density (>0)**	
	N (periwinkle)	**Average**	**St.Dev**	**Average**	**St.Dev**
Clarin River	3810	5.77	7.13	8.39	7.21
Eddy Island	484	3.08	3.44	5.09	3.05
Kinvara Bay to Doorus	705	1.03	2.74	4.46	4.15
New Harbour_Tawin Island	1921	3.54	4.02	5.82	3.65

Oranmore Bay	549	2.08	2.66	4.32	2.23
St. Georges Bed	773	3.87	16.22	6.96	21.31
West of Doorus	427	0.82	4.41	5.14	10.00

Pacific oysters

Pacific oysters occurred mainly in the Clarin River estuary (prevalence 5%) and to a lesser extent in Kinvara Bay and Tawin (prevalence 1%). They were absent west of Doorus and only 1 was recorded in Eddy Is, Oranmore Bay and St. Georges (Table 3). Densities when present varied from 1.6-2.7 oysters.m^{-2}.

Table 3. Prevalence (% positive records) and density of Pacific oysters in different areas of the south east Galway Bay during summer-autumn of 2018.

	N (quadrats)	Absent	Present	Prevalence	
Clarin River	660	627	33	5.0%	
Eddy Island	157	156	1	0.6%	
Kinvara Bay to Doorus	685	676	9	1.3%	
New Harbour_Tawin Island	543	535	8	1.5%	
Oranmore Bay	264	263	1	0.4%	
St. Georges Bed	200	199	1	0.5%	
West of Doorus	518	518	0	0.0%	
		Density (all quadrats)		**Density (>0)**	
	N(Pacific oysters)	**Average**	**St.Dev**	**Average**	**St.Dev**
Clarin River	54	0.08	0.53	1.64	1.76
Eddy Island	1	0.01	0.08	1.00	
Kinvara Bay to Doorus	24	0.04	0.56	2.67	4.30
New Harbour_Tawin Island	14	0.03	0.29	1.75	1.75
Oranmore Bay	1	0.00	0.06	1.00	
St. Georges Bed	1	0.01	0.07	1.00	
West of Doorus	0	0	0	0	

Mussels

Mussel prevalence was low varying from 7.3% of quadrats in the Clarin River estuary, 5.7% in Oranmore Bay and less than 3% in other areas (Table 4). Mussel density was more variable and aggregated than other species. Densities were less than 1 mussel.m^{-2} in all areas other than Oranmore Bay. Average density in Oranmore was 28 mussel.m^{-2} in quadrats where mussel was present.

Table 4. Prevalence (% positive records) and density of mussel in different areas of the south east Galway Bay during summer-autumn of 2018.

	N (quadrats)	Absent	Present	Prevalence	
Clarin River	660	612	48	7.3%	
Eddy Island	157	157	0	0.0%	
Kinvara Bay to Doorus	685	673	12	1.8%	
New Harbour_Tawin Island	543	528	15	2.8%	

Oranmore Bay	264	249	15	5.7%	
St. Georges Bed	200	197	3	1.5%	
West of Doorus	518	516	2	0.4%	
		Density (all quadrats)		**Density (>0)**	
	N(Mussel)	**Average**	**St.Dev**	**Average**	**St.Dev**
Clarin River	123	0.19	1.33	2.56	4.30
Eddy Island	0	0.00		0.00	
Kinvara Bay to Doorus	26	0.04	0.34	2.17	1.47
New Harbour_Tawin Island	138	0.25	2.01	9.20	8.30
Oranmore Bay	424	1.61	20.56	28.27	84.47
St. Georges Bed	4	0.02	0.17	1.33	0.58
West of Doorus	2	0.00	0.06	1.00	

Saddle Oyster

Prevalence of saddle oyster was 4-6% in the Clarin River estuary and Oranmore Bay, 1% in Tawin and West of Doorus and absent from other areas. Densities were generally 1 saddle oyster.m^{-2} when present (Table 5).

Table 5. Prevalence (% positive records) and density of saddle oyster in different areas of the south east Galway Bay during summer-autumn of 2018.

	N (quadrats)	**Absent**	**Present**	**Prevalence**	
Clarin River	660	621	39	5.9%	
Eddy Island	157	157	0	0.0%	
Kinvara Bay to Doorus	685	685	0	0.0%	
New Harbour_Tawin Island	543	536	7	1.3%	
Oranmore Bay	264	252	12	4.5%	
St. Georges Bed	200	200	0	0.0%	
West of Doorus	518	511	7	1.4%	
		Density (all quadrats)		**Density (>0)**	
	N(Saddle oyster)	**Average**	**St.Dev**	**Average**	**St.Dev**
Clarin River	73	0.11	0.68	1.87	2.14
Eddy Island	0	0.00		0.00	
Kinvara Bay to Doorus	0	0.00		0.00	
New Harbour_Tawin Island	7	0.01	0.11	1.00	0.00
Oranmore Bay	14	0.05	0.27	1.16	0.57
St. Georges Bed	0	0.00		0.00	
West of Doorus	7	0.01	0.12	1.00	0.00

Discussion

Native oyster occurred in 13% of intertidal quadrat samples and where it occurred was at an average density of 2.4 oyster.m^{-2}. Although native oyster stocks in the area are depleted relative to their former range and the present stronghold is in sub-tidal areas east of Eddy Island (see below), the patches of oyster recorded in intertidal habitats are significant for a number of reasons. Firstly, they may signal the presence of unknown, although probably small, beds of native oyster sub-tidally in such areas. Secondly the density on the shoreline, even if such oysters are in patches isolated from the main spawning stock, is sufficient for successful fertilisation and avoidance of *allee* effects (low fertilisation rates at low density). Thirdly, the survey has shown that there are patches of reproducing oysters in a significant number of locations all of which contribute to larval production and distribution.

Pacific oysters were uncommon on the shoreline and occurred in generally less than 1% of samples outside of the Clarin estuary where the prevalence was 5%. The Clarin estuary has supported extensive production of Pacific oysters on the seabed over the past 20 years and although stocks are now depleted there is a residual spawning stock in the area. A number of Pacific oyster farms occur in inner Galway Bay. Some of these now use triploid oysters to prevent reproduction and naturalisation of this species. However, the low prevalence of Pacific oysters is noteworthy against the history of Pacific oyster production in the Bay and provides evidence that no significant naturalisation has occurred. Where the species has naturalised it usually occurs to a greater extent on the intertidal than native oyster and should be detected effectively using the methods used here. This species has naturalised in Lough Swilly, Co. Donegal and is currently the dominant species of oyster in the Lough (Marine Institute, 2019-2022).

The prevalence (3%) of mussels was very low in the survey and occurred in numbers in only a few locations in the Clarin estuary and Oranmore Bay. This is surprising given the expected ubiquitous distribution and production of mussel larvae in the Bay as evidenced by spat fall onto mussel long lines in aquaculture sites and spawning of mature mussels in these sites. Evidently mussel spat fall is uncommon or else post settlement survival of mussel was extremely poor in 2018.

2. Distribution of native and Pacific oysters in intertidal habitats in the Clarinbridge Fishery order area

Emma White[1], Sarah Clarke[1], Guillermo Martin[1], Oliver Tully[1], Gerry O Halloran[2], Alec Reid[2], Diarmuid Kelly[2], Nicolas Chopin[3]

1; Marine Institute, 2; Cuan Beo, 3;BIM

Acknowledgements: Members of the Clarinbridge oyster co-operative and members of the Gort River walk group participated in this survey.

Introduction

In the 1970s, the rights to maintain and fish the oyster bed in the Clarin/Dunkellin estuary were granted to the local Clarinbridge Oyster Co-operative in the form of a fishery order under the Fisheries Act 1959. Following the decline in native oyster stocks in the area Emerald Oysters Ltd. started to culture Pacific oysters on the seabed in the fishery order area during the 1990s. This involved deployment of Pacific oyster spat on the seabed followed by harvesting for commercial sale using dredges. Harvesting was restricted to December by the conditions in the fishery order. This in itself limited the marketing scope of the company to sell product and production ceased in the early 2000s. A residual stock of Pacific oysters remain on the seabed intermixed with a relic native oyster stock. Observations in 2020 showed that although settlement of native oyster was common in the area, mortality was also very high as shown by the absence of oysters over 2 years of age.

The Leanach is a locally named area within the fishery order area (Figure 5). Historically, the area supported a productive native oyster (*Ostrea edulis)* bed and fishery.

The area is of interest therefore, because of the co-occurrence of both species in the same habitat but also, because the suitability of the area for oysters may have declined due to increased siltation and freshwater input. Marine Institute hydrodynamic models classify the area as high risk for oysters because of low salinity events as reported below.

An intertidal survey was conducted in March 2022 in order to estimate the density and size of native oyster (Ostrea edulis) and Pacific oyster (*Magallana gigas*) in the area.

Survey area and methods

The survey was undertaken at low tide by members of the Clarinbridge Co-op, Cuan Beo, BIM, MI and citizens from the surrounding area. Protocols for sampling were explained to the team of 16 surveyors beforehand. The area was sampled using 1m^2 quadrats. Eight teams of two were spaced approximately 20m apart across the bed. A quadrat was thrown randomly by each team every 20m, generally heading in an east-west direction. A GPS position was recorded at each sampling station using a mobile device. For each quadrat, native oysters and pacific oysters were counted and measured to the nearest mm and a count of clams or cockles was recorded. A 1m^2 raked area was sampled next to each quadrat in a sub-sample of stations.

Figure 5. Ebbing tide looking west towards Eddy Island and the Burren (left), and satellite view of survey area in red showing the estuaries of the Clarin and Dunkellin Rivers (right).

Results

A total of 112 stations were sampled; 91 stations were sampled using a 1m^2 quadrat and 21 of those quadrat stations had an adjacent 1m^2 raked area. The survey encompassed a combined area of 0.99 km^2 with a total sampling effort of 88 m^2 (Figure 5).

Native oyster

Biomass of native oysters (*Ostrea edulis*), including all sizes, varied from 0.02-0.052 kgs.m^{-2} (Figure 6). The biomass of native oysters was estimated to be 4.7 tonnes. Biomass of native oysters over 76 mm was 0.4 tonnes or 8.5 % of the total stock. The size distribution data indicated that mortality rates above 60mm were high. No significant indication of recruitment (spat) was observed.

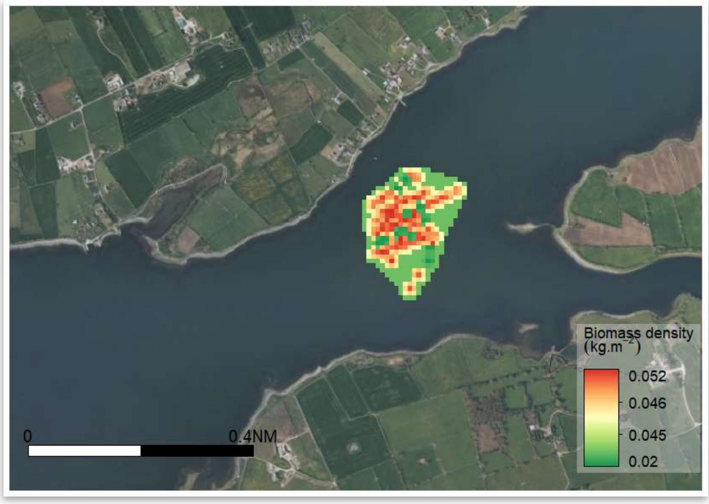

Figure 6. Biomass of native oysters in the Leanach 2022 intertidal survey.

Pacific oysters

Biomass of pacific oysters (*Magallana gigas*) varied from 0.13-1.2 kgs.m^{-2} (Figure 7) with a modal size of 120mm. The biomass of pacific oysters was estimated to be 57.9 tonnes in total.

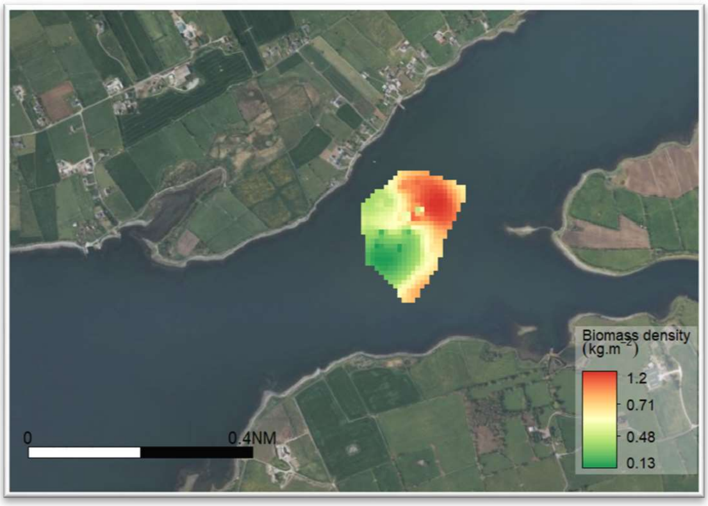

Figure 7. Biomass of pacific oysters in the Leanach 2022 intertidal survey.

Discussion

An intertidal survey of oysters in the estuary of the Dunkellin and Clarin Rivers in Inner Galway Bay found both native oysters and Pacific oysters co-habiting the same area. The presence of Pacific oysters is a legacy of earlier commercial production of the species in the area and naturalised spat settlement from the residual spawning stock left in the area from that production.

Native oysters continue to recruit to the area although their density is low due to ongoing high mortality rates. The mixed size range of Pacific oysters recorded during the survey shows that natural spat settlement is occurring in the area. This residual stock is therefore a potential source of expansion of Pacific oysters into waters to the west of the Leanach where the main native oyster beds occur. Temperatures at the Leanach can reach 20°C and are likely to be higher than this during short periods given that local air temperatures frequently exceed 20°C in summer. Spawning of Pacific oysters is expected to occur in these conditions.

3. Distribution, biomass and mortality rates of oysters in inner Galway Bay

Emma White, Sarah Clarke, Guillermo Martin, Oliver Tully

Marine Institute

Acknowledgements: Annual surveys of oyster stock were funded by the EU Data Collection Programmes (DCF) and the Irish Government. Cyril Kane, Pat Joe Bannon and PJ Martyn provided and crewed survey vessels. Many people in the Marine Institute participated in these surveys between 2011 and 2023.

Introduction

Surveys to estimate biomass, distribution and size structure of oysters in Galway Bay have been undertaken by the Marine Institute annually since 2011. In recent years these surveys were part funded by the EU Data Collection Framework (DCF) and the Irish Government. The original purpose of the surveys was to provide fishery advice to the management authority (Inland Fisheries Ireland) and the Clarinbridge Oyster Co-operative whose members hold dredge licences. However, the availability of commercial size oysters in the beds has generally been very low and no fishing occurred between 2018-2023. Annual stock surveys undertaken in late autumn or winter of each year provide evidence of the frequency of spat settlement and recruitment and also mortality rates in larger size classes. The survey time series are presented here and, in particular, new information on mortality rates of oysters are presented.

Survey description

Surveys were completed between 2011 - 2023. The surveys usually focused on the main oyster beds between Eddy Island and Rincarna Bay and south of Eddy Island towards the entrance to Kinvara Bay. Most of this area is within the St. Georges fishery order area but the beds continue west of the fishery order into public beds and east into the Clarinbridge fishery order area, towards the estuaries of the Clarin and Dunkellin Rivers. Oyster beds, or the relics of oyster beds, in Oranmore Bay, Rinville Bay and Mweeloon were surveyed intermittently during the period 2011-2023 (

Table 6).

The surveys provide biomass indices, absolute biomass estimates and size structure of the oyster stocks sampled. The main uncertainty in providing absolute estimates of biomass is the dredge efficiency. Dredge efficiency estimates of 35% have been used to raise the survey indices to absolute estimates based on experimental data derived previously from a number of sources and methods, including a study conducted in 2010 and 2021 in Lough Swilly. All surveys used locally designed (traditional) dredges and fishermen with many years of experience fishing oysters in the area.

The total geographic area covered by the surveys varied each year. Annual biomass estimates are therefore not comparable and accordingly, are reported as both total biomass and biomass per square kilometre (tonnes.km^{-2}) surveyed. The surveys were usually completed in late autumn (Sept-Nov). There was no survey in 2015 but the area was surveyed in March 2016. There was also no survey in 2020 due to Covid-19 restrictions in place at the time.

Table 6. Areas surveyed for native oyster in Galway Bay 2011-2023.

Year	Month	Area covered
2011	April	St Georges Fishery order (FO), Kinvara
2012	February/November	St Georges FO north
2013	November	St Georges FO
2014	November	St Georges FO
2015	No survey	
2016	March	St Georges FO North
2017	November	St Georges FO North
2018	October/November	St Georges FO North
2019	October/September	Oranmore/Rinville/Mweeloon
2020	No survey	
2021	November 21/January 22	St Georges FO
2023	September	St Georges FO

Biomass estimation

Biomass was estimated from the survey data using a geostatistical model accounting for spatial autocorrelation or patchiness in the distribution of oyster abundance. This model was used from 2017. Prior to this, a similar approach was used which interpolated the survey data and estimated density and biomass within contoured densities using inverse distance weighting methods.

Selectivity

The size distribution data are used in the estimation of biomass, recruitment and mortality rates. Smaller size classes of oysters may be underrepresented in the data for two reasons; in autumn surveys it is difficult to detect and count spat as they are <10mm in size at this time. Secondly oysters in their second year may be poorly selected by the dredge particularly if they occur as single oysters and not aggregations. These issues compromise the use of the survey data in developing a metric of settlement and recruitment even if some spat and 1+ year old oysters are present in the data.

Estimation of mortality rates

Mortality is the reduction or decline in numbers of oysters of a given age class over time. However, oysters in natural populations cannot be aged and it is not possible, therefore, to follow specific age classes and estimate mortality rates directly. However, size is a proxy for age and if the time required to grow from one size class to another is known (i.e. the growth rate) then size can be converted to pseudo-age and the total mortality rate (Z) can be estimated by the decline in the numbers between successive pseudo-ages. In fished populations it is common to divide this mortality into that caused by fishing (F) and that caused by other sources (so called natural mortality or M). As there was no fishing in Galway Bay between 2017 and 2023, Z=M and F= 0 during this period.

The shape of the size distribution constructed from survey data contains a lot of information on oyster population dynamics. The left side (small oysters) of the distributions provides evidence of recruitment, whereas the decline in numbers with size on the right side of the distribution provides evidence of mortality or at least the balance of growth and mortality. At a given growth rate therefore, the slope of the right side of the size distribution i.e. how numbers decline with size, contains information on mortality rate. There are some assumptions here; if recruitment is very variable then this variability will, as oysters grow, show up in the right side of the distribution and confound the estimation of mortality. If the growth rate changes it will also compromise the estimate of mortality.

In populations with high growth rate and low mortality, the slope of the decline of numbers with age will be low and we can expect a lot of oysters to reach large size. The opposite also holds true.

Different size based approaches were used to estimate mortality and are described below.

The Ratio – mortality metric

Simple metrics of mortality could include the ratio of the number of oysters greater than the commercial size, or some other large size, compared to numbers below that size. Assuming it is not influenced by variable recruitment, it may provide a mortality index. This ratio would be sensitive to the number of oysters recruiting to the stock. Metrics such as the ratio between the size at 50% maturity (in this case 49mm, O'Neill and Tully, 2012) to above 60mm (the size above which mortality seems to significantly increase) reduces the bias caused by variable recruitment to some extent.

Beverton-Holt method

There is an inverse relationship between the mean length of a population and its mortality rate, and although it is not as straightforward as the mean length decreasing over time while the mortality rate increases, the Beverton-Holt length-based mortality estimator uses observed mean lengths, along with growth parameters to calculate an estimate of instantaneous mortality rate (Z):

$$Z = \frac{K(L_{inf} - L_{mean})}{L_{mean} - L_{cutoff}}$$

where, K is the von Bertalanffy growth parameter, L_{inf} is the asymptotic maximum length from the von Bertalanffy growth equation, L_{mean} is the mean length of individuals larger than L_{cutoff}, and L_{cutoff} is the length above which individuals are fully vulnerable to the fishing gear. Using the growth parameter estimates from work on oyster spat described in Section 6, annual estimates of Z were calculated using this equation. This method has a number of assumptions, which are unlikely to be met by native oysters. A variation on the Beverton-Holt method (Gedamke and Hoenig 2006) was also used. This variation follows significant changes in the mean length of a population over time and provides estimates of Z before and after the change in L_{mean} (Gedamke and Hoeing, 2006). For Galway Bay oysters, four scenarios were investigated to identify significant changes in mean length. Models were run based on no change in mean length, one change in mean length, two changes in mean length and three changes in mean length over the survey time series. The models were compared using Akaike's Information Criterion (AIC) to determine the best fit model.

Length Converted Catch Curve (LCCC) method

The total instantaneous rate of mortality (Z) was estimated using a length converted catch curve (LCCC) (Pauly, 1983). Using the growth parameters estimated in Section 6 of this report, the length frequency data collected from the surveys was converted to a relative age-frequency distribution. The relative ages were plotted against Ln(F/dt), where F is the number of oysters in each age class and dt is the time taken to grow from one length class to the next. A regression line was fitted through the decreasing and linear part of the catch curve and the slope of this line provides an estimate of Z. Effectively this method is looking at the right hand side of the size frequency distributions and identifying the rate of decline in numbers with size (but converting size to age to account for changes in growth with size).

The instantaneous rate Z can be converted to an annual rate of loss (A or the proportion lost) as:

$$A=1-\exp(-Z)$$

Results

Biomass estimates

Biomass of oysters in surveyed areas ranged from 14 tonnes.km^{-2} in 2011 to 148 tonnes.km^{-2} in 2017 (Table 7). The 8 tonnes.km^{-2} in 2019 refers to the Oranmore/Rinville/Mweeloon areas surveyed in that year where lower densities of oyster were recorded. The north St. Georges bed was sampled in all years other than in 2019. The density of oysters in this area is generally low but this area contains most of the biomass (

Figure 8). Biomass increased from 2011 to 2017 peaking at 148 tonnes.km^{-2} in 2017. The index then declined from 2018 onwards.

Table 7. Stocks of native oyster in Galway Bay 2011-2023 estimated from dredge surveys.

Year	Month	Survey Area (km^2)	Biomass (tonnes/km^2)	Biomass (tonnes)
2011	April	2.46	14.05	34.56
2012	February	1.17	24.52	28.69
2012	November	1.11	49.77	55.25
2013	November	1.02	42.94	43.8
2014	November	0.91	65.12	59.26
2016	March	0.73	106.85	78
2017	November	0.71	148.59	105.5
2018	October/November	0.72	97.78	70.4
2019	October/September	0.97	8.79	8.53
2021/2022	November/January	2.3	59.39	136.6
2023	September	3.3	27.48	90.7

Size distribution data

Oyster size data were collected during all surveys (

Figure 9). There was evidence of spat settlement in 2014 and 2016 with a small mode at approximately 10mm and in later years but generally spat are poorly represented in the data. There are higher numbers of oysters around 30-40mm from 2013 onwards compared to 2011 and 2012. The mean lengths of oysters declined from 63mm mean length in 2012 to 43mm in 2023. The mean length was more stable in recent years compared to earlier years in the series.

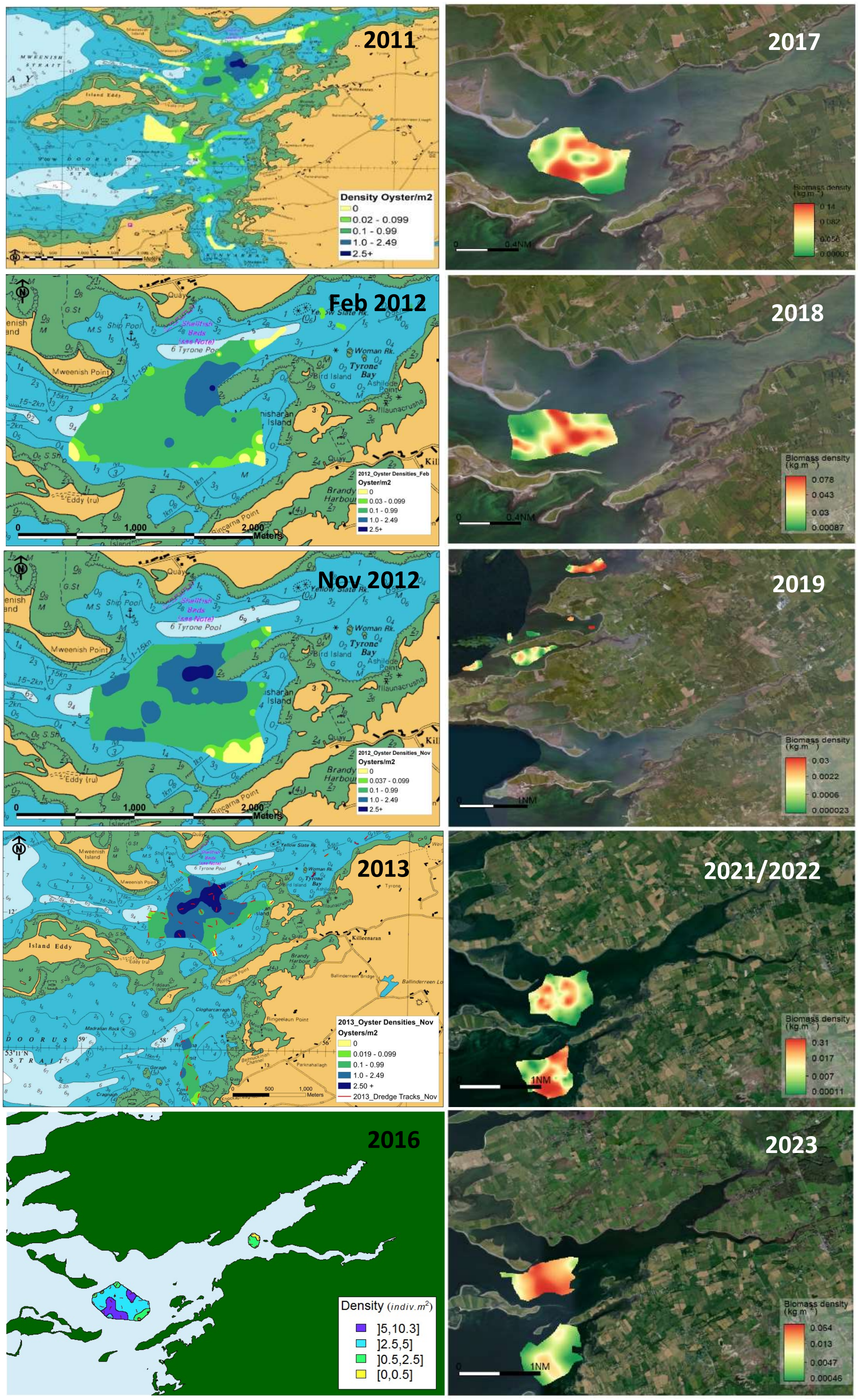

Figure 8. Biomass and distribution of native oysters between 2011 and 2023. All years were corrected for dredge efficiency (35.5%) apart from 2018. For 2017-2023 densities are displayed in kg/m². For 2011-2016 the biomass densities are displayed in oysters/m².

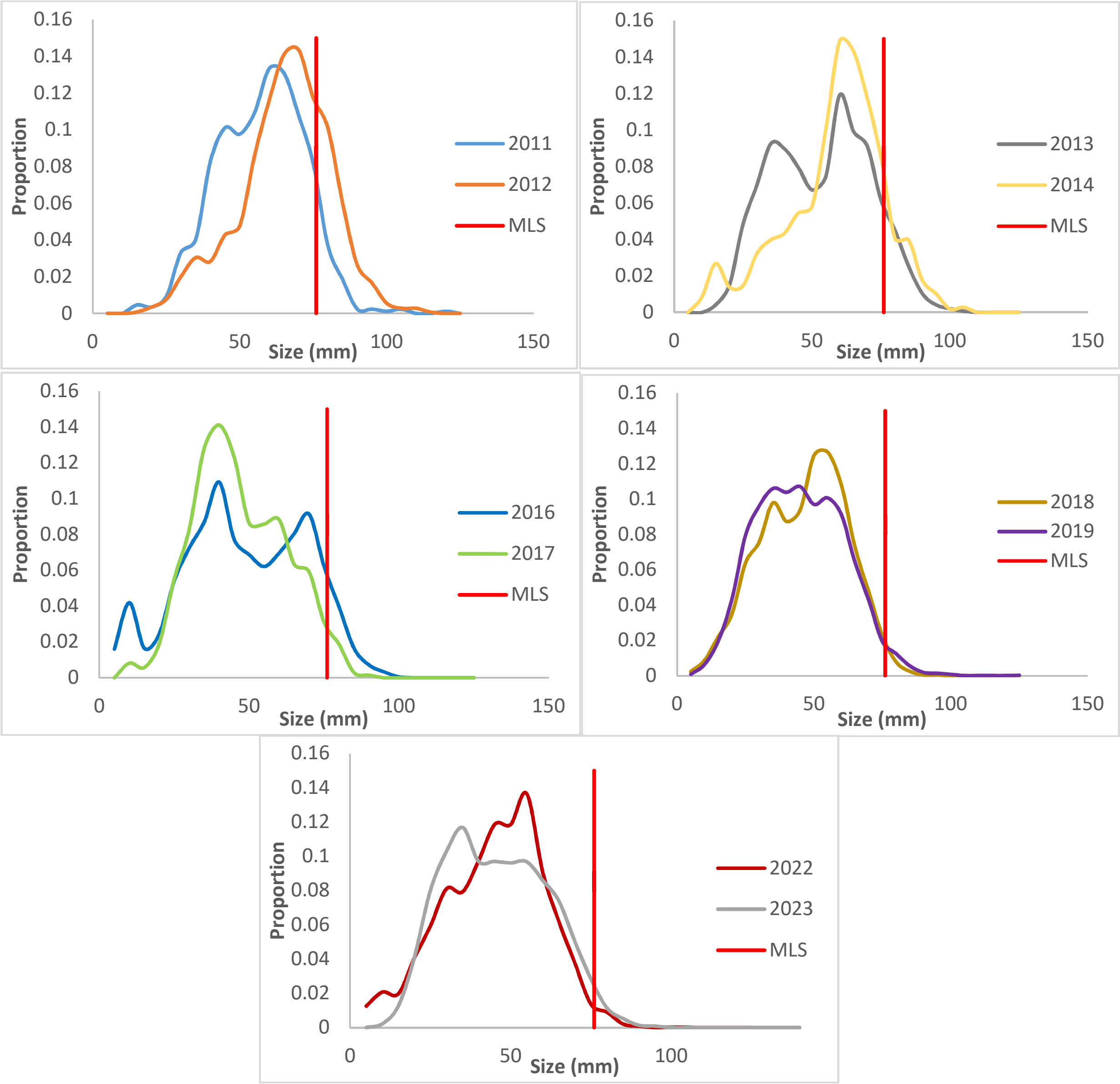

Figure 9. Size distribution of native oysters in Inner Galway Bay between 2011-2023 based on the proportion of individuals at each size class. The red vertical line indicates the minimum landing size (MLS) of 76mm.

Ratio – mortality metric

The ratio of oysters in the size class 49-59mm to oysters ≥60mm declined over the 12-year period (Figure 10). This, coupled with the decline in mean length of approximately 20mm, shows that the size structure of oysters shifted to smaller size classes. The decline in the ratio suggests that mortality rates increased. Over that 12-year period there was no progression into larger size classes.

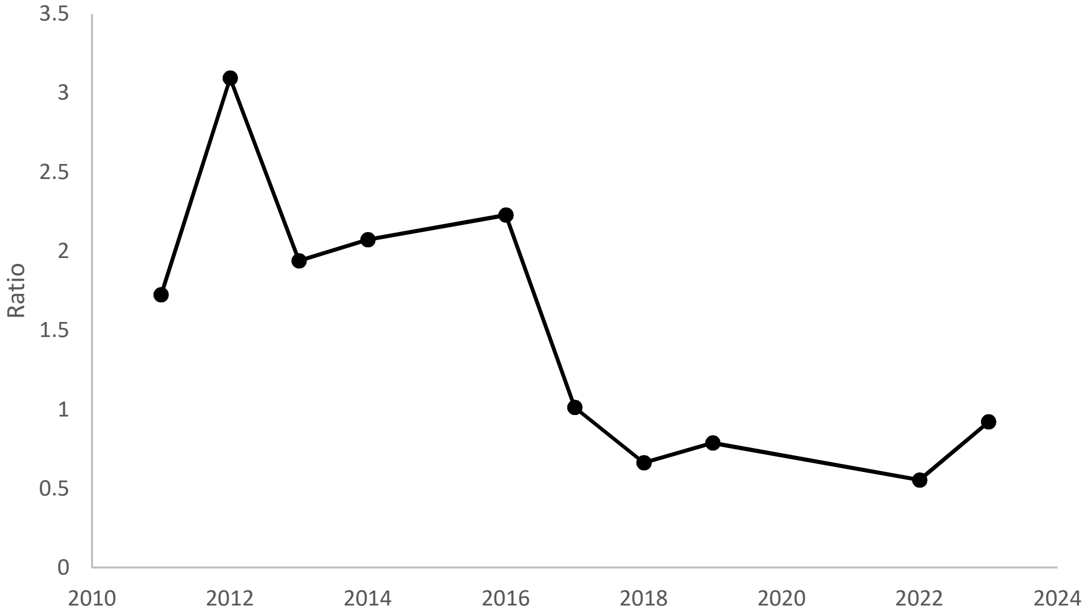

Figure 10. Ratio of oysters greater than 60mm to oysters in the size class 49-59mm for each year.

Beverton-Holt method estimates

Beverton-Holt length based mortality rate (Z) estimates increased from 1.64 year^{-1} in 2011 to 2.29 year^{-1} in 2023 (Figure 11). Using a variation of the Beverton-Holt method, four models were compared using AIC as a model comparison indicator. The lowest AIC value indicated the best fit model was for one significant change in the mean length over the 12 year survey period (Table 8). That change occurred in 2015/2016 and mortality rates Z_1 and Z_2 were calculated for the periods 2011-2015 and 2016-2023 respectively (Table 9). Z_1 was 1.32 and Z_2 was 2.48.

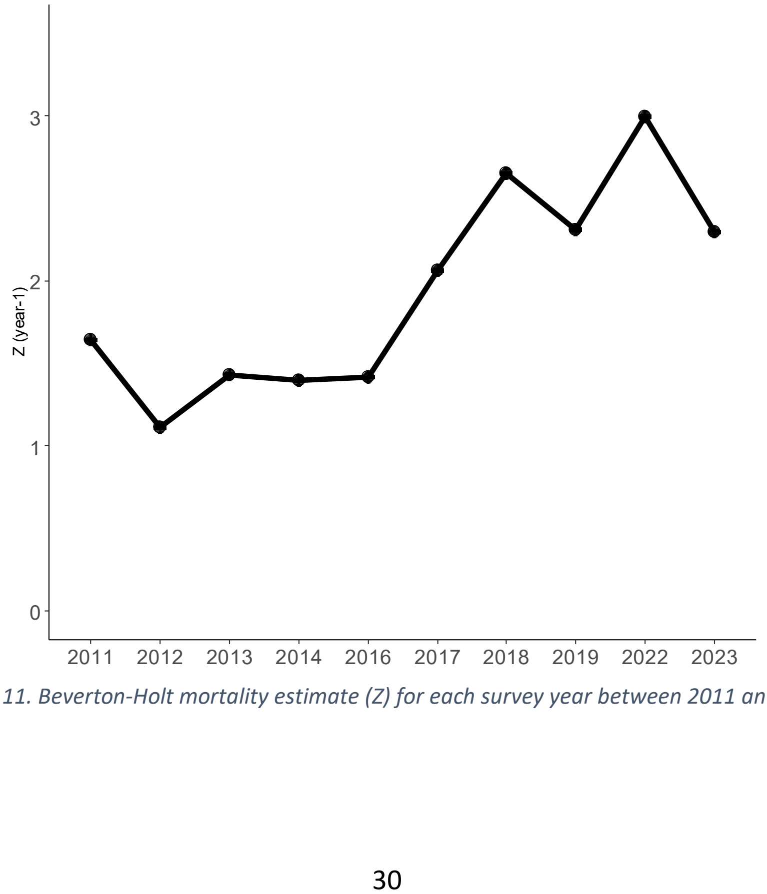

Figure 11. Beverton-Holt mortality estimate (Z) for each survey year between 2011 and 2023.

Table 8. Total mortality estimates, using the method of Gedamke and Hoenig (2006), containing different number of change points in mean length and AIC goodness of fit.

Variable	negLL	Npar	AIC	deltaAIC
1 change point	16.54	4	41.08	0.0
2 change point	15.59	6	43.18	2.1
3 change point	16.08	8	48.16	7.08
0 change point	26.57	2	57.14	16.05

Table 9. Results from the mortality estimations for the first level of mortality (Z_1), the second level of mortality (Z_2) and the year of change predicted using the method of Gedamke and Hoenig (2006).

Variable	Estimate	Standard error
Z1	1.326	0.075
Z2	2.479	0.139
Year of change	2015.7	0.307

Length converted catch curves (LCCC) method estimates

Length converted catch curves were produced for each year and for 3 year groups. Similar to the Beverton-Holt estimates, mortality estimates from the LCCC showed an increase in mortality over the survey period. Z was relatively stable between 2011-2014 but fluctuated from 2016-2023 (Figure 12). To minimise bias in Z that may arise from year to year variation in recruitment (equilibrium assumptions) or survey effects, the survey data were collated into to 3 year groups; 2011-2013, 2014-2017 and 2018-2023 (no data available for 2015 or 2020), and an estimate of Z calculated for each year group. Z increased from about 2.0 year^{-1} in 2011-2013 to 2.6 year^{-1} in 2018-2023 (Figure 12). These estimates equate to actual losses of 80% of oysters per year.

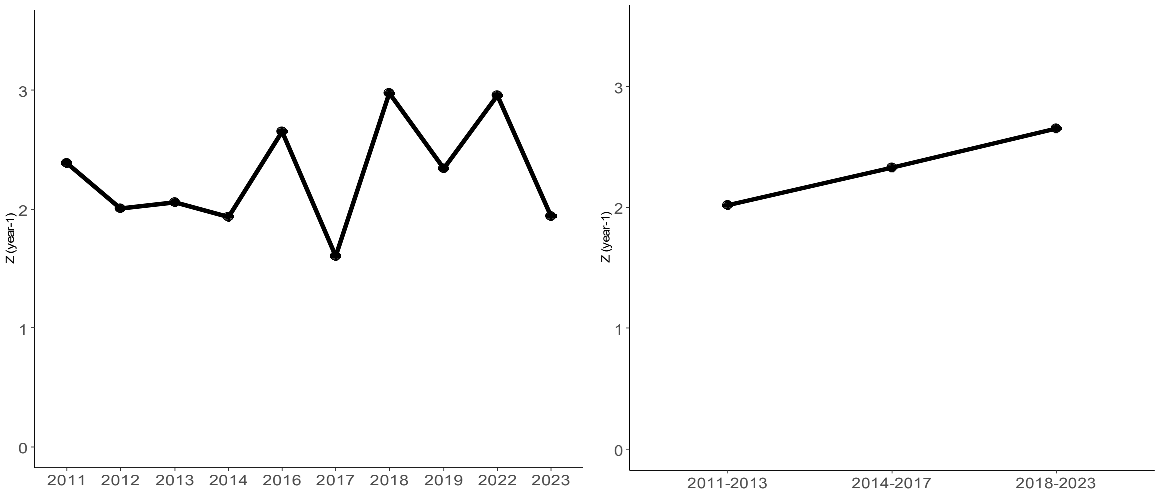

Figure 12. Total mortality (Z) estimates using the LCCC method for oysters in Galway Bay annually between 2011 and 2023 (left) and for three year grouping 2011-2013, 2014-2017 and 2018-2023 (right).

Discussion

Oyster mortality rates were estimated using length based methods. Each length based mortality estimation method has underlying assumptions that could cause over or under estimation of mortality. However, all methods indicated a general increase in mortality rate over a 12-year period from 2011 to 2023. The mortality rates reflect the changes in biomass and size structure that have been observed in the population over this time period. Estimates of mortality for oysters in Galway Bay were also calculated by Tully and Clarke (2012) for 2011 and 2012. The Z estimates of 1.32 year^{-1} for 2011 and 1.04 year^{-1} for 2012, were similar to the estimates obtained here using the Beverton-Holt method. The LCCC estimates of mortality were higher for these years. Huynh *et al*. (2018) compared length based mortality estimation methods, including LCCC and Beverton-Holt, and concluded that these two methods performed comparably and the study could not make any recommendations for choosing one over the other.

Twelve-years of survey data of native oysters in Galway Bay shows that settlement and recruitment occurs frequently and usually on an annual basis within the main beds but that this recruitment is not translating into higher biomass of larger oysters because of high mortality rates. Although a number of factors could be involved in high oyster mortality, including exposure to low salinities in some areas, it is likely that the main cause is *Bonamia* infection. Oysters in estuaries of the Clarin and Dunkellin Rivers, in addition, are likely to suffer mortality due to low salinities. Mortality rates have increased during the 12 year period. The reasons for this are unclear. Stronger recruitment, higher biomass and densities of smaller oysters may be increasing the prevalence and mortality caused by *Bonamia* as the spread of the disease may be density dependent.

The data shows that increasing recruitment will not necessarily result in increases in biomass of large oysters. Restoration methods, therefore, to increase settlement and recruitment may not lead to re-building of commercial stocks if mortality remains high, although massive increases in settlement would probably result in some increase in the biomass of oysters up to 60mm in size.

Assessing the scope to select for *Bonamia* tolerance or resilience and its genetic basis is important. The rate of development of tolerance by natural selection may be slow given that oysters with no tolerance contribute to spawning before succumbing to the disease i.e. the size at maturity is lower than the size at which *Bonamia* induced mortality really increases. Approaches to mitigating the effect of *Bonamia* infestation are discussed in a separate report below.

4. Settlement of native oyster (*Ostrea edulis*) and other bivalves on mixed cultch at sentinel sites in Galway Bay in 2018 and 2019

Oliver Tully[1], Owen O Connell[2], Gerry O Halloran[2], Diarmuid Kelly[2]

1; Marine Institute, 2; Cuan Beo

Acknowledgements: Tommy Connolly and Owen O'Connell managed the deployment and recovery of cultch stacks. Gerry O Halloran managed the counting of spat at The Redbank Food Company. Tommy Connolly, Fergal Langley, Mattie Larkin, David Krause, Brian Krause and Gary Harty maintained the cultch stacks on their aquaculture sites. Martin Burke, B. Burke, Ciara O'Halloran, Gerry O Halloran, Tommy Connolly and Owen O'Connell counted spat on cultch. Bernard Whelan provided razor clam cultch from Clifden Bay.

Introduction

A study was designed to look for evidence of spat fall of native oysters in areas surrounding and at various distances from the main oyster spawning stocks in Galway Bay and to quantify settlement rates at these sites. Given that settlement may be sensitive to substrate, 3 types of cultch (bivalve shell) were used. The trials were small in scale but provide indications of the potential to increase oyster recruitment at various locations in the Bay if larger volumes of cultch were provided to promote settlement and also provide a method for development of a settlement and recruitment index for native oyster. Large scale trials are also reported separately in Section 6 below. Settlement substrate may be a significant bottleneck to oyster production and previous trials in other areas suggest that enhancing settlement habitat increases spat fall, provided spawning stock is suitably located at densities that are sufficient to achieve fertilisation, and where temperature and feeding conditions provide for viable and competent larvae.

Methods

Deployment of cultch

In 2018 mussel (*Mytilus*), Pacific oyster (*Magallana gigas*) and razor clam (*Ensis magnus*) shells (subsequently referred to as cultch) were packed into stacked round sectioned trays and suspended underneath oyster trestles (4 sites) or on mussel long lines (1 site) in inner Galway Bay (

Table 10, Figure 13, Figure 14). Pacific oyster shell was crushed to variable size pieces prior to deployment. Some of this material was fine and resulted in siltation into some of the trays containing Pacific oyster cultch during deployment. Mussel shell was deployed whole. Razor clam shell, a by-product of the razor clam fishery in Clifden Bay, was also mixed with a number of clam species such as *Lutraria*, *Spisula* and *Venus* spp but razor clam was the dominant species. These shells were not crushed.

Each stack of cultch consisted of 3 trays each with 4 sections (Figure 15). Mixed clam cultch, Pacific oyster cultch and mussel cultch were placed in the top, middle and lower trays respectively in each stack. These trays were topped by a 4th empty tray. The mesh size of the trays was up to 20mm and enabled significant water exchange through the stack.

Stacks were deployed in early July.

Similar deployments were completed in Killeenaran (10 stacks) and Muckinish (7 stacks) in 2019.

Table 10. Number of cultch stacks deployed at each site in Galway Bay in 2018

Site	Number of cultch stacks	Location name
Site 1	22	Killeenaran
Site 2	18	Kinvara Bay
Site 3	23	Doorus Pt
Site 4	18	Muckinish
Site 5	7	Ardfry
Total	88	

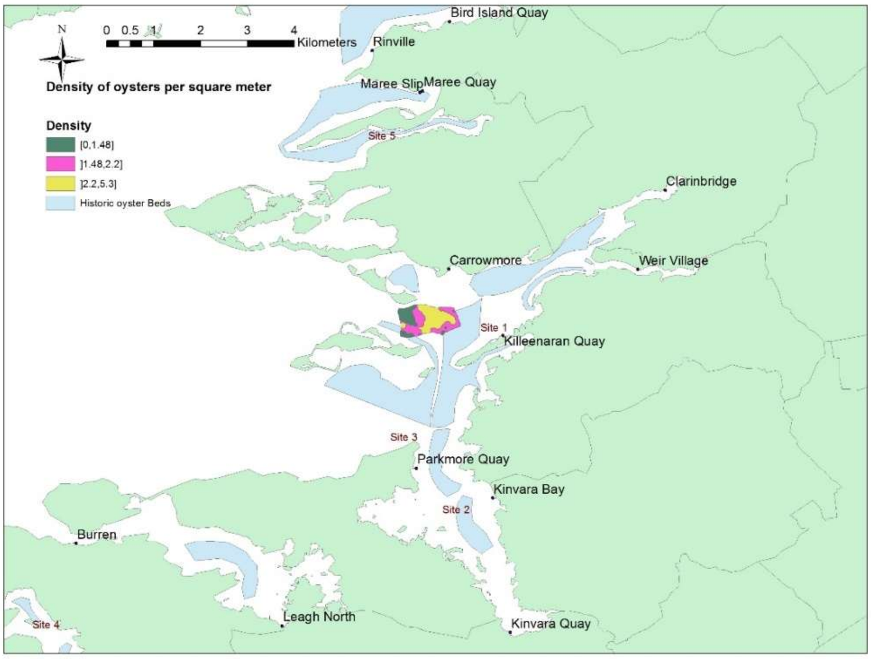

Figure 13. South East inner Galway Bay showing the location of 5 sites where cultch was deployed. The distribution of historic public and private oyster beds is shown.

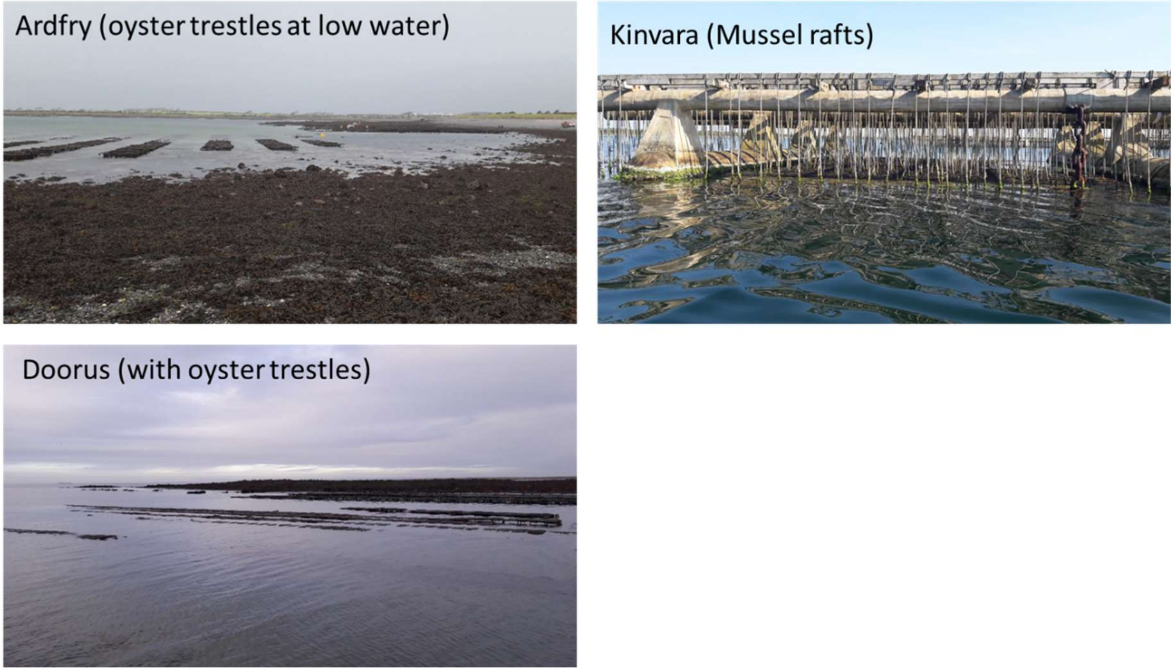

Figure 14. Images of 3 of the 5 sites where cultch was deployed. Cultch stacks were suspended underneath trestles at all sites other than Kinvara where they were suspended under mussel rafts in open water.

Figure 15. Cultch stacks recovered from Site 2 (Doorus Pt). Each stack consists of 3 trays each with 4 sections and a cover tray (see insert). The trays are suspended using a rope through the middle of the stack.

Predicting the time of spawning

Oysters that are preparing to release larvae can easily be identified from the dark colouration of the mantle cavity where the larvae are held prior to release. Although exhaustive monitoring of maturity and larval development was not undertaken for this cultch trial, oysters held at Killeenaran (Site 1) just before the cultch was deployed were not spawning and had no larvae in the mantle cavity. The cultch was, therefore, deployed prior to the main spawning season.

Counting of oyster spat

Cultch stacks were recovered from the sea between early November 2018 (Site 3-5) and January 2019 (Site 1 and 2). Stacks were individually tagged and removed to indoor flow through seawater tanks at Redbank Food Company Ltd., New Quay prior to counting of spat. All cultch in all sections of the stacks was weighed and inspected for native oyster spat and for other species including mussel (*Mytilus* sp), scallop (*Chlamys varia*), Pacific oyster (*Magallana gigas*) and saddle oyster (*Anomia ephippium*). Spat numbers were converted to spat.kg^{-1} of cultch. The average weight of cultch in each section of each tray was 726g (Table 11).

Native oyster spat were identified by the presence of a streaked calcium deposit perpendicular from the umbo, the extension of the umbo beyond the margin of the shell and the dull and non-reflective shell in contrast to the iridescent shell of saddle oyster (, Figure 17). Identification was aided by the use of high intensity LED head lamps worn by people searching the cultch for spat. This increased the contrast between saddle oyster and native oyster in particular. Spat were counted by 7 different people working intermittently during November 2018 to January 2019. Standard protocols and data sheets for identifying spat and recording of data were used by all counters.

Table 11. Average weight of cultch per tray section in cultch stacks used to monitor settlement of oysters and other species in Galway Bay autumn 2018.

Site	Gigas	Mussel	Mixed clam	Site average
Ardfry	854	668	517	679
Doorus Pt	803	613	752	724
Killeenaran	842	651	493	657
Kinvara Bay	885	758	715	786
Muckinish	909	703	789	800
Cultch type average	**852**	**675**	**657**	**726**

Data analysis

The primary objective of the experiments was to determine the distribution of native oyster spat fall at the 5 sentinel sites and if the type of shell influenced the settlement of native oyster larvae. Three types of cultch were deployed across 5 sites in the same stack configurations and for the same effective period of time. The primary variables of interest, therefore, was the site location and cultch type and also variability between stacks within the site.

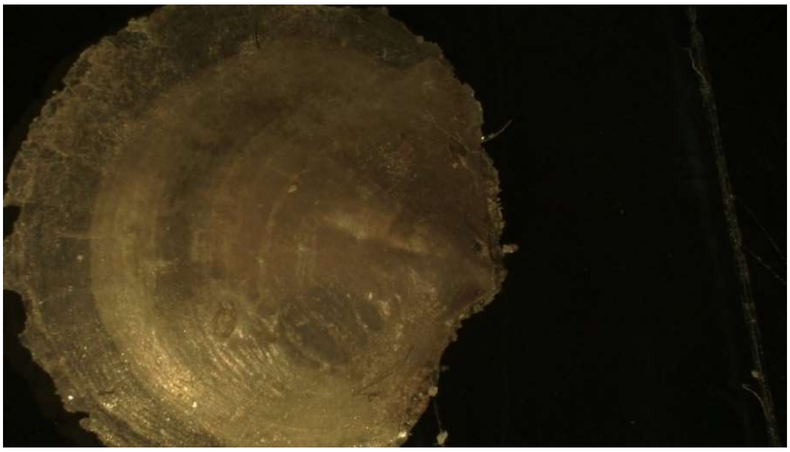

Figure 16. Spat of the native oyster. Diagnostic features include the presence of a white calcium deposit reaching perpendicular from the umbo and the extension of the umbo beyond the margin of the shell. The shell is dull.

Figure 17. Examples of bivalve and crustacean settlement onto cultch stacks. The diagnostic white calcium streak from the umbo of Ostrea is visible.

Results 2018

Data for 88 stacks and 953 tray sections of cultch were obtained across 5 sites. Native oyster (*Ostrea*), saddle oyster (*Anomia*), variegated scallop (*Chlamys varia*) and mussel (*Mytilus*) settled onto the cultch. Native oyster spat varied from 5-10mm in size in the first cultch samples counted in November 2018 but were up to 20mm in cultch inspected in late January 2019. No Pacific oyster spat were recorded. Brown crab (*Cancer pagurus*) and spider crab (*Pisa* sp.) were also recorded. The dominant settlement in most cases was of saddle oyster. These were not counted.

Oyster spat settlement

The overall average settlement of native oyster was 8.4 spat.kg^{-1} cultch. Site, shell type and stack number all had significant effects on settlement but shell type had the dominant effect (

Table 12). Settlement was lowest on Pacific oyster shell at 5.3 spat.kg^{-1}cultch compared to 8.7 spat.kg^{-1}cultch on mussel shell and 11.1 spat.kg^{-1} cultch on mainly razor clam shell. Settlement levels were generally similar across sites except for Muckinish where settlement was lower (Figure 18,

Table 13).

Table 12. Analysis of variance (ANOVA) for effects of Site, Shell type and Stack (3 trays) on settlement of native oyster spat. The F ratio indicates the relative contribution to variance from each factor (Site, Shell type, Stack number)

Source	df	SS	MS	F-ratio	Prob
Const	1	67596	67596	314	< 0.0001
Site	4	686	171	5	<0.0009
Shell type	2	5303	2651	73	< 0.0001
Stack	83	17841	215	6	< 0.0001
Error	855	30851	36		
Total	944	60594			

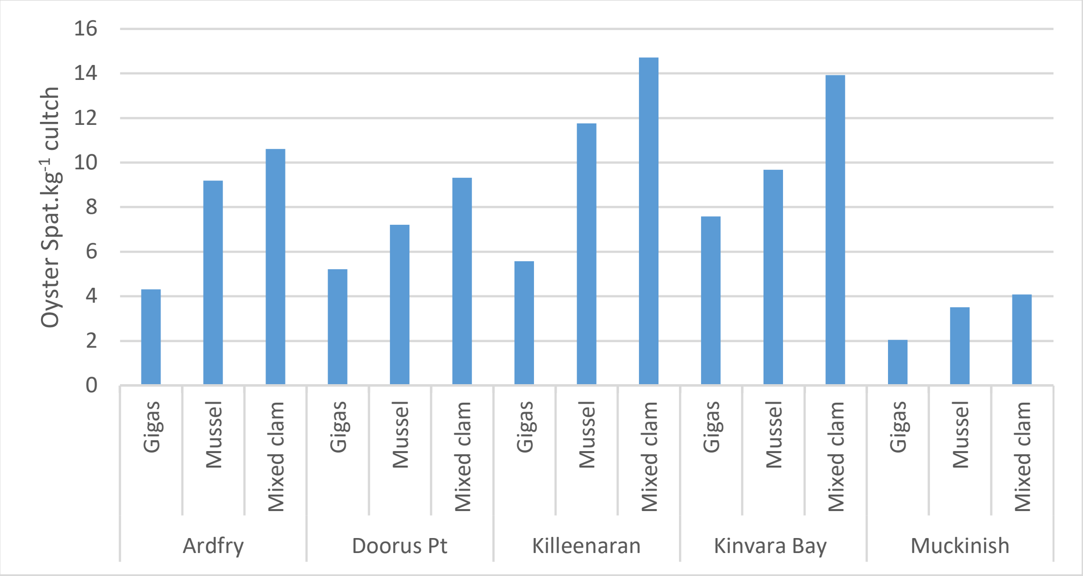

Figure 18. Average number of oyster spat per kg of cultch for 3 types of cultch deployed at 5 sites in Galway Bay in autumn of 2018.

Table 13. Levels of settlement of native oyster spat across 5 sites and 3 shell types

Site and Cultch type	**Spat.kg^{-1} cultch**	
	Mean	St. Dev.
Ardfry (average)	**8.03**	**8.33**
Gigas	4.30	6.58
Mussel	9.19	9.16
Mixed clam	10.60	7.98
Doorus Pt (average)	**7.29**	**7.88**
Gigas	5.22	5.03
Mussel	7.20	6.86

Mixed clam	9.32	10.20
Killeenaran (average)	**10.82**	**8.63**
Gigas	5.57	4.95
Mussel	11.75	6.88
Mixed clam	14.71	10.29
Kinvara Bay (average)	**10.41**	**6.92**
Gigas	7.58	4.76
Mussel	9.68	5.67
Mixed clam	13.92	8.30
Muckinish (average)	**3.24**	**5.07**
Gigas	2.04	3.18
Mussel	3.50	5.46
Mixed clam	4.07	5.90

Scallop spat settlement

The overall average settlement of variegated scallop was 23.7 spat.kg^{-1}cultch. Site, shell type and stack number all had significant effects on settlement but variability between stacks was high (Table 14). Settlement was lowest on Pacific oyster shell at 19.9 spat.kg^{-1}cultch compared to 24 spat.kg^{-1}cultch on mussel shell and 27.1 spat.kg^{-1}cultch on mixed clam shell. Settlement levels were generally low (2-5 spat.kg^{-1}cultch) at sites other than Kinvara which had dramatically higher settlement at approximately 86 spat.kg^{-1}cultch (Figure 19,

Table 15).

Table 14. Analysis of variance (ANOVA) for effects of Site, Shell type and Stack (3 trays) on settlement of variegated scallop.

Source	df	SS	MS	F-ratio	Prob
Const	1	532894	532894	38	< 0.0001
Site	4	8021	2005	5	<0.0009
Shell type	2	12104	6052	14	< 0.0001
Stack	83	1150630	13863	32	< 0.0001
Error	851	363361	427		
Total	940	2609700			

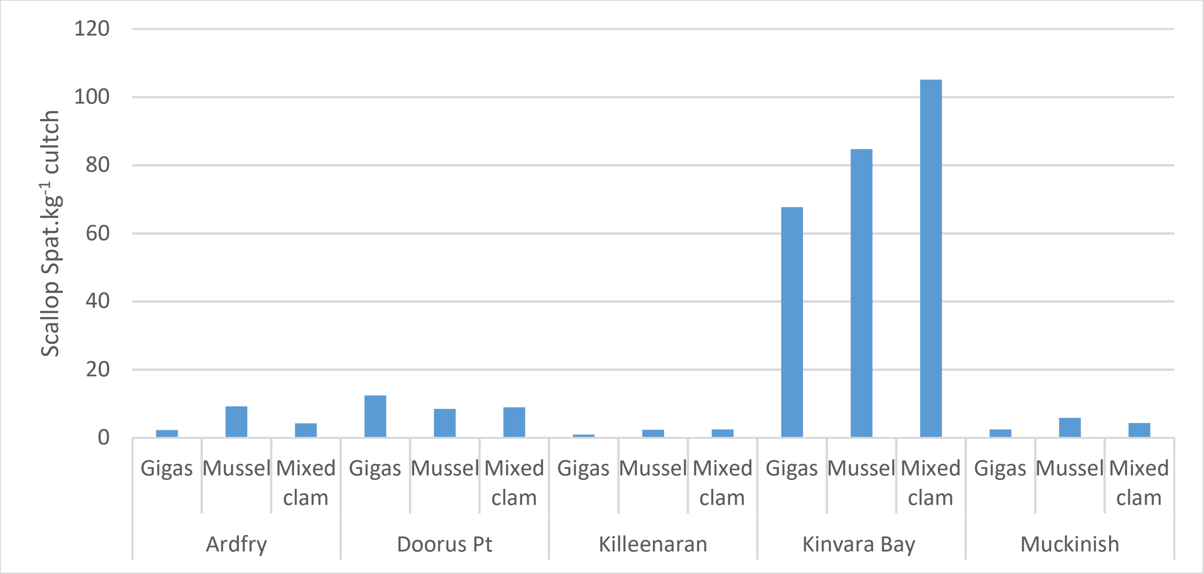

Figure 19. Average number of scallop spat per kg of cultch for 3 types of cultch deployed at 5 sites in Galway Bay in autumn of 2018.

Table 15. Levels of settlement of scallop spat across 5 sites and 3 shell types

Site and Cultch type	Scallop spat.kg-1 cultch	
	Mean	St. Dev.
Ardfry	**5.18**	**6.99**
Gigas	2.22	3.31
Mussel	9.16	10.00
Mixed clam	4.17	3.53
Doorus Pt	**9.90**	**12.71**
Gigas	12.40	14.61
Mussel	8.42	11.28
Mixed clam	8.92	11.80
Killeenaran	**1.88**	**2.82**
Gigas	0.87	1.21
Mussel	2.33	3.28
Mixed clam	2.37	3.15
Kinvara Bay	**85.94**	**83.04**
Gigas	67.69	64.83
Mussel	84.73	87.53
Mixed clam	105.14	90.94
Muckinish	**4.26**	**5.56**
Gigas	2.41	2.21
Mussel	5.84	7.68
Mixed clam	4.34	4.81

Mussel spat settlement

Mussel spat settled in very low numbers and mainly in Kinvara Bay (at the mussel rafts). Settlement at other sites was effectively absent (Figure 20). Analysis of variance also showed a significant effect of shell type on settlement with significantly higher settlement occurring on mixed clam shell (Figure 20, Table 16, Table 17)

Table 16. Analysis of variance (ANOVA) for effects of Site, Shell type and Stack (3 trays) on settlement of mussel.

Source	df	SS	MS	F-ratio	Prob
Const	1	0.0019	0.0019	6.1421	<0.0152
Site	4	0.0001	0.0000	0.2657	<0.9
Shell type	2	0.0009	0.0004	8.5764	<0.0002
Stack	83	0.0263	0.0003	6.2647	< 0.0001
Error	855	0.0433	0.0001		
Total	944	0.0741			

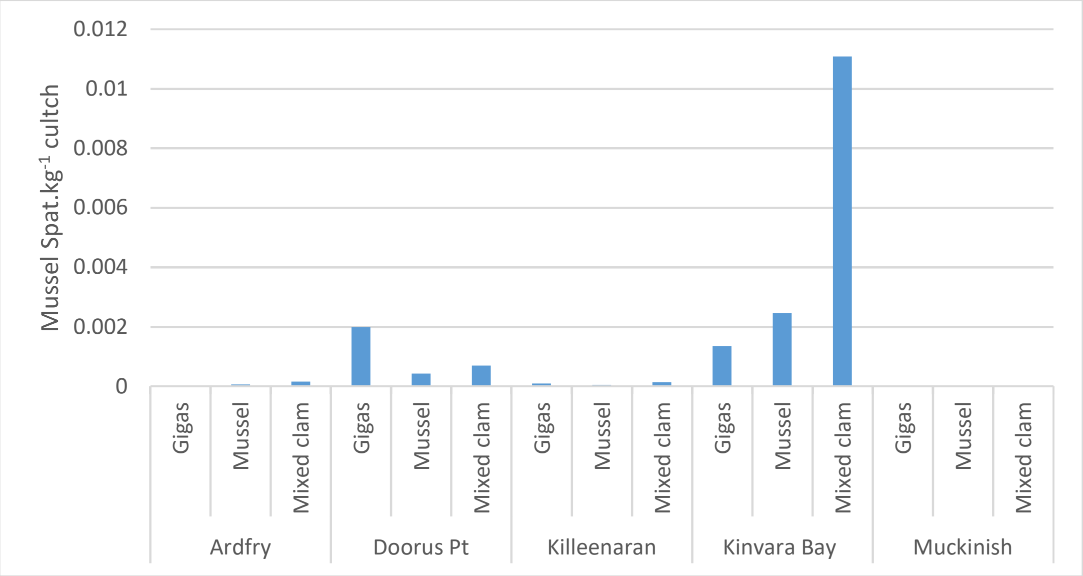

Figure 20. Average number of mussel spat per kg of cultch for 3 types of cultch deployed at 5 sites in Galway Bay in the autumn of 2018.

Table 17. Levels of settlement of mussel across 5 sites and 3 shell types

Site and Cultch type	Mussel spat.kg-1 cultch
	Mean
Ardfry	**0.0001**
Gigas	0.0000
Mussel	0.0001
Mixed clam	0.0002
Doorus Pt	**0.0010**
Gigas	0.0020
Mussel	0.0004
Mixed clam	0.0007
Killeenaran	**0.0001**
Gigas	0.0001

Mussel	0.0001
Mixed clam	0.0001
Kinvara Bay	**0.0050**
Gigas	0.0014
Mussel	0.0025
Mixed clam	0.0111
Muckinish	**0.0000**
Gigas	0.0000
Mussel	0.0000
Mixed clam	0.0000

Results 2019

Oyster spat settlement

Data on oyster spat settlement in 2019 confirmed higher settlements onto razor clam shell at the two sites monitored in that year. In contrast to 2018 settlement was approximately twice as high at Muckinish compared to Killeenaran (Table 18,

Figure 21).

Table 18. Levels of settlement of native oyster spat across 2 sites and 5 shell types.

Site and shell type	**Average spat.kg^{-1} shell**
Killeenaran	**7.93**
clam	8.90
gigas	6.88
mix	6.98
mussel	6.31
razor	13.26
Muckinish	**15.20**
clam	15.51
gigas	12.25
mix	14.79
mussel	12.71
razor	22.83
Grand Total	**11.63**

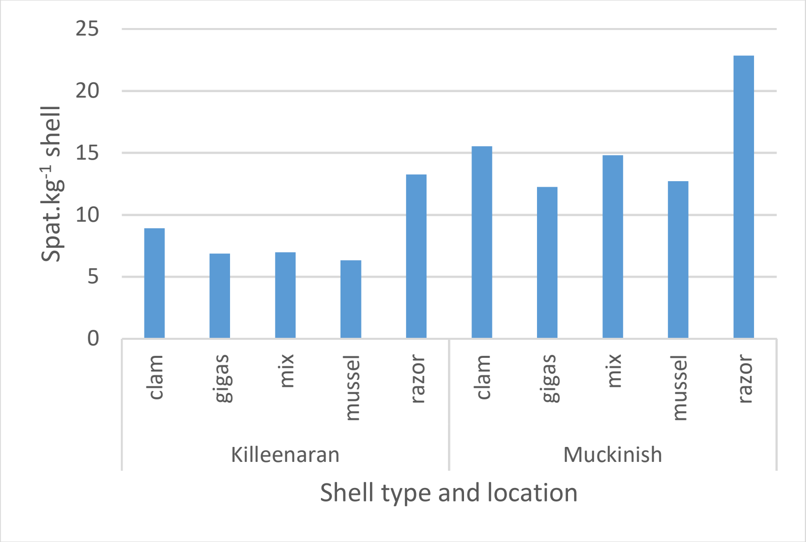

Figure 21. Average number of native oyster spat per kg of cultch for 5 types of cultch deployed at 2 sites in Galway Bay in the autumn of 2019.

Discussion

Settlement of native oyster spat occurred at all sentinel sites monitored in Galway Bay demonstrating widespread larval production, dispersal and successful settlement throughout the south east area of the Bay. Settlement was higher on clam shell, dominated by *Ensis magnus*, than on mussel (*Mytilus*) or Pacific oyster (*Gigas*) shell. This shell effect was consistent across the 5 sentinel sites and suggests that razor clam (*Ensis*) shell is more attractive to settling oyster larvae than mussel or Pacific oyster shell. Settlement of *Chlamys* was more variable across sites and not consistently higher on mixed clam cultch. Mussels settlement was uncommon.

Settlement of approximately 10 oyster spat per kg of cultch occurred across 3 sites closest to the main spawning stock. However, similar settlement levels occurred at Ardfry (Site 5) which is remote from the known spawning biomass. It is likely that additional spawning stocks occur close to Site 5. Lower settlement at Site 4 (Muckinish) suggests this site is isolated from the main larval supply. However, the presence of settlement at all sites demonstrates that oyster larvae were widely distributed in the area during the trial. This includes open water areas, where mussel rafts are moored, and suggests that spat could be collected not only by using cultch on the seabed but also by placing suitable settlement substrate in the water column.

The reason for the consistently higher settlement of oyster spat on mixed clam shell compared to settlement on Pacific oyster or mussels across all sites is unknown. The total height of the stacks was approximately 50cm so it is unlikely that the position of the tray in the stack had a significant effect (it was not possible to test this as the cultch was not randomly distributed to different levels in the stack). Attractiveness of substrate to settling larvae may be increased by aged biofilms (Campbell *et al.*, 2011) so different rates of development of biofilms on different shell material could therefore influence settlement. Waterborne chemicals from biofilms also act as a settlement cue (Zimmer-Faust and Tamburri 1994). We have no evidence for different biofilm formation on different cultch used in the trials reported here. One significant difference, although unquantified, between cultch type used here was the shell size. Pacific oyster shell was crushed to varying sizes with some fine components. Mussels were not crushed although some were broken. Mixed clam shell, dominated by *Ensis*, was composed of individual shells, many of which were large (*Lutraria*, adult *Ensis*). The size profile of the shells was, therefore, different and this could have resulted in different shear stress and turbulence at the settlement surface that may have affected settlement. Hydrodynamic properties at the settlement surface of shell can affect settlement rates and dislodgements. Whitman and Reidenbach (2012) found that settlement of oyster was higher in interstitial regions between high-roughness topography where shear stress is reduced and recommended re-constructing 3 dimensional benthic topography similar to established oyster reef to enhance settlement. Although the stacks of cultch used in the trials reported here are 3-D and probably provide highly variable hydrodynamics at the settlement surface, razor clam shell provides a smoother surface than Pacific oyster or Mussel shell.

Settlement rates seen in the small trials reported here translate to about 10000 spat per tonne of cultch. There is obvious potential to enhance spat settlement using cultch at larger scale. Additional trials that would optimise the configuration of the cultch (on seabed or on structures), the type of cultch, the deployment time relative to spawning and the location relative to spawning and larval dispersal in the area will provide more information on how this could be achieved. Larger scale cultch deployments are reported below in Section 6. These show high annual and spatial variability in settlement with possible shell substrate effects but also that significant enhancement of settlement can be achieved by scaling up cultch deployments.

5. Growth and survival of known age juvenile oysters

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1, Marine Institute, 2; Cuan Beo, 3; BIM,

Acknowledgements: Iarfhlaith Connellan produced spat in spatting ponds at Jasconius Ltd, Auginish, Co. Clare. Frank Flanagan deployed cages subtidally at Rinville and Tawin. Mattie Larkin, Fergal Langley, Brian Krause, David Krause, James Linnane and Iarfhlaith Connellan maintained cages on oyster trestles and provided samples.

Introduction

Early life history traits of oyster play an important role in determining the productivity of oyster populations. Variation in settlement, mortality and growth in the first year can have dramatic consequences for the evolution of biomass of a given cohort. Mortality rates in particular are likely to be very high after settlement and in the first winter and small variation in these rates, when the number of individuals in a cohort are at a maximum, can have significant consequences for the biomass of that cohort as it ages. Growth and survival in the early life stages influence population dynamics and how recruitment translates to adult (exploited or unexploited) biomass. Native oysters, *Ostrea edulis*, in Galway Bay have declined since the 1980s and despite the cessation of fishing in 2017 have not recovered. Changes in environmental conditions and *Bonamia* infestation are thought to be key factors in this decline.

Interventions such as transplanting native oyster spat from hatcheries or spatting ponds into natural oyster habitat may have a role to play in restoring stocks. Information on the performance of these spat post release would provide evidence as to the efficacy of such an approach (Pouvreau *et al.*, 2021). Will the balance of growth and mortality lead to an increase in biomass of a cohort over time? How do survival rates vary in time and space and what conditions, including size at transplant, temperature and salinity conditions, might favour higher survival?

This report provides estimates of growth and survival rate of transplanted native oyster aged 6 months to 30 months. Spat, settled onto bivalve shell in spatting ponds, were held in cages at different sites around Galway Bay and some were broadcast on the seabed. Survival and growth of different known aged cohorts were monitored over a 2.5 year period. The advantage of using spat from spatting ponds is that the absolute age and birth date is known in contrast to the length based methods reported above from the survey time series. It is thereby possible to follow the fate of individual age classes over time.

Methods

Spat production in spatting ponds in 2020

The production of spat in spatting ponds in Auginish (Jasconius Ltd.) was financed by the EMFF oyster restoration project in 2020. The main purpose of this work was to produce a spat population of known age and to monitor growth and survival of this population at various sites in Galway Bay over 2021 and 2022. In addition, and funded separately by BIM, spat were produced in 2019 also by Jasconius Ltd. Both year classes were available for deployment and monitoring. Spatting ponds enhance larval production and settlement intensity (onto shell substrate) as water in the ponds are a couple of degrees above ambient.

Broodstock were sourced from Galway Bay in early summer 2019 and 2020 under a Section 59 authorization from Inland Fisheries Ireland (IFI). Broodstock (about 800 oysters each year) were transferred to spatting ponds at Jasconius Ltd. Larvae produced from these oysters were settled onto mussel and oyster shell (spatted cultch) deployed in bags around the sides of the ponds (Figure 22).

Figure 22. Spatting ponds at Jasconius Ltd, Auginish, County Clare. Bags of cultch are deployed on the sides of the ponds onto which oyster spat settle.

Cage (enclosure) deployments

Two year classes of spatted cultch were deployed to cages or broadcast on the seabed;

- 2019 year class: Approximately 2000kg of cultch with oyster spat was grown on trestles at oyster farms and in Ortac baskets in a number of locations between October 2019 and December 2020.
- 2020 year class: Approximately 3500kg of cultch with oyster spat was produced from the spatting ponds in 2020. The average number of spat per kg of cultch was 210±92 and a total population of 0.78±0.32million spat.

In December 2020, spat on cultch produced in 2019 and 2020 were measured and counted. The cultch was then divided into purpose designed cages (Figure 23) according to year class, with approximately 6-8kg of cultch in each cage. The spatted cultch was deployed in cages to intertidal and sub-tidal sites across Galway Bay (Figure 24). Intertidal sites were oyster farms and the cages were fixed underneath existing oyster trestle frames. Cages in sub-tidal sites were deployed by a local lobster fisherman. Oyster farmers and fishermen extracted samples from the intertidal and sub-tidal cages, respectively, once a month from January to November 2021, where possible. Samples were weighed and oyster spat were measured (Table 19). Density was expressed in numbers.kg^{-1} cultch.

Figure 23. (a) details of cages used for deployment of spatted cultch from spatting ponds. Mesh insert is 14mm. (b) cages deployed in the lower intertidal zone under oyster trestles.

Seabed (broadcast) deployments

Cultch with 2019 and 2020 spat was also broadcast at lower intertidal sites in Mulroog North (Figure 24, Figure 25). The 2020 year class was partly broadcast in December 2020 with the remainder broadcast in March 2021 where it was retained in the spatting ponds until that time. At each site a rectangular area was marked with poles driven into the sediment. Separate areas were established for deployment of 2019 and 2020 cohorts. One pole was subsequently used as a zero grid reference and samples taken on a 5*5m grid from that point to the edges of the cultch deployments. The cultch distribution was stable during the sampling period although larger oysters from the surrounding seabed were washed into the area. Samples were usually taken with a 0.25m^2 quadrat or sieve (0.0315m^2) or when tidal conditions did not allow this, a modified pond net (hand dredge) with rigid frame and teeth was used. The area swept by the dredge was estimated. All oysters were counted and measured. Sample counts were raised to grid cell area of 25m^2 to obtain population size estimates in the plot area.

Figure 24. Sentinel sites for monitoring of growth and survival of 0+ and 1+ aged oysters spatted onto mussel and oyster shell in spatting ponds in 2019 and 2020.

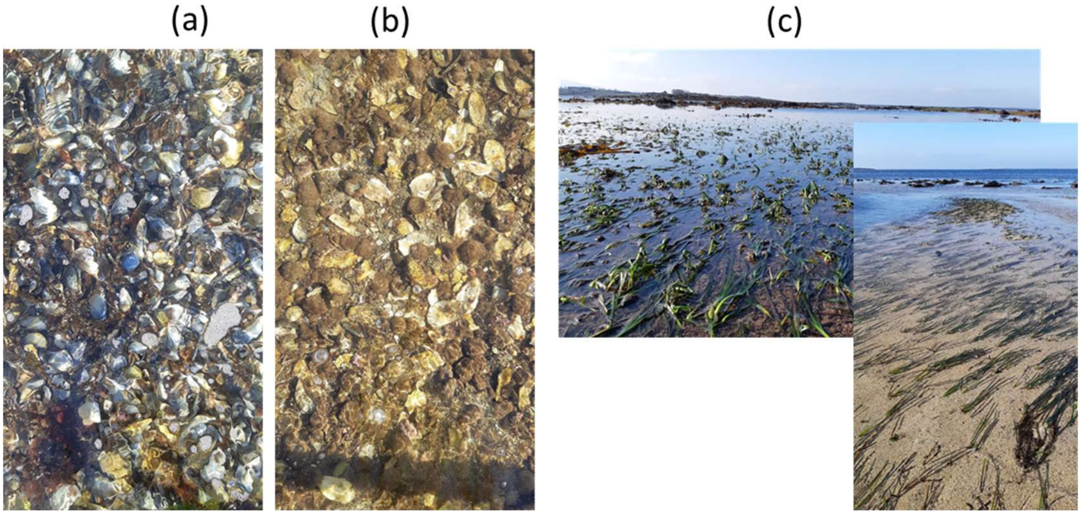


Figure 25. Images from Mulroog broadcast sites. (a) 100% ground cover of mussel cultch and (b) high % cover of pacific oyster cultch. Both spatted with native oyster. (c) A seagrass bed extends for about 100m west of Mulroog North site. The bed is not dense and is mixed with maerl.

Table 19. Summary of sampling carried out from cages containing the 2019 year class and the 2020 year. Tonnes of cultch deployed in cages and on the seabed is shown.

	2019 year class	2020 year class
Tonnes of cultch	2	1.5
No. of samples taken	100	99
No. of spat measured	1530	3571
Age range (months)	18-29	6-17

Results

Growth at cage monitoring sites

The average size of native oysters measured from the cages were calculated per quarter over the 12 month monitoring period (Figure 26). Growth in the first two years was seasonal. A smoothing function fitted to the length-at-age data showed that growth was slow during winter months - October-April, and much higher during May-September. The 2020 year class demonstrated a clear distinction between winter and summer growth in oysters aged 6-17month old (Figure 27). The difference between winter and summer growth was not as clear for the 2019 year class but an increase in growth during the summer months was evident in 18-29 month old oysters (Figure 28). The slope of the line, measured during the summer months was lower for the 2019 year class (slope = 4.28mm per month) than the 2020 year class (slope = 6.26 per month), which indicated a decrease in the growth rate of 1-2year old oysters compared to 0-1 year old oysters. Apparent negative growth (decrease in shell size) was observed during winter (age 16-17months). This can occur due to effects of turbulence and abrasion on the fragile, new growth, edge of the shell.

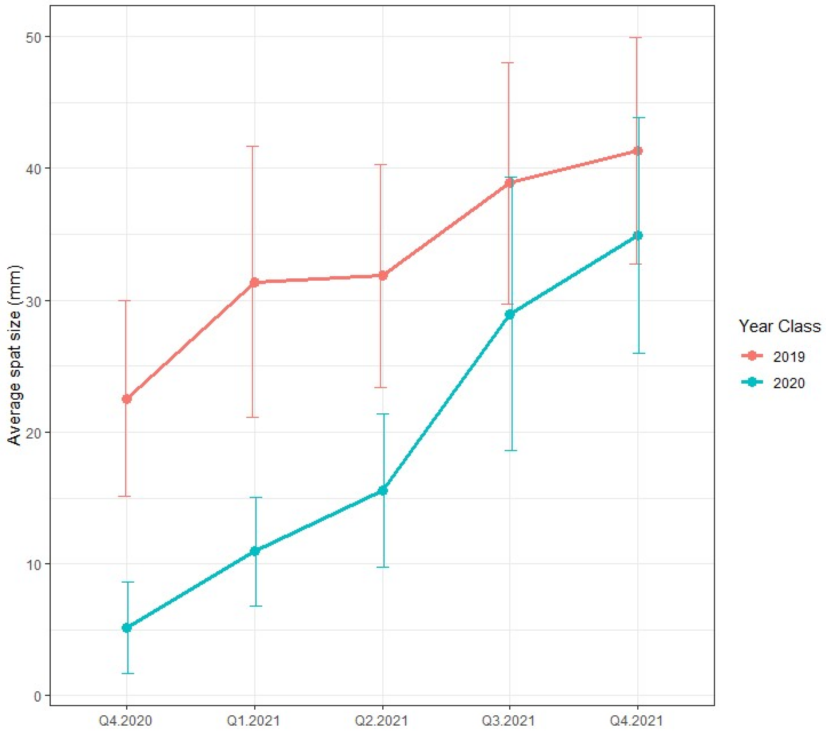


Figure 26. Average native oyster spat size (plus and minus one standard deviation) per quarter, for both year classes.

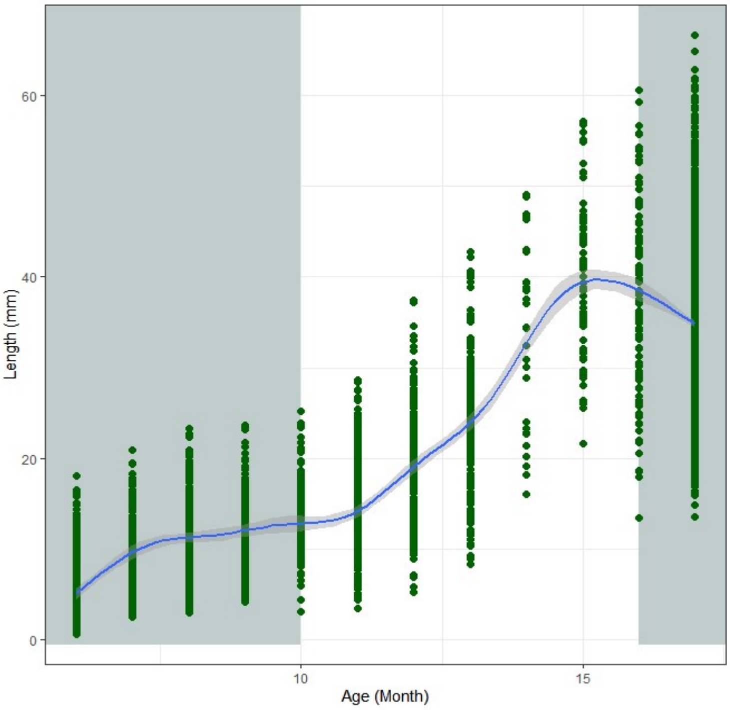


Figure 27. Length-at-age data for the 2020 year class. Data collected from 6-17 months old. Grey shaded areas indicate “winter” months October to April when growth is slower.

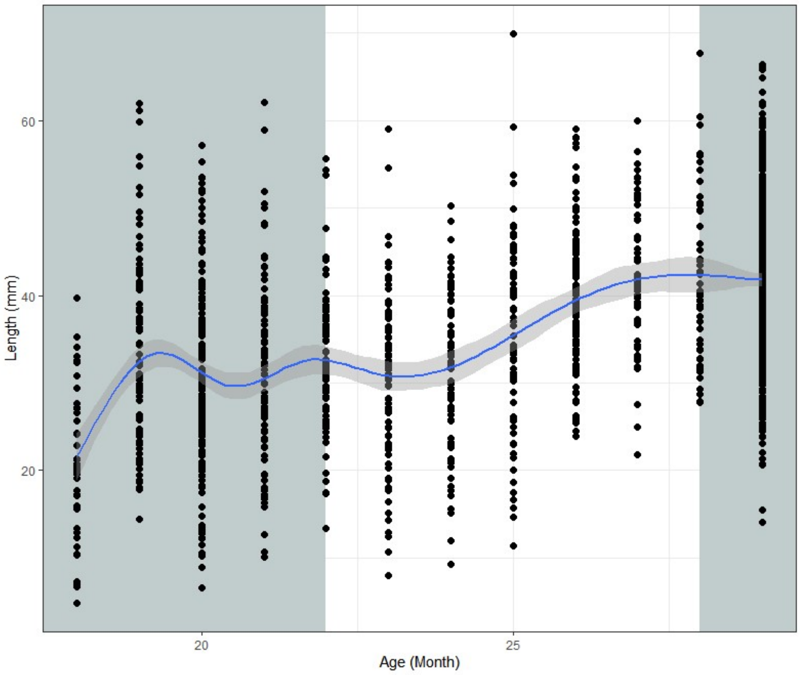


Figure 28. Length-at-age data for the 2019 year class. Data collected from 18-29 months old. Grey shaded areas indicate "winter" months October to April when growth is slower.

Survival at cage monitoring sites

The density of spat was calculated as the number of spat per kilogram of cultch. This was then used as a measure of survival throughout the sampling period;

$$\% \text{ Survival rate} = (D_t / D_0) * 100$$

where D_t is the density of oysters at time t, and D_0 is the initial density. Reductions in average density over time was more evident in age 0+ oysters (Figure 29). The initial high density in Q4 2020 is a result of measurements taken when sampling all of the cultch from the spatting ponds before it was divided into the cages and deployed. There was a large decrease in density from Q4 2020 to Q1 2021 in the 2020 year class. The oyster spat were 6-7 months old at this stage. Mortality, therefore, of these smaller spat in the first 2-3 months at sea, following transfer from the spatting ponds was very high. To get true indications of mortality rate in the cage and broadcast sites the density from Q1 2021 was used as the initial density (D_0) for calculating the subsequent percentage survival rate (Table 20, Figure 30).

Survival was higher in the 2019 year class. These oysters were larger than the 2020 year class at the time of deployment. The estimated percentage survival for oysters kept in cages in the first year and a half after settlement was approximately 20%, but for oysters 1 year older was approximately 40%.

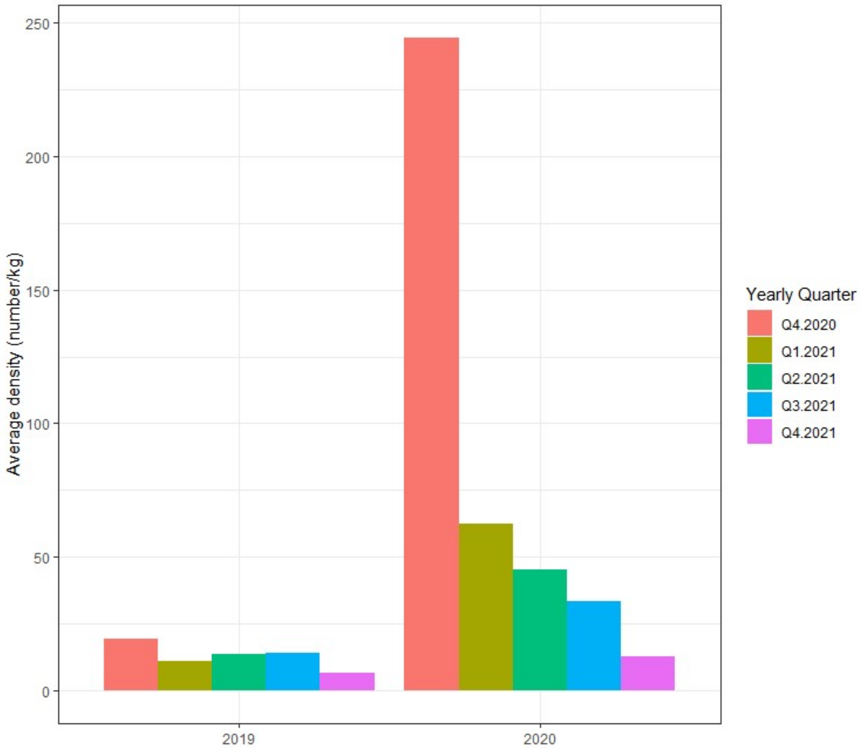


Figure 29. Average density, based on the number of oyster spat per kg of cultch, per quarter for the 2019 and 2020 year classes.

Table 20. The percentage survival rate (%SR) of oyster spat from a 2020 year class and a 2019 year class assuming Q1 is the starting density.

Year 1 - 2020 cohort		**Year 2 - 2019 cohort**	
Quarter	**% SR**	**Quarter**	**% SR**
Q1	100	Q1	100
Q1 to Q2	62.8	Q1 to Q2	67.1
Q1 to Q3	17.9	Q1 to Q3	62.2
Q1 to Q4	18.8	Q1 to Q4	39.1

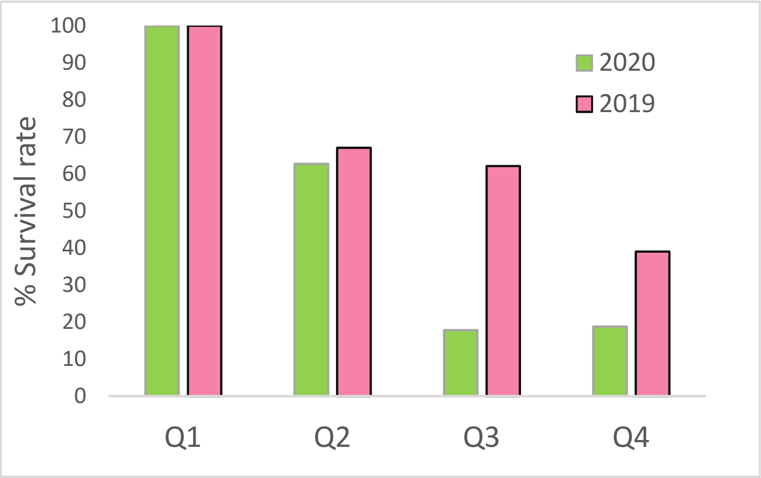


Figure 30. An estimate of the percentage survival rate across one year of sampling native oysters spat from a 2019 year class and a 2020 year class. Q2-Q4 are relative to Q1.

Growth of spat at Mulroog broadcast sites

At Mulroog North, the average size of spat was calculated per month for 2019 year class, 2020 year class and the 2020 year class retained in spatting ponds over winter and deployed in March 2021 (2020SP) (Figure 31). There were gaps in the data for both 2020 year classes, but in general, there is an increase in the size of spat. Overall, the 2020SP oyster spat were slightly smaller than the 2020 year class that was deployed in December 2020, despite having a similar average size in April 2021 (Figure 31). When deployed in March 2021, the oysters would have taken time to adjust to their new environment which may have delayed their development. The 2019 year class showed a clearer picture of the change in spat size throughout the year. The average size decreased from Jan-Mar and from Oct-Feb.

Figure 31. Average native oyster spat size (plus and minus one standard deviation) per month for the 2019 year class, the 2020 year class and the 2020 year class deployed in March 2021 (2020SP).

Age was estimated for the oyster spat based on a July 2019 and July 2020 birth month in the spatting ponds. A smoothing function was fitted to the length-at-age data for oysters aged 7-32 months old (Figure 32). Despite the gaps in data for the younger oysters, the smoothing function predicts an expected steady increase in growth during the summer months and zero or negative growth during the winter, similar to oysters kept in cages (Figure 27, Figure 28). Individual large size at age of a small number of oysters seem outside the possible growth rate. This could be due to asymmetrical elongated shell growth or represent oysters washed into the area from surrounding oyster beds.

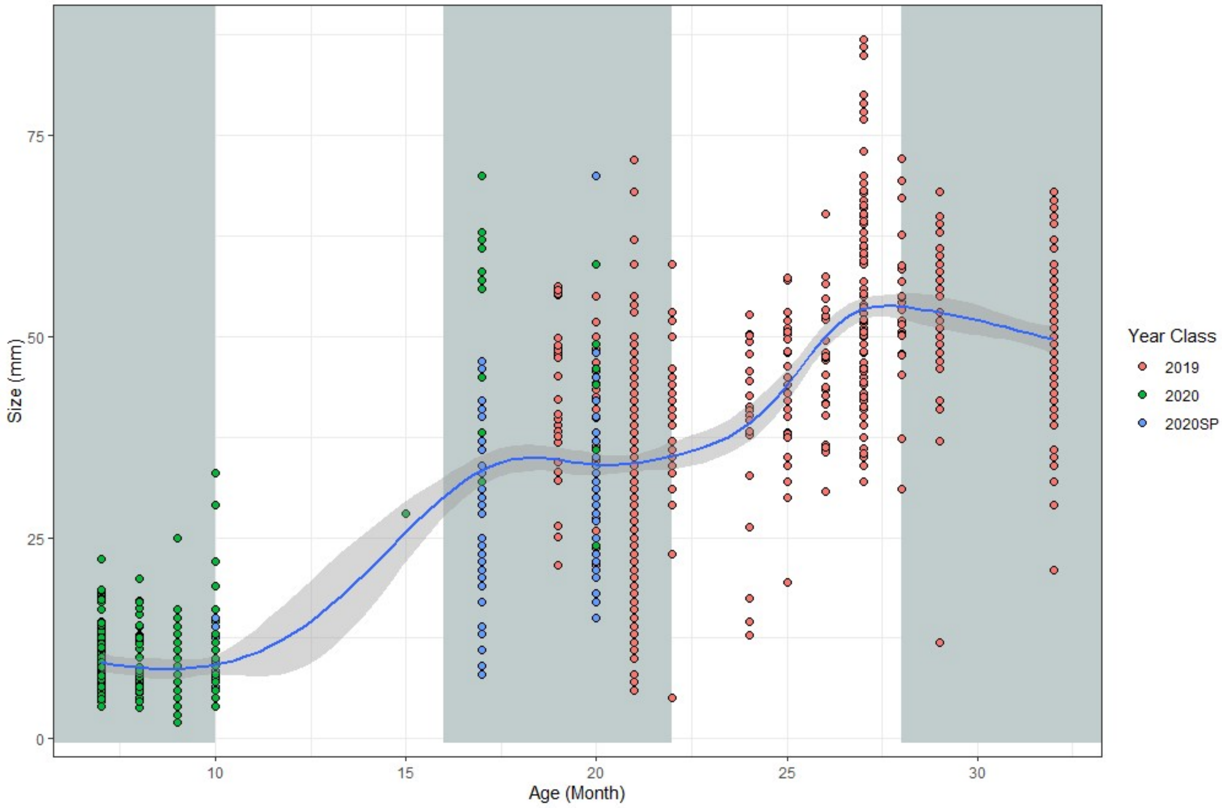


Figure 32. Length-at-age data for the three year classes. Data collected from 7-32 months old. Grey shaded areas indicate "winter" months October to April when growth is slower.

Survival of spat at Mulroog broadcast sites

The density of oysters was estimated as the number of oysters per m^2 (Figure 33). Only oysters sampled using a quadrat are reported here. The percentage survival rate was estimated per quarter for each batch of oysters. The average density of oysters for quarter 1 was used as the initial density, D_0 (Table 21). The 2020 year class that was deployed on the seabed in December 2020 had a survival rate of 5.5% at the end of the year, which is much lower than the 20% survival rate for the same year class of oysters that were kept in cages. The 2020 year class which was not deployed until March 2021 had a 12.5% survival rate so although these oysters were slightly smaller than the other 2020 year class oysters, their survival rate was improved by delaying deployment. The 2019 year class had a high survival rate of 65% at the end of the year, which is higher than the survival rate estimated from the cages of the same year class (Table 20).

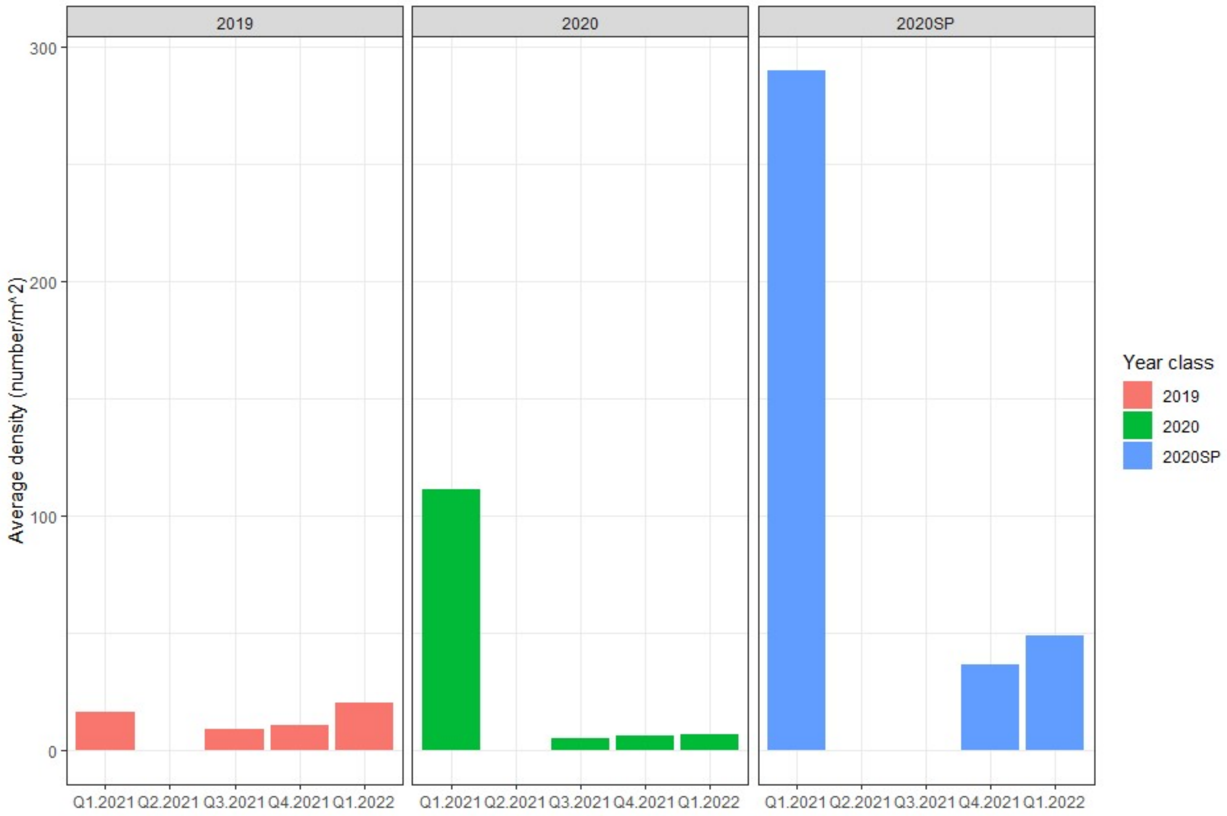


Figure 33. The average density of oyster spat (number per m2) for the 2019 year class, 2020 year class and the 2020 year class deployed in Spring, sampled at Mulroog North, using a 0.25m² quadrat.

Table 21. The percentage survival rate (%SR) of oyster spat from a 2020 year class, a 2020 year class deployed in Spring and a 2019 year class assuming Q1 is the initial density.

Year 1 - 2020 cohort		**Year 1 – 2020 cohort Spring**		**Year 2 - 2019 cohort**	
Quarter	**% SR**	**Quarter**	**% SR**	**Quarter**	**%SR**
Q1	100	Q1	100	Q1	100
Q1 to Q3	4.5	-	-	Q1 to Q3	57.2
Q1 to Q4	5.5	Q1 to Q4	12.5	Q1- to Q4	65.1

Discussion

Monitoring native oyster spat of known age held in enclosures or broadcast on the seabed in Galway Bay gave an insight into growth and survival of native oysters in their first 2.5 years of life and quantified the performance of spat on cultch produced in spatting ponds.

Growth was seasonal in oysters aged 6-29 months, with a significant increase in growth during the summer months and slow or even negative growth (due to shell edge erosion) in winter. Growth in shell height in 2+ year old oysters was lower than in 1+ year old oysters. Seasonal growth is expected as below 10°C there is a discontinuity in metabolic response which can be ascribed to a switch between "summer" and "winter" physiological states. These states are thought to be characterised by changes in the metabolic biochemistry (Hutchinson and Hawkins, 1992). Hutchinson and Hawkins (1992) describe minimal metabolic activity of *O. edulis* in its "winter" physiological state, this allows survival at low temperatures and salinities which the species normally encounters during the winter months in shallow coastal waters.

The survival rate was very low in the first 18 months but particularly in the months following transfer of spat from spatting ponds. Survival was twice as high in oysters aged 18-30months compared to oysters <18 months held in enclosures. On the seabed, survival in the lower intertidal zone in the first year of life was only 5.5% but approximately 65% in the second year. It was expected that the oysters kept in cages would have a higher survival rate, but for 2+ year old oysters survival on the seabed was higher than in enclosures. These rates are comparable to those reported by Laing *et al*. (2005) in UK oyster beds. Transfer of spat to sea from spatting ponds prior to their first winter resulted in high mortality. This may have been due to physical stress and air exposure during transfer although this was kept to a minimum and metabolic rate of spat in winter, when the transfer occurred, would have been low. Survival of 1+ oysters in enclosures and on the seabed following transfer from ponds and ortac baskets was high. Maintaining good survival of spat in the first year of life is therefore critical for subsequent performance at sea.

6. Large scale cultch deployment and monitoring of spat settlement 2019-2023

Oliver Tully[1], Emma White[1], Owen O Connell[2], Alec Reid[2], Diarmuid Kelly[2], David Krause[2], Brian Smyth[4]

1; Marine Institute, 2; Cuan Beo, 3; BIM, 4; Hydromaster Ltd.

Acknowledgements: Oyster shell cultch in 2020 was provided by Conor Reid. Scallop and whelk cultch in 2021 was provided by Sofrimar Ltd, Co. Wexford.

Introduction

Oyster spat require ‘clean’ hard substrate on which to settle. Any bivalve shell and many artificial substrates are suitable for oyster settlement. Productive oyster beds produce new shell through recruitment and growth. In cases where fishing is absent or well managed, limited amounts of shell (live oysters) are removed and the shell budget is positive i.e. more shell is produced than is lost through removal or fragmentation caused by dredging or natural disturbance from wave action. This may not be the case where fishing is uncontrolled and where recruitment declines. Wave action and fishing can both bury shell and upturn new shell that may be suitable for settlement. In estuarine conditions in particular where the siltation rate may be high new shell may be covered by silt, rendering it unsuitable for oyster spat settlement. Habitats that are suitable for maintenance and restoration of oyster should have low sediment mobility (<0.8cm.day^{-1}) and suspended sediments of less than 60mg.L^{-1} (Preston *et al*. 2020). These parameters are reflected in ground type which should be free of silt and be composed of mixed sediments with high shell content.

Spreading of clean bivalve shell (cultch) is one method of providing new clean substrate to increase the shell budget and to enhance spat fall and is a useful strategy particularly where there is evidence that low shell cover on the seabed may be a bottleneck to recruitment. In Galway Bay, surveys since 2010 (Section 2 above), indicate poor shell availability in many areas. This is unsurprising given the high mortality rates of juvenile oysters and generally poor recruitment of large oysters into the populations over the past 40 years. Section 4 above shows however that when shell is provided, settlement occurs in densities that suggest scaling up cutch deployment could significantly increase recruitment.

Cultch deployments

Different shell material including Pacific oyster, mussel, whelk and scallop were used as cultch in 2019-2021 to enhance spat settlement (Figure 34, Table 22). Although the 2018 small scale trials (Section 4) showed that razor clam shell consistently had higher settlement of oyster spat than shell of other species, razor shell is not available in Ireland in any significant volumes. Although landings of razor clams are significant at between 500-1000 tonnes per annum in the Irish Sea, all of this is exported live in the shell.

In each year the deployments were timed to coincide with larval production. Timing is important; on the one hand early deployment of cultch allows a biofilm to develop on the shell which increases its attractiveness as a settlement substrate, but on the other hand if deployment is too early it may become silted. Gametogenesis and larval brooding in mature oysters was monitored at Killeenaran. Cultch was deployed usually towards the end of June when oysters were brooding larvae. The pelagic larval phase is temperature dependent and is approximately 10-15 days at temperatures between 15-

20°C. Metamorphosis can be further delayed by a number of days if suitable substrate for settlement is not found (Rodriquez-Peres *et al*. 2021). Spawning may also be predicted when the number of degree days above 7°C from January 1st in the year of spawning reaches 576 (Maathius *et al*. 2020). In Galway Bay this usually occurs towards the end of June.

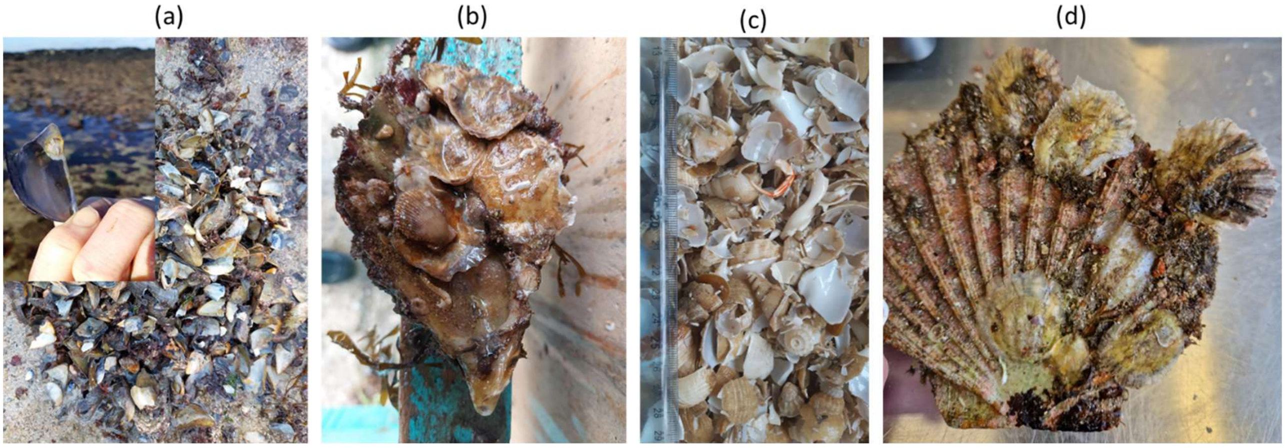


Figure 34. Cultch material used in large scale deployments in 2019-2023 in Galway Bay. (a) mussel shell used in 2019 showing typical sample taken from the lower intertidal zone and (insert) oyster spat on mussel. (b) Pacific oyster shell deployed in 2020 at two sites in Galway Bay with settlement of native oyster, saddle oyster, variegated scallop and barnacles. (c) crushed whelk shell prior to deployment and (d) flat shell of scallop (Pecten maximus) deployed in 2021 and recovered in 2022 with oyster settlement.

2019

Small quantities of Pacific oyster, Native oyster and Razor clam shell were deployed in Tyrone Bay and Rincarna Bay in 2019 (Table 22, Figure 35). These areas support some native oyster but shell cover on the seabed is low and siltation occurs in Tyrone Bay. Oyster shell was sourced locally and dead razor shell was extracted by dredging from Clifden Bay.

Table 22. Volumes of cultch (gigas, razor and native oyster shell) deployed in 4 areas in 2019.

		Cultch volume (kgs)		
Cultch areas	**Pier**	Pacific oyster	Razor clam	Native oyster shell
Tyrone Bay	Ballynacourty	2250	450	337.5
Rincarna Bay	Ballynacourty	2250	450	337.5
Rincarna Spit	Tarrea	2250	450	337.5
Laughaun	Tarrea	2250	450	337.5

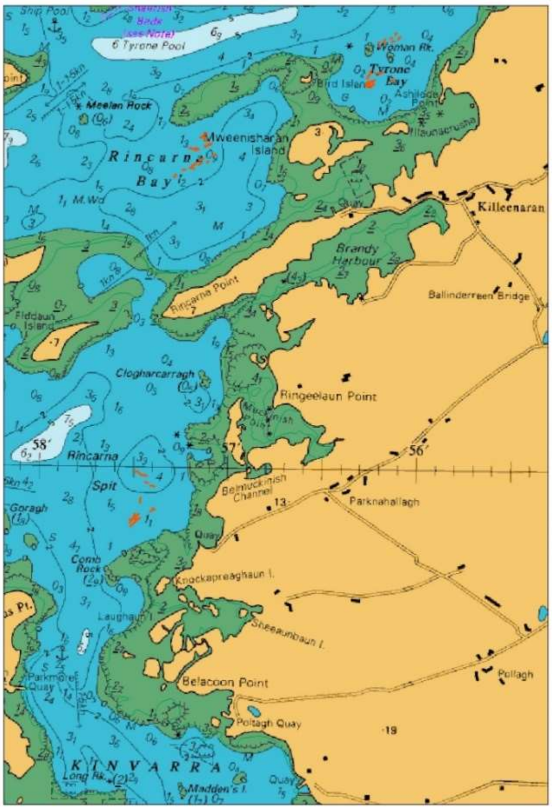


Figure 35. Locations of cultch deployment on seabed in 2019

2020

Two discrete areas in the St. Georges fishery order area were chosen for cultch deployment in 2020 (Figure 24; St Georges north buoy and St Georges south buoy). Approximately 200 tonnes of weathered Pacific oyster shell was sourced from Donegal Ocean Deep Oysters Ltd. and transported to Ballynacourty and Tarrea piers for deployment. A shell movement notification for the transport and deployment of this shell was approved by the fish health unit at the Marine Institute.

Following deployment, the areas were mapped using side scan sonar by BIM which verified the spatial extent of the deployment and the relief above seabed that was established (Figure 36). The center of both areas were marked with a permanent mooring surface buoy.

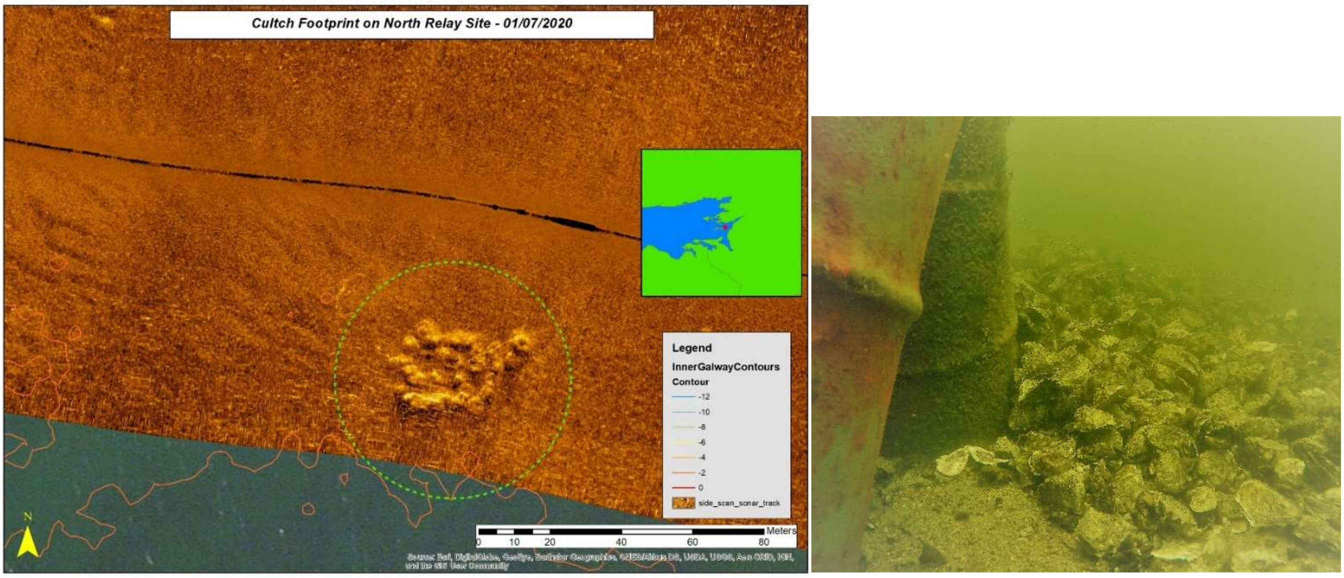


Figure 36. Side scan sonar image of cultch deployment at the St Georges north site in 2020. The spatial extent and relief above seabed is shown inside the dotted circle. Image by Nicolas Chopin BIM (left). Underwater image of the Pacific oyster shell on the seabed beside the surface buoy mooring anchor (right) (Pic. Owen O'Connell).

2021

Cultch deployment was scaled up further in 2021. Approximately 400 tonnes of crushed whelk shell and 200 tonnes of whole flat scallop shell was deployed in June 2021 in the south St. Georges fishery order area (Figure 37). Shell was sourced from Sofrimar Ltd, Kilmore Quay, Co. Wexford. Crushed whelk shell is a by-product from whelk processing and is sterile having been through a cooking process at 100°C. Scallop shell is a product of scallop processing (schucking for meat extraction). These scallop shells have residual flesh content. Scallop shells were stored and weathered for 3 months prior to deployment to exclude any risk of transfer of disease into the site. The fish health unit at the Marine Institute inspected the shell prior to deployment.

Shell was deployed from 1 tonne bags using a crane operated on a cargo vessel contracted in from Kilkieran, Connemara. This method of deployment resulted in an uneven coverage on the seabed and resulted in shell mounds with small scale relief, single shell layer on the seabed and variation in the percentage of seabed with shell cover. The effective locations of the deployed shells were subsequently mapped using multibeam echosounder Norbit iWBMS on a survey vessel by Hydromaster Ltd. The multibeam was coupled to an Applanix POSMV Wavemaster navigation and positioning system (Figure 37; Figure 38). These surveys picked up aggregations of scallop shell but not crushed whelk shell. Whelk shell was visible on the seabed but became mixed into the sediments and over the following months was not detectable.

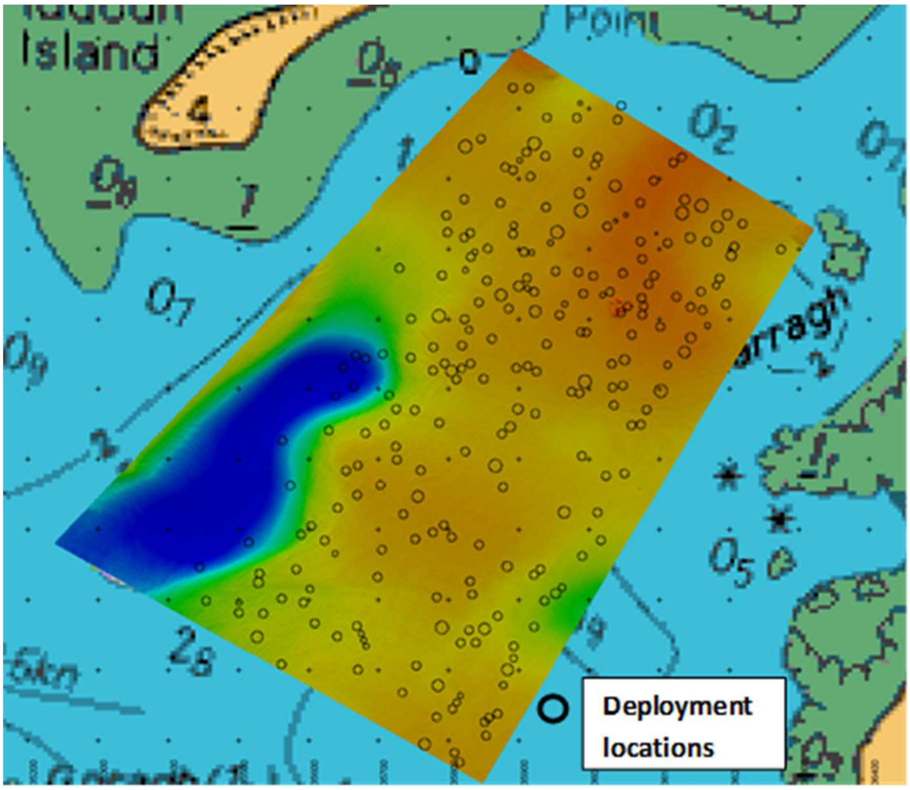


Figure 37. Bathymetry of the area of cultch deployment in south St Georges fishery order area 2021 as estimated by multibeam acoustic profiling of the deployment area. (image from Hydromaster)

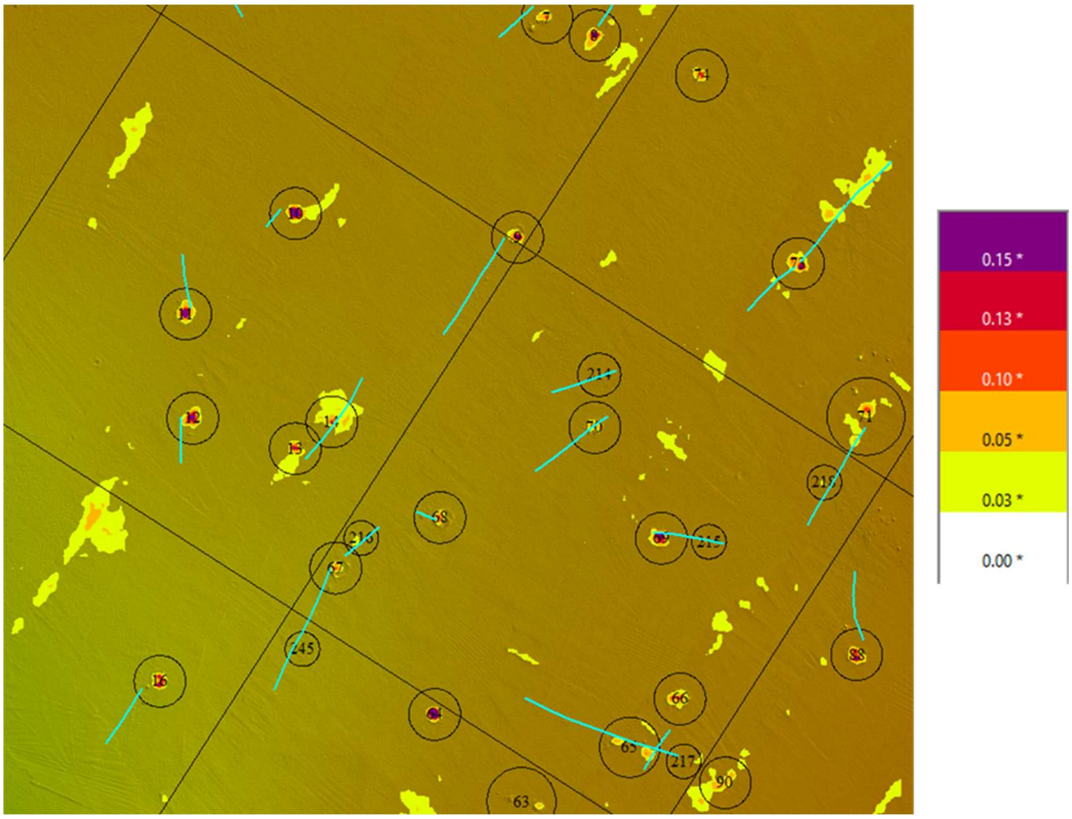


Figure 38. Multibeam acoustic profiling of the deployment area. Blue lines are the tracks of the vessel during deployment. Colour codes show patches of shell from the deployment meters above seabed (Image from Hydromaster)

Benthic habitats and marine communities in the scallop cultch area

The area where scallop cultch was deployed is designated as a fishery order area (FO) for the purpose of maintaining oyster beds. The Order is currently vested with BIM. The Order area was previously an important area for commercial production of oysters.

Scallop shell was deployed on sandy mud and mixed sediments community complex (as described by NPWS 2013). There is large variation in the fractions of fine sand, very fine sand, silt-clay and coarser gravel fractions in this habitat. The mixed sediment community is characterised by polychaetes and bivalves including *Ostrea edulis*. Dead shell is common at the seabed surface or in surficial sediments given the presence of bivalves such as *Ostrea, Fabulina, Kurtiella* and *Thyasira*. This dead shell content is not described by NPWS 2013 but Marine Institute oyster surveys in the area show variable levels of shell content in surficial sediments. The shell budget (shell production minus loss of shell due to erosion and weathering) in the area has probably declined since the 1980s resulting in lower shell content in surficial sediments and at the sediment surface than previously as oyster productivity declined.

There is 4560ha of the sandy mud to mixed sediment community in the inner Galway Bay Special Area of Conservation (SAC). The total surface area of scallop shell (4.3 million shells) deployed was 4.1ha which was 0.09% of the total area of the sandy mud and mixed sediments community (Figure 39). This was dispersed over an area of 52.6ha (interpolated, Figure 39) and 1.1% of the sandy mud to mixed sediment community.

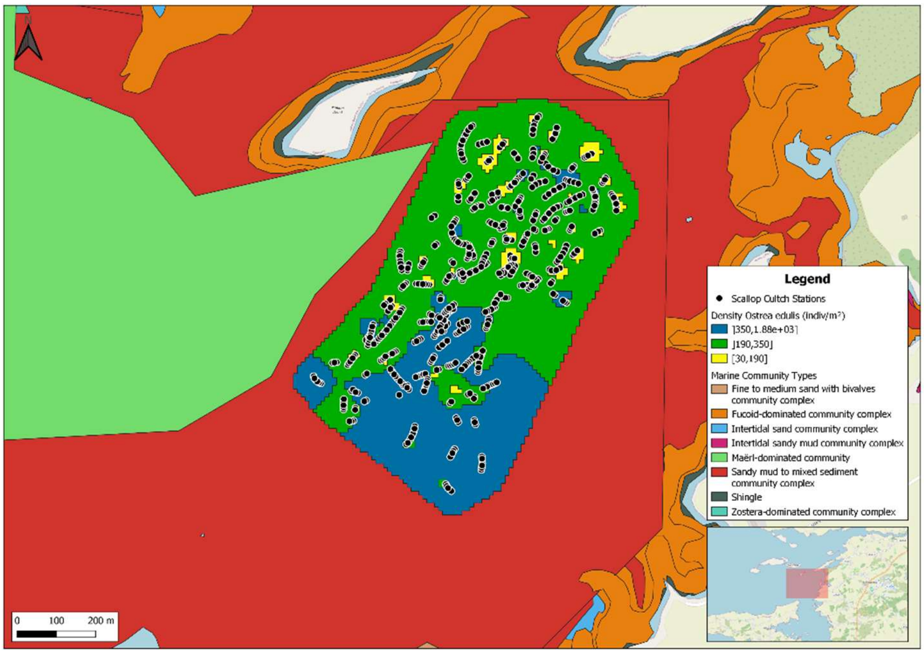


Figure 39. Overlap of scallop shell deployment tracks and resulting interpolated density of oyster from 2021 and 2022 settlement on scallop shell on benthic marine communities in inner Galway Bay. The scallop shell overlaps with the sandy mud to mixed sediments community complex.

Monitoring of spat settlement on deployed cultch; settlement metrics, growth and survival

Different methods of sampling were employed at the different sites to monitor wild spat settlement, including dredging, grab sampling and snorkelling.

2019 mixed cultch on sedimentary substrates

No data were obtained from the 2019 deployments. Cultch volumes were low and subsequently difficult to find using dredging. The sediments in these areas were also softer and cultch may have been buried by silt or sediment movement.

2020 Pacific oyster shell reef

The 2020 deployments of 200 tonnes of Pacific oysters in St. Georges north and south were stable and could be detected using side scan sonar (Figure 36). The spatial extent of these shell reefs was less than 40m diameter. These shell reefs were monitored by snorkelling during 2020, 2021 and 2022. Random samples of shell were removed and bagged from different parts of the reef and returned to either the Red Bank Oyster company at New Quay or to the Marine Institute for analysis. The total weight of cultch and individual oyster lengths were recorded from each sample.

2021 Scallop shell in oyster bed

The maximum total surface area of the scallop shell deployed was 0.04km^2 (4.3million shells by 0.0094m^2 per shell) assuming no overlap of shells on the seabed. Sampling of the scallop shell deployed in June 2021 commenced in October 2021 when spat from 2021 larval production was measurable. Grabs and dredges were used initially to sample but this was inefficient as few scallop shells were recovered. Sampling commenced again in June 2022 when it was suitable to snorkel on the site. Good sampling coverage of the site was achieved through snorkeling by the end of August 2022 and the settlement of a 2021 year class was recorded. Monthly sampling commenced in September 2022, to sample both the 2021 year class and the newly settled 2022 year class of oysters (Figure 40). All oysters were measured and density of spat (number of spat per kg of scallop cultch) at each sample site was estimated.

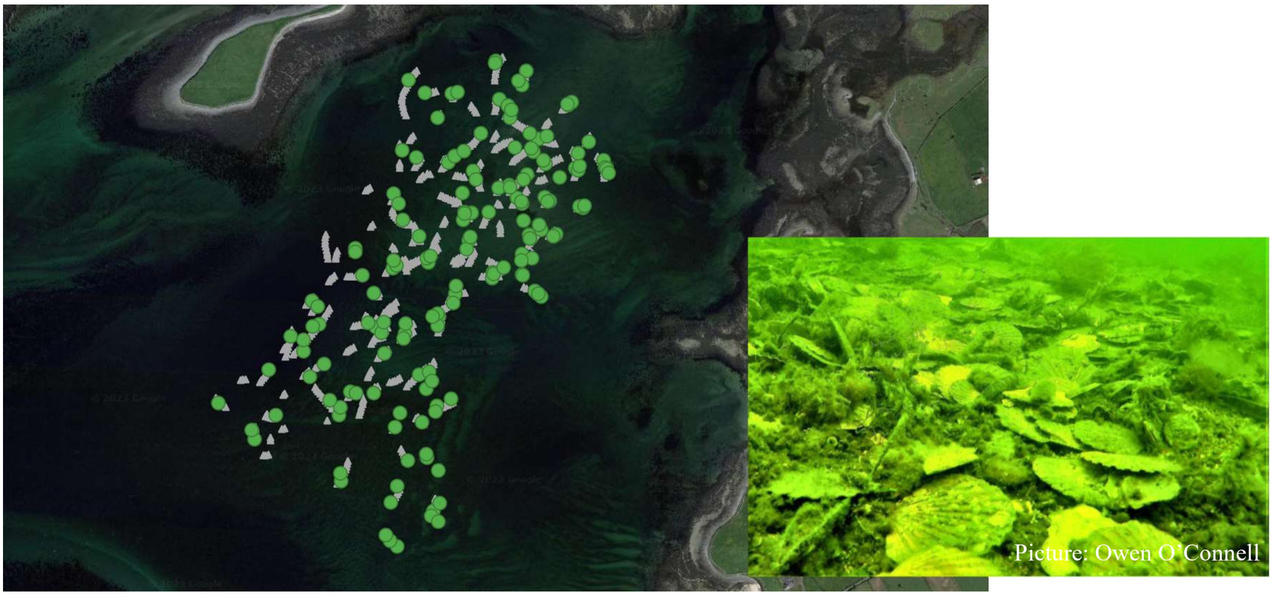


Figure 40. Scallop cultch deployment tracks (grey triangles) and the sites sampled for spat settlement to date (green circles) in the south St Georges fishery order area. The insert image was taking of the seafloor during a snorkel on the scallop cultch site (Pic. Owen O'Connell).

Results

Pacific oyster cultch 2020 deployment

The size frequency of spat in cultch samples taken between December 2020 and September 2022 showed a steady increase in size at both St Georges North and St Georges South cultch sites (Figure

41). The number of oysters obtained in the samples was low. In order to get larger samples and information on growth 58kg of cultch were sampled Q3 2022. The average size of oyster was estimated for each quarter at the two sites (Figure 42). The change of oyster size throughout the year followed a similar pattern observed in data from oyster spat of known age (Section 5 above); zero or negative growth in winter and a significant increase in size during warmer months. Similar average sizes per quarter occurred at both sites apart from Q3 2022 where average spat size at St Georges North was lower probably due to recent settlement of spat from 2022 spawning.

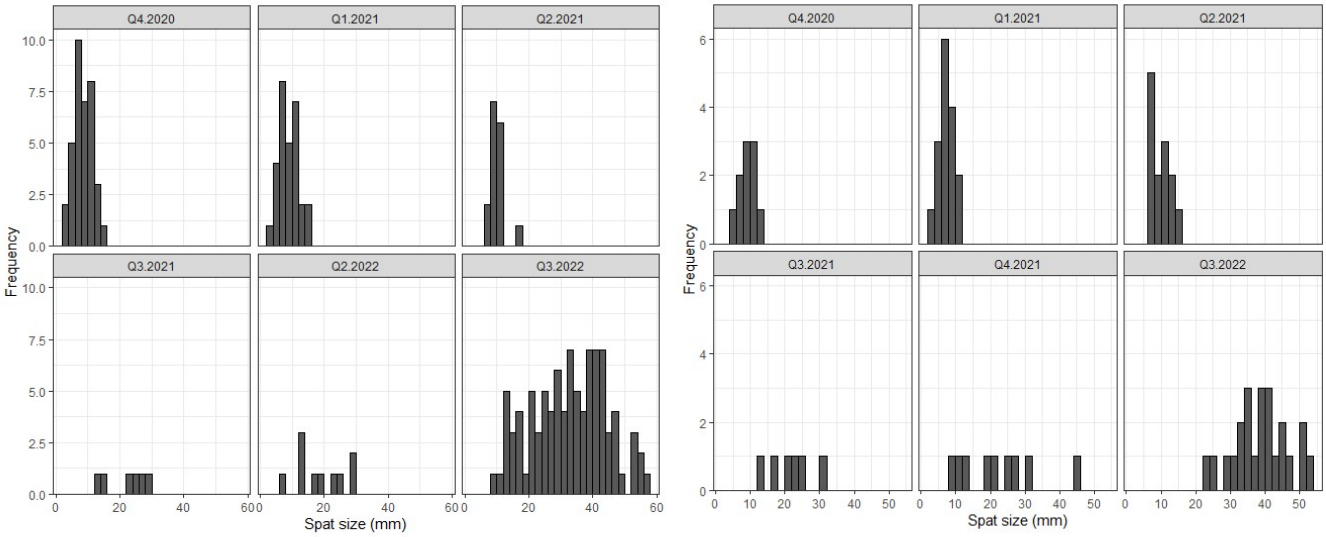


Figure 41. Size frequency of native oyster spat collected from Pacific oyster shell cultch deployed at St Georges North (left) and St Georges South (right).

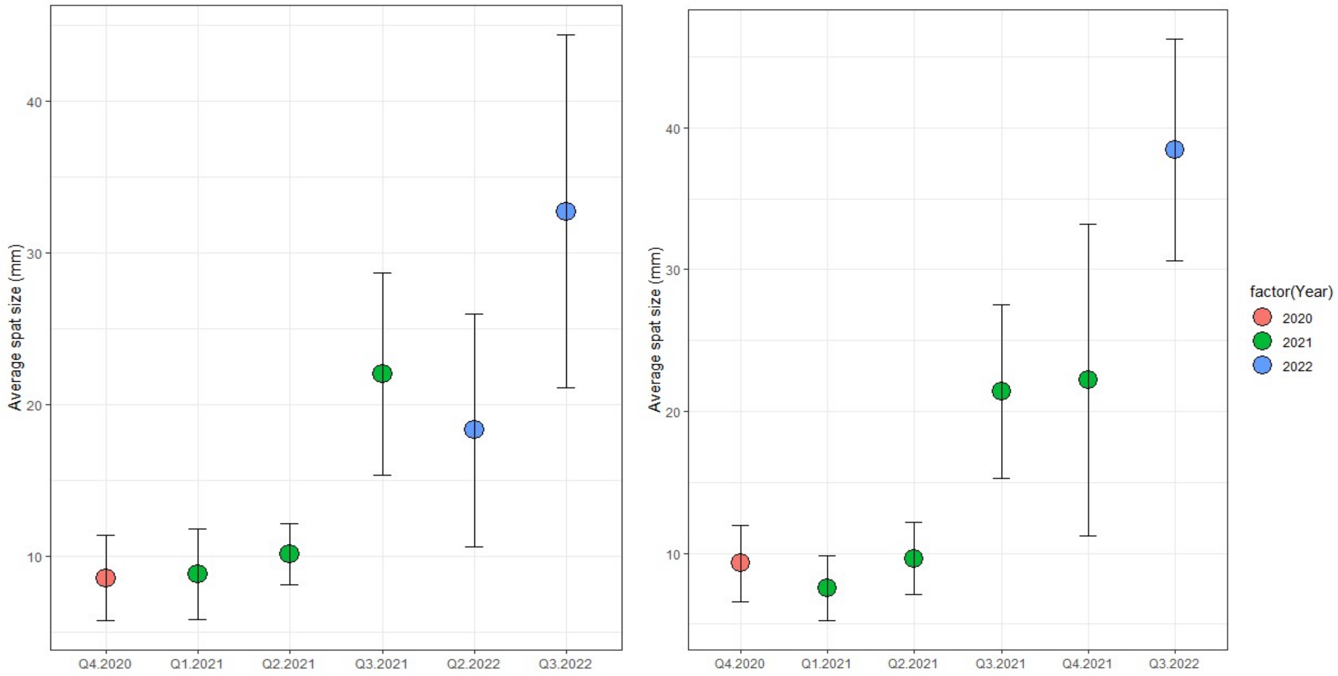


Figure 42. Average size of native oyster spat collected from Pacific oyster shell cultch in St Georges North (left) and St Georges South (right). The different colour points indicate the year that the measurements took place.

Settlement was generally poor at both sites. The average density of oysters showed a clear decrease until Q3 2021 in St Georges North. In St Georges South, density in Q4 2020 was lower than Q1 2021 and decreased until Q3 2021 (Figure 43). For both sites, the higher densities in Q3 2022 reflect the selective sampling (shell with spat) for estimation of growth and as a result Q3 data were excluded from estimates of mortality. In St Georges North, the percentage survival after approximately one year was 5% (Table 23). In St Georges South, the mean density of spat was 2.2 spat per kg. Density decreased from Q1 to Q3 2021 but trends were not clear (Table 23).

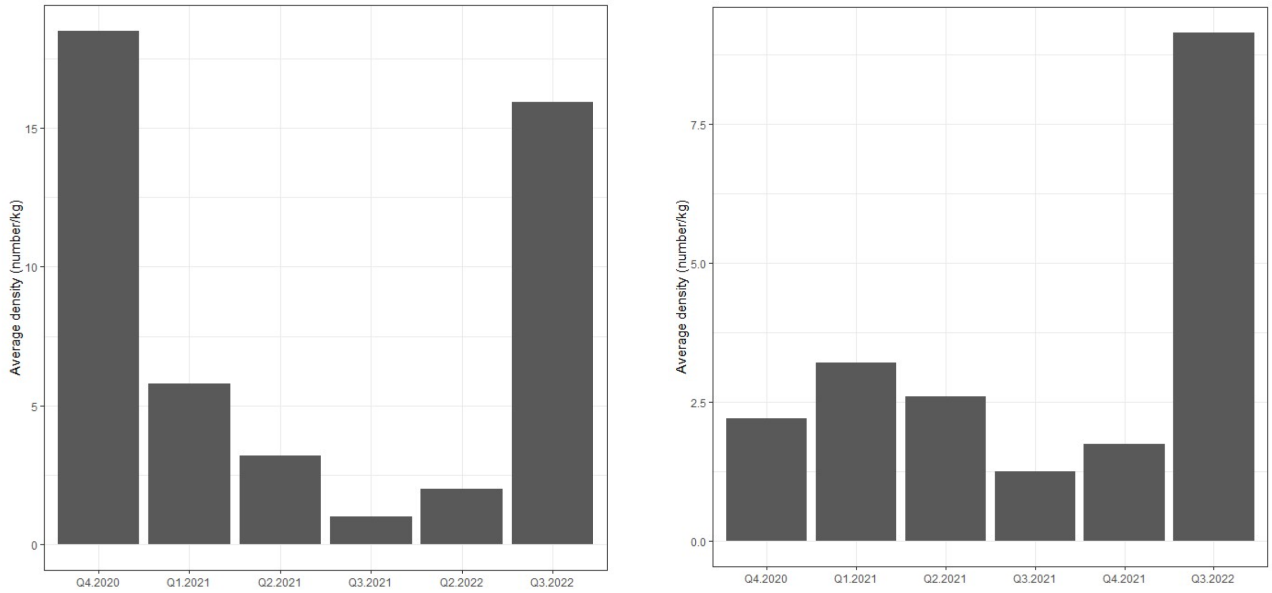


Figure 43. Average density of native oysters (based on the number of spat per kg of cultch) estimated from the Pacific oyster shell cultch per quarter for St Georges North (left) and St Georges South (right). Note different scales on vertical axis.

Table 23. Mean density and percentage survival rate (%SR relative to Q4 2020) of native oysters per quarter from the Pacific oyster shell cultch deployed in St Georges North and South, Galway Bay.

Year	Quarter	North		South	
		Mean density	%SR	Mean density	%SR
2020	Q4	18.5	100	2.2	100
2021	Q1	5.8	31.35	3.2	145.45
2021	Q2	3.2	17.30	2.6	118.18
2021	Q3	1	5.41	1.25	56.82
2021	Q4	-	-	1.75	79.55
2022	Q2	2	10.81	-	-

Scallop shell 2021

By October 2023, 12 samples were taken using a grab sampler and 173 samples were collected by snorkeling. The length distribution from each month showed a gradual increase in size until September 2022, when the modal size (approximately 5mm) was similar to the modal size for October 2021 (Figure 44). These smaller spat measured in Sep-22 belong to the 2022 year class. The same profile in the length frequency was expected in September 2023 but very few spat were observed at ~5mm due to poor settlement.

From September 2022 onwards there was more than one year class in the population. The cohorts were not clearly discernible in the size distribution data however, suggesting that settlement is protracted or growth rate is variable. The average size of spat was, therefore, estimated using mixture distribution methods which can identify overlapping distributions in grouped data, i.e. monthly spat length frequencies with more than one year class. The method provides an average size and standard deviation for each year class detected (Figure 45). The change in average size over the year shows a clear pattern of seasonalised growth; increased growth during the warmer summer months and limited growth during the colder winter months. A seasonalised von Bertalanffy Growth model resulted in estimates of L_∞ (approximates to maximum size) = 104mm and a growth coefficient K = 0.43. A similar K value has been reported in native oysters at low density in Italy (Carlucci *et al*., 2010) and from two different areas in England (Richardson *et al.*, 1993).

The survival rate of spat was approximately 44% in the first year (Figure 46). This was much higher than obtained in deployments of spatted cultch in intertidal areas, in sub-tidal cage enclosures or on cultch in the St. Georges reef sites. Complete spatial coverage of the deployment area was not possible during each sampling event and there was significant spatial variability in densities of spat. Interpolation of densities, using inverse distance weighting (IDW) methods, showed that highest densities of oysters were concentrated in the south and southeast of the sampling area (Figure 47). Spatial variability confounded the estimation of mortality given the limited scope of sampling.

The total spat recruitment onto scallop shell in 2021 was estimated using the average weight of a clean scallop shell (46g), which equated to 4,347,826 shells in 200 tonnes of scallop cultch deployed. The frequency distribution of oyster spat on individual scallop shells was recorded for a sample of 308 scallop shells taken in Oct 2021 and June and July 2022 (5, 13 and 14 months post deployment respectively). This distribution was raised to the total number of scallop shells deployed (Table 24, Figure 48) to provide an estimate of 13.9 million spat recruited from the 2021 settlement. A second settlement of 5.9million spat was detected in autumn 2022. These were identified and separated from the 2021 settlement using a mixture distribution model. The 2022 settlement was therefore much lower than in 2021 or post settlement mortality was higher.

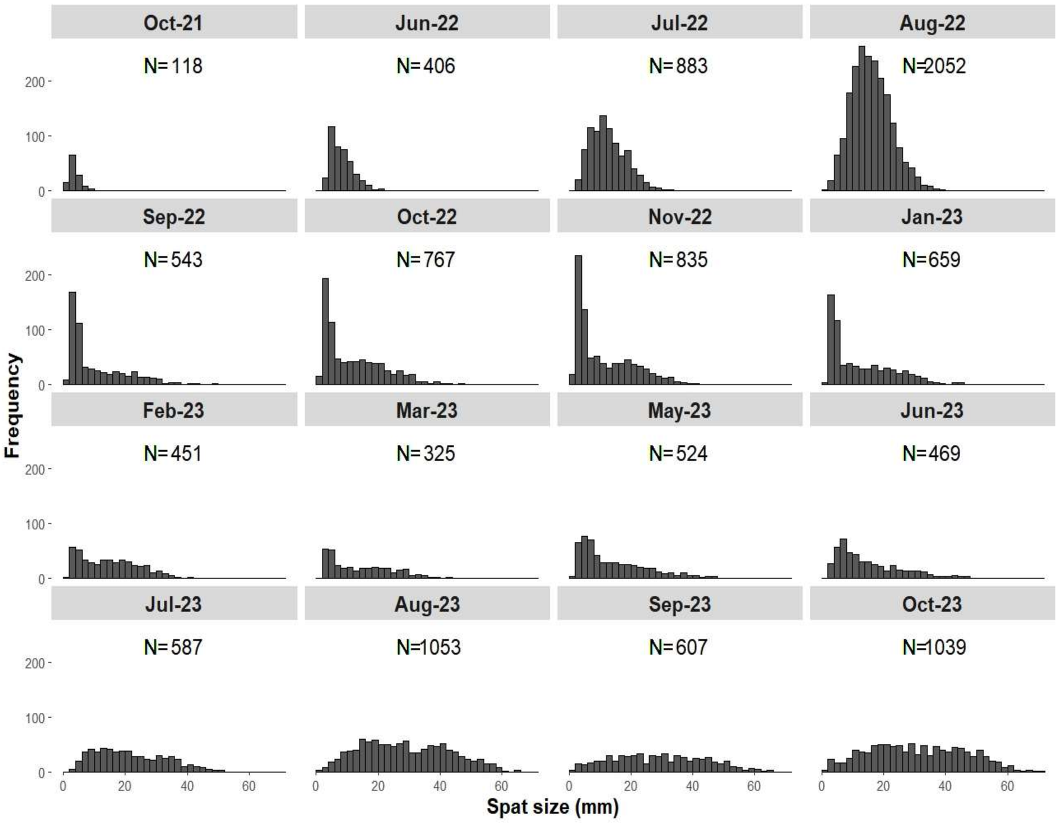


Figure 44. Length distribution of native oyster spat sampled from the scallop cultch in St Georges South area between October 2021-October 2023.

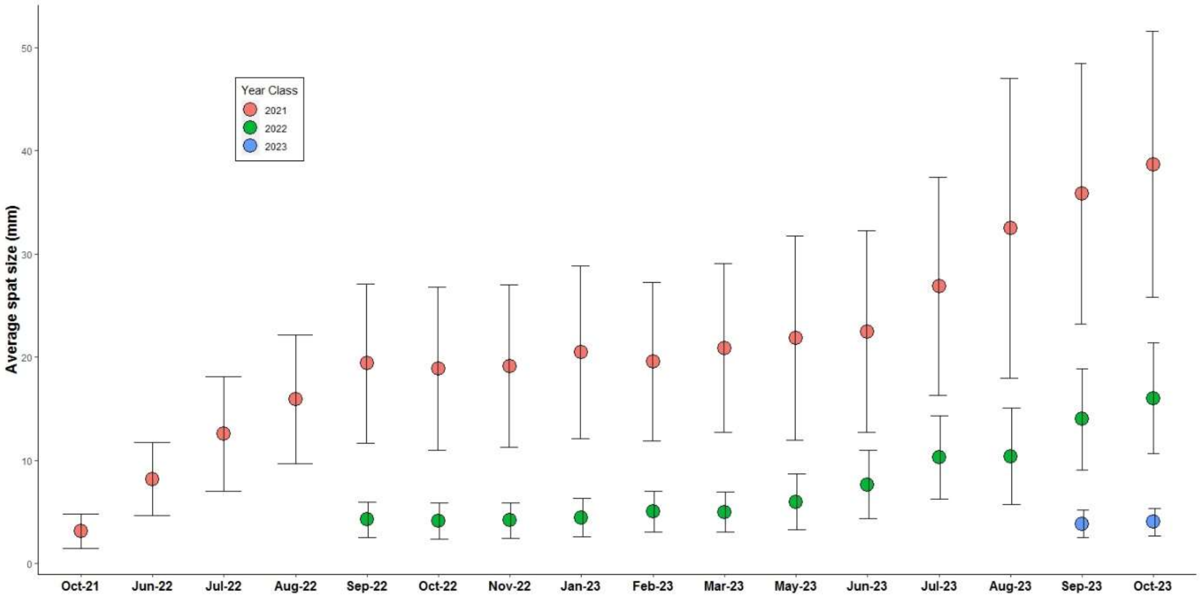


Figure 45. Average size of oyster spat, ± standard deviation, settled on the scallop cultch deployed at St Georges South area, Galway Bay. The different colour points indicate the three year classes.

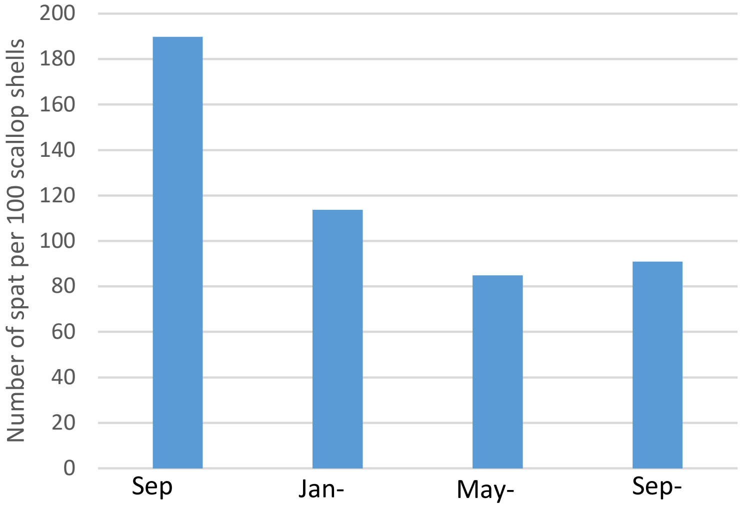


Figure 46. Oyster spat count per 100 scallop shells across the first year and 3 months of the 2022 year class (September 2022 – October 2023.

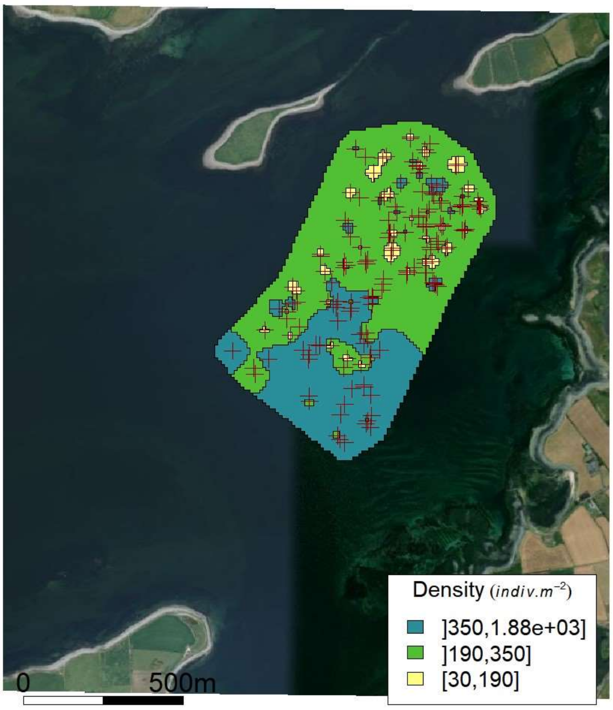


Figure 47. Distribution of oyster spat densities calculated using IDW interpolation.

Table 24. Proportion of oyster spat per scallop shell.

No. spat per scallop shell	Proportion of total spat
0	0.356
5	0.444
10	0.104
15	0.040
20	0.013
25	0.011
30	0
35	0.003

40	0.003
45	0.003
50	0

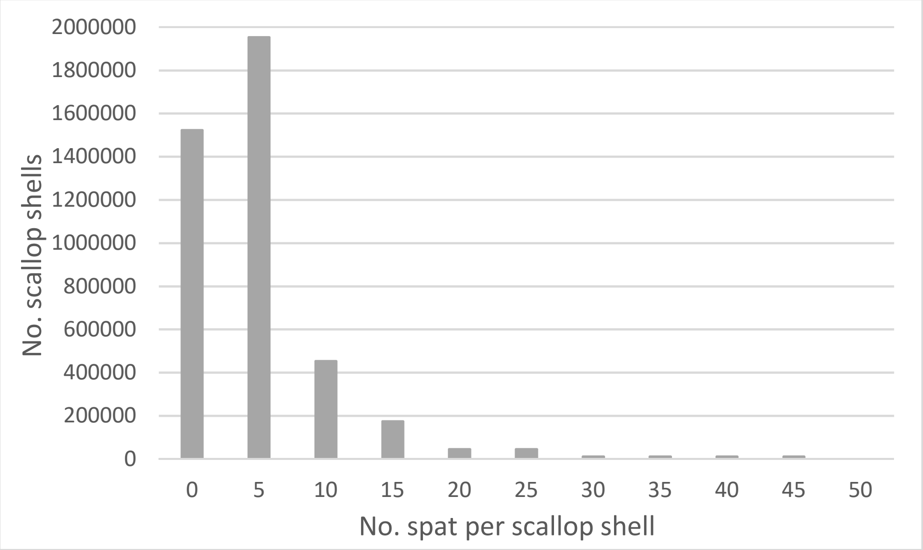


Figure 48. Number of oyster spat per scallop shell divided in 5 spat count bins.

Discussion

Bivalve shell was broadcast on the seafloor at a number of sites within fishery order areas in Galway Bay in 2019, 2020 and 2021. Deployments were scaled up each year and evidence of changes in seafloor relief and shell content (as a substrate for oyster settlement) was obtained by acoustic surveys following deployment and monitoring of settlement of oyster spat onto the shell in the autumn following summer spat fall.

The density of native oyster spat on Pacific oyster shell deployed in 2020 was low at both sites used. Settlement onto scallop shell in 2021 over a broader area than in 2020 was much higher.

The Pacific oyster cultch site formed a physical reef approximately 2 meters in height above the seabed in the first year and this slowly reduced due to re-distribution of the shell by currents over time. Although oyster spat density on the reef was low in 2021, biodiversity increased with species of crabs and lobsters taking up residence (O. O'Connell, pers comm.). Whelk also spawned on the reef in 2020 and high growth of *Ulva* seaweed occurred in one site. Comprehensive monitoring of changes in biodiversity following formation of the reef structure was not undertaken.

The survival rate of oyster spat on the Pacific oyster reef was estimated at approximately 5% in the first year. This low survival highlights the vulnerability of oysters during their early benthic phase and was corroborated by monitoring of known age spat from spatting ponds which were distributed in enclosures and on the seabed in a separate study reported in Section 5 of this report.

Whole scallop and crushed whelk shell were deployed in 2021. The crushed whelk shell did not persist at the sediment surface or where it was still visible and possible to sample no oyster spat were observed on it. Whole scallop shell on the other hand persisted and provided clean settlement substrate for oyster spat over three settlement seasons. Spat settlement on the scallop shell cultch was much higher in 2021 and 2022 than on the Pacific oyster reef in 2020. In 2023, settlement was poor on the scallop shells but was also generally poor in Galway Bay and in spatting ponds in Galway Bay probably due to low water temperatures in July.

Over 13 million spat settled onto scallop shell in 2021. Although mortality rates in the first year is expected to be high, the numbers are significant and demonstrate that it is feasible to increase recruitment at ecologically relevant scale by providing settlement substrate. Scallop shell persisted on the sediment surface and also attracted a significant spat settlement in 2022 and a smaller settlement in 2023. This method of enhancing recruitment, although logistically difficult at least in the case of inner Galway Bay, seems more effective and scalable than production of spat in spatting ponds, especially if natural settlement occurs annually which appears to be the case. Spat production from spatting ponds in summer of 2020 and deployed to sea in December 2020 and March 2021 was 0.78million.

Settlement intensity and survival of oyster spat are expected to vary annually depending on spawning activity, larval dispersal dynamics which may be driven by weather conditions during the larval phase, seawater temperature and its effects on larval competence to settle, timing of settlement and how this will determine growth and maximum size of spat prior to their first winter. The data presented here, which standardizes the reporting of settlement to a unit of shell (cultch) material provides a method of monitoring annual recruitment and survival of spat into oyster beds. Together with the small scale trials reported from 2018 (Section 4 this report), it is also evident that different shell material may attract different levels of settlement and that a standard surface or a range of surfaces (as reported in Section 4) be used to monitor recruitment. Building a recruitment and early life history survival index time series would eventually provide valuable information for both restoration and for fisheries management measures.

7. Prevalence and intensity of *Bonamia ostrea* infections in native oysters in Galway Bay

Deborah Cheslett, Killian Coakley, Oliver Tully

Marine Institute

Acknowledgements: monitoring of Bonamia in the late 1980s and 1990s was funded by the Marine Institute. Monitoring since 2018 was funded by the EMFF MBS oyster restoration project.

Introduction

Bonamia ostrea has been present in Galway Bay oysters since the mid-1980s. There is no national monitoring programme currently in place as the disease is endemic and no mitigations to reduce its impact have been identified. Monitoring of *Bonamia* was undertaken from 1993-2008 and in 2013. Under the EMFF oyster restoration project monitoring was re-initiated in 2018 and continued to 2021. All of the data is brought together in this report.

Methods

Standard methods for *Bonamia* detection, using heart smears (prints), have been used throughout the monitoring programme. In 2018 PCR methods were used to detect *Bonamia* DNA in oysters and a comparison of the infection data from the two methods is ongoing. The PCR method however is very sensitive and is likely to report a higher prevalence than the standard histological method. Samples were taken in Spring and Autumn in the earlier years of the programme and sample sizes were larger in those years than in later years. Samples were taken from the Clarin River estuary (Cave), St. Georges and the public bed west of St. Georges. A total of 3929 oysters were sampled during the period. The quality of the slides in 2020 was compromised. Prevalence (the % of oysters positive for *Bonamia*) are reported for all samples. The quantification of the infection (intensity or the level of infection) were reported in some years. The scale for quantification of intensity (Table 25) is based on Bachere *et al*. (1982).

Table 25. Quantification of the intensity of Bonamia infections (Bachere et al. 1982).

Level	Description
0	Negative
1	1-10 parasites across entire slide
2	10-100 parasites observed
3	Parasites in most fields
4	Overwhelming number of parasites in each field

Results

Data from 1993-2021 suggest that small sample sizes (<80) may lead to underestimation of *Bonamia* prevalence (Figure 49**Error! Reference source not found.**). Small samples were taken in 1999-2017 (Table 26). Prevalence declined from 1993-1997 and was usually higher in spring samples compared to autumn samples at that time (Table 27). Prevalence was below 20% from 1997-2017. Prevalence declined from 38% in 2018 to 10% in 2021. However, the 2018 estimate is not directly comparable as PCR methods were used in that year. In 2021 oysters were infected mainly at intensity Levels 1 and 2. Tralee Bay oysters that had been transplanted to Galway in 2021 and sampled months later in 2021 had higher infection intensities mainly in Levels 2 and 3 (Table 28). Sample size for Tralee oysters was however low.

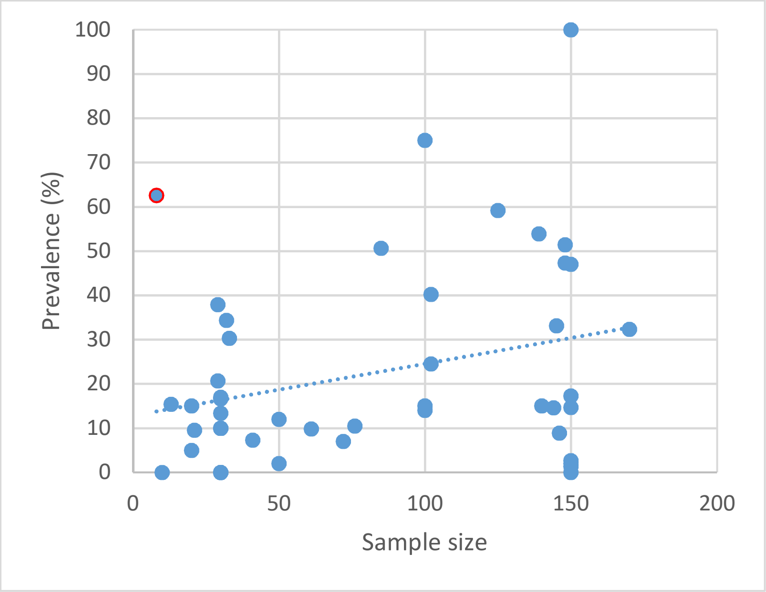


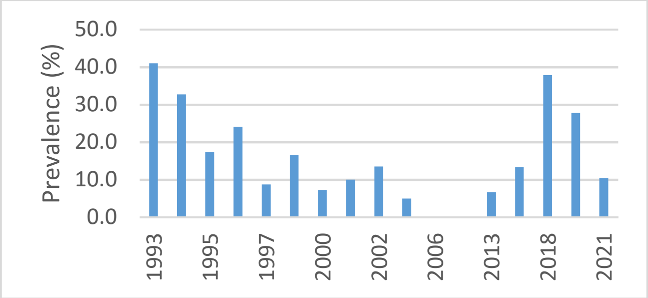
Figure 49. Correlation between Bonamia prevalence (%) and sample size. The red dot is for Tralee oysters transplanted to Galway Bay in 2021 and sampled in 2021.

Table 26. Sample size (number of oysters) in annual and seasonal monitoring of Bonamia in oysters Galway Bay 1993-2021. Sample sizes between 1999 and 2017 were low and may not provide accurate or precise estimates of prevalence of the disease.

Year	Autumn	Spring	All
1993	600	139	739
1994	298	505	803
1995	242	294	536
1996	446	318	764
1997		148	148
1999	30		30
2000	41		41
2001	30		30
2002	30	30	60
2004	30	30	60
2006	30		30
2007	30		30
2013	50		50
2017		30	30
2018	302		302
2020		136	136
2021	132		132
Grand Total	**2291**	**1630**	**3921**

Table 27. Prevalence of Bonamia in various locations in Galway Bay 1993-2021. PCR, histology and heart smear (histology) methods included. These figures include all positive detections irrespective of intensity of infection.

Year	Autumn	Spring	All
1993	37.8	53.9	41.0
1994	25.7	36.2	32.7
1995	27.6	10.5	17.4
1996	13.6	39.8	24.1
1997		8.8	8.8
1999	16.6		16.6
2000	7.3		7.3
2001	10.0		10.0
2002	10.0	17.0	13.5
2004	10.0	0.0	5.0
2006	0.0		0.0
2007	0.0		0.0
2013	6.7		6.7
2017		13.3	13.3
2018	37.8		37.8
2020		27.7	27.7
2021	10.5		10.5
All	**19.2**	**24.8**	**21.6**



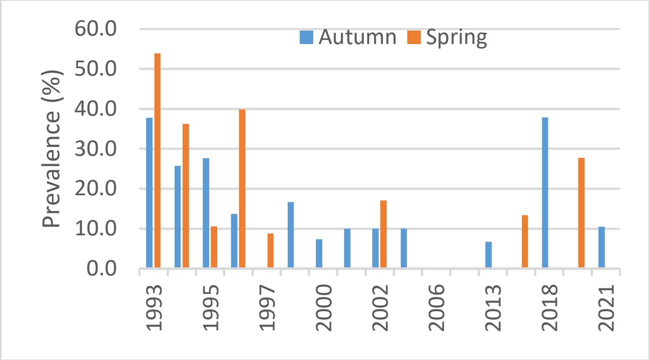


Table 28. Intensity (level) of Bonamia infections in 2021 excluding Tralee Bay transplanted oysters

Infection level	Galway		Tralee (transplant to Galway)	
	N	%	N	%
Level 1	7	50	1	20
Level 2	3	21	2	40
Level 3	2	14	2	40
Level 4	2	14	0	0

Discussion

Although *Bonamia* infection is known to cause high mortality rates in oysters, demonstrating a link between prevalence, intensity of infection and mortality is difficult and has not been shown directly here. This is a general problem for all diseases and parasites that cause mortalities mainly because the monitoring programme is sampling survivors; *Bonamia* prevalence in dead oysters cannot be compared to prevalence in live oysters. Estimating the mortality rates in natural populations of wild oysters and when it occurs is also difficult as oyster age is unknown. Size based estimates of mortality in the oyster survey time series is reported in section 2 above. This assessment shows high mortality rate especially in larger size classes but linking this to *Bonamia* prevalence given the time lag between infection and mortality is not possible. Time series monitoring of increases in *Bonamia* intensity and subsequent observations of mortality rates could be done in experimental set ups that follow the progression of both the disease and the progression of mortality.

Past trials and recent evidence suggests that there is differential tolerance or resilience to *Bonamia* in different strains of oysters and that this has a genetic basis (Sambade *et al*. 2022). If this is so, then natural selection would be expected to increase resilience over time. The rate at which such resilience could develop depends on the pathogenicity of the parasite, the size at which mortality usually occurs relative to the size at first spawning and the heritability of resilience. Oyster mortality from *Bonamia* infections usually increases in the 3rd year of life at about 50-60mm. Spawning occurs in oysters as small as 32mm and mean size at maturity is 49mm in Galway (O'Neill and Tully 2012). Oysters that have no resilience to *Bonamia*, but have not yet died, may therefore contribute to spawning and dilute the evolution of resilience in the population. Importing of native oysters from Tralee Bay or oysters from anywhere that have no resilience, or at least no previous exposure, to *Bonamia* into Galway Bay may also slow the evolution of resilience.

Assessing the scope to select for *Bonamia* resilience and its genetic basis would seem to be important. Screening for the presence and level of resilience in natural populations, using the markers reported by Vera *et al*. (2019) and Sambada *et al*. (2022) is a first step in this process. This work commenced in 2023 in the Marine Institute. Over 1100 oysters are being screened for genetic markers for *Bonamia* resilience from Lough Swilly, Clew Bay, Kilkieran Bay, Galway Bay, Tralee Bay and Cork Harbour.

8. Effects of temperature and salinity on survival and feeding rate of oysters

Oliver Tully[1], Gerry O'Halloran[2] , Diego Pereiro[1], Guillermo Martin[1], Sara Palma Pedraza[1]

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Introduction

The life cycle of marine bivalves is strongly affected by environmental parameters such as temperature, salinity and food availability (Robert *et al*. 2017). The capacity of oysters to respond or adapt to changes in temperature and salinity depend on the rate of change in these parameters. Obviously oysters experience gradual seasonal changes in temperature which they acclimatize to. The stabilized metabolic rate of well acclimatised oysters will be different to the temporary response to short term change in salinity or temperature. At 34 ppt salinity respiration rate is linearly related to temperature over the temperature range of 10 to 25 °C. Below 10 °C there is a discontinuity in the response which can be ascribed to a switch between "summer" and "winter" physiological states. These states are thought to be characterised by changes in metabolic biochemistry (Hutchinson and Hawkins, 1992). Minimal metabolic activity of *O. edulis* in its "winter" physiological state enables survival at low temperatures and salinities which the species normally encounters during the winter months in shallow coastal waters. Optimum conditions for the active summer physiological phase is 28-34 ppt salinity and 15 to 20 °C temperature. Oysters can tolerate temperatures and salinities outside of this range but their scope for growth and its components, filtration rate and oxygen consumption, may be reduced. It is probable that an acclimatisation of 30 days (Buxton *et al*. 1981) or 70 days (Newell *et al*. 1977) is insufficient to obtain a good growth yield at temperatures higher than 20 °C. Sunderlin *et al*. (1976) found that *O. edulis* grew to 100 mm in length after 12 to 16 months in water at 22 to 29 °C. In Israel, where the temperature varies between 14 and 28 °C, the market size for *O. edulis* is obtained after 2 years (Shpigel, 1989).

At reduced salinities *O. edulis* has lower filtration rates and reduced oxygen consumption (Hutchinson and Hawkins, 1992). The decrease in oxygen consumption could be caused by an increased duration of valve closure in response to reduced salinities. However, oysters held at 25 °C, especially those in salinities of 16 ppt and 19 ppt, were exceptions to this trend. Most likely this was due to higher metabolic rate at the higher temperature which necessitated valve opening to excrete ammonia.

O. edulis has a plasticity of response to variation in temperature and salinity and different ranges of temperature and salinity that may occur seasonally or in different locations. These are acclimated responses or even adaptive responses (if there is a genetic component) to gradual change. There are limits to this acclimation capacity. High die-offs of *O. edulis*, mainly reported in coastal populations, occurred during the extreme low temperatures in the winter of 1962-1963 (Gercken and Schmidt, 2014). The stock from the Eastern Scheldt estuary in the Netherlands was estimated to have declined from 120 million to 4 million oysters (Drinkwaard, 1998). Piano *et al*. (2004, 2005) found that *O. edulis* expresses the 69 kDa (HSP69) isoform heat shock protein, which is an indicator of physiological stress, in response to thermal stress after 1 h exposure to 32°C or higher.

Rapid changes in temperature and particularly salinity may occur in estuarine areas that could be both outside the acclimation threshold of oysters or that do not enable sufficient time for acclimation to new environmental conditions. This is the case in inner Galway Bay where surface freshwater inflows from the Rivers Corrib, Clarin and Dunkellin and sub-surface inflows from the surrounding limestone areas are significant and lead to reduced salinities following heavy rainfall events. Upstream drainage works at the Dunkellin and proposed works leading to Kinvara Bay may also change the rate of freshwater inflow into inner Galway Bay and therefore the rate and level of change in salinity. Climate change in Ireland is forecast to lead to increased severity and frequency of rainfall events and more intense river and coastal flooding (www.epa.ie) that will lead to rapid and short term changes in the salinity profile of estuarine and coastal waters. These conditions may be lethal to oysters in some locations. Oysters stocks that previously occurred in the estuaries of the Dunkellin and Clarin (Leanach oyster bed; reported above) are no longer present or where recruitment occurs survival past 1-2 years is extremely low. In addition, oyster mortality rates in the main stock distribution area, as reported above, are such that although recruitment occurs annually, biomass remains low due to high rates of mortality. Unsuitable or lethal combinations of salinity and temperature could be a contributory cause of mortality in some locations or could lead to increased physiological stress and an increase in mortality of oysters infected with *Bonamia*.

Current and future interventions to restore native oysters need to focus on areas that provide suitable habitat. Habitat suitability modelling with respect to temperature, salinity, chlorophyll, larval retention and seabed stability will be important in this respect. Capacity to model the distribution of salinity and temperature at high resolution in inner Galway Bay under these scenarios has recently been developed under the Horizon 2020 FORCOAST project by the Marine Institute. The response of local populations of oysters to these changes also needs to be assessed so that areas unsuitable for restoration of oyster populations can be avoided. In this study we characterise non-acclimated responses (mortality, feeding rate) of oysters to changes in temperature and salinity that may occur over a number of days, in inner Galway Bay, over a range of temperatures and salinities and predict areas that may pose high risk for oysters due to periodic exposure to lethal and sub-lethal reductions in salinity in particular and where the response depends on the interactive effects of temperature and salinity.

Methods

Experimental set up

Oysters were sourced from the St. Georges oyster bed in Galway Bay by dredging in early November 2020. The bed is subtidal but partly dries on extreme low water spring tides. Oysters were transferred to a flow through seawater holding tank at temperature and salinity reflective of ambient conditions (12-15°C, >30ppt salinity). They were held there for 7 days prior to distribution to the experimental conditions.

Five tanks were set up at temperatures of 5, 10, 15, 20 and 25°C. Five 30L containers with water at 5 salinities of 5, 10, 15, 20 and 25ppt were placed in each temperature condition (tank). Temperature in the 5 tanks was controlled by chilling below ambient or heating above ambient until the correct temperature was reached and was stable. Salinities were controlled by mixing natural seawater with de-chlorinated freshwater. Reservoirs of chilled (5°C and 10°C) and heated (20°C and 25°C) freshwater and seawater were maintained to enable renewal of water in the experimental containers without interruption of the respective temperature salinity conditions (Figure 50).

Oysters (30 oysters approximating to 1.5kg to each container) were transferred from the holding tank to each of the experimental containers while the containers were still at ambient temperature and salinity. Temperatures were then gradually reduced or increased and salinities were gradually reduced over a period of 5 days until the experimental temperature and salinities were reached in order to avoid temperature shock. Oysters were fed with phytoplankton cultures (*Isochrysis* and *Chaetocerus*) sourced nearby from Jasconius Ltd. All containers were aerated using pressurized air diffused through airstones. Pseudofaeces and detritus was removed from the tanks each day by suction and filtering onto a 63um mesh. Temperatures and salinities were monitored daily.

Oyster mortality was measured daily for 30 days. Dead (gaping) oysters were removed from the experimental containers daily.

Oysters were left at their experimental temperature and salinity conditions for a period of 5 days prior to measurement of feeding rates. Feeding rate was measured by the rate at which oysters cleared phytoplankton from the water as measured using a fluorescence (Chlorophyll) probe. This is a proxy measurement of filtration rate. Aliquots of water, with phytoplankton, were taken from the experimental containers at the same time as fluorescence was measured and phytoplankton cell density was subsequently estimated by microscopy to establish the relationship between fluorescence and cell densities. After thorough mixing of the water in the containers fluorescence was measured using a YSI fluorescence probe. Repeat measurements were made at 0, 3 and 6-7 hours. The rate of clearance of phytoplankton (feeding) was estimated by the slope of a linear regression through the resulting data points and expressed in fluorescent units.hr^{-1}.kg^{-1} oysters. The rate of change in fluorescence, given the weight of oysters and capacity of the experimental containers, was scoped at ambient temperature prior to starting the experiment proper. After the measurements were taken water in the experimental containers was filtered to remove remaining phytoplankton and detritus and then replenished with new water. Measurements were then repeated on successive days for 3 days.

Figure 50. Experimental set up for assessment of response of oysters to 5 temperatures and 5 salinities (25 units). The temperature in each main container is constant and controlled by a combination of heating and chilling (essentially a water bath). There are 5 smaller containers at each temperature each at a different salinity. Aeration is provided by airstones.

Modelling mortality rates

Two approaches to modelling the effects of temperature and salinity on oyster mortality rate were adopted. These involved generalized additive modelling (GAM) and nearest neighbor interpolation (NNI) to produce predicted response surfaces across temperature, salinity and the interactive effects of both variables on oyster mortality. The NNI predicted response surface was used to predict spatio temporal mortality of oysters in inner Galway Bay based on modelled temperature and salinity conditions experienced by oysters in the bay. These conditions were predicted separately from a hydrodynamic model developed for the area in the EU H2020 FORCOAST project (https://forcoast.eu/.)

General Additive Modelling

Generalized Additive Models (GAM's) were used to assess the individual and interactive effects of temperature and salinity over time on oyster mortalities. GAMs were chosen, as non-linear relationships between these covariates and oyster mortality were expected. Model selection was assessed using the Akaike Information Criterion (AIC). Starting from the most complex model, with a full tensor product across covariates (three-way interaction and single effects), five nested models were constructed. The most parsimonious model (lowest AIC value) included all three, two-way interactions, and their single effects:

$$M \sim \text{Beta}(\mu,\sigma^2)$$

$$E(M) = \mu$$

$$\sigma^2(\mu) = \mu(1-\mu)/(1+\varphi)$$

$$\text{logit}(\mu) = \text{Intercept} + s(t) + s(s) + s(d) + ti(t, s) + ti(t, d) + ti(s, d)$$

where M is the oyster cumulative mortality and Beta is assumed to be distributed with mean μ and variance σ^2 with parameter φ being estimated during fitting. The Beta distribution is useful for proportion data (0, 1), in this case mortality, which cannot be model as a binomial. However, any data exactly at 0 or 1 were reset to be just above 0 or just below 1 (± 0.01) in order to keep the log-likelihood bounded for all parameter values. The mean (μ) was modelled as a function of an intercept plus a cubic spline smoothing function "s()" of temperature (t), salinity (s) and day (d) with their respective two-way tensor product interaction "ti()". The number of knots for each smoothing term was selected as part of the fitting procedure.

Nearest neighbour interpolation

In this approach, a function or response surface of the daily mortality as a function of temperature *T*, salinity *S* and the exposure time *Δt* is determined:

$$M_d = M_d(T, S, \Delta t)$$

Under this definition, the daily mortality M_d is a number between 0 and 1 that, when multiplied by the number of individuals *N*, returns the number of deaths on that day. It is then possible to apply this function to a temperature and salinity time series to estimate the cumulative mortality in a particular site. The first step to obtain the function M_d from the experimental data on the relationship between mortality and salinity and temperature, described above, consists of fitting a logistic curve to the cumulative mortality series from each of the 25 experiments conducted under varying temperature and salinity conditions. The rate of change of this curve is the daily mortality for the given *T*, *S* and *Δt* (Figure 51).

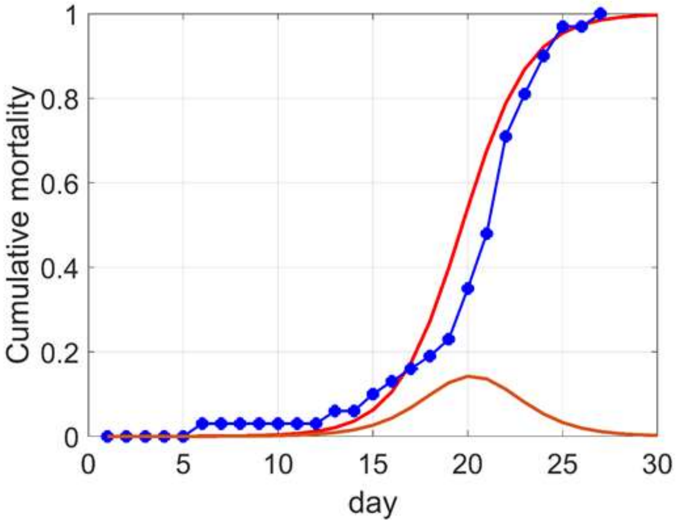


Figure 51. Experimental cumulative mortality under 5°C, 5 ppt (blue); modelled cumulative mortality after fitting the experimental data to a logistic curve (red); estimated daily mortalities under these conditions for 30 days (orange).

This first step predicts the daily mortalities under all experimental conditions. Nearest neighbour interpolation was then used to determine M_d for any temperature in the range from 5-25°C and any salinity from 5-29 ppt. In addition, in order to be able to apply this model to any combination of temperature and salinity conditions occurring in the bay, natural neighbour extrapolation of M_d was used for conditions outside of the experimental range (i.e. below 5 °C and above 25 °C, below 5 ppt and above 29 ppt).

When M_d is applied to a time-varying series of temperature and salinity, the exposure time Δt grows by +1 day when the daily temperature and salinity conditions are within a range that, according to the experimental data, causes a 30-day cumulative mortality above 0.1. On the other hand, 30-day cumulative mortalities are below 0.1 for $S > 20$ ppt and $T < 22.5$ °C. In this approach, these conditions were considered to be "safe" for oysters and the exposure time Δt was reset to 0 days whenever the conditions entered that "safe" range, assuming a total recovery of the individuals as soon as the salinity increases above 20 ppt and the temperature falls below 22.5 °C. Total recovery is a valid assumption if the effect of unsafe conditions is to lead to valve closure to protect tissues from osmoregulatory damage. On the other hand, total recovery is not expected if such damage occurs or if valve closure is prolonged to the extent that elevated ammonia concentrations causes tissue damage.

Results

Mortality rate (GAM prediction)

Plots of mortality under all experimental conditions of temperature and salinity are in Annex I.

The GAM showed that the prolonged non-lethal (safe zone) temperature and salinity domain is at salinities above 15ppt and at temperatures lower than approximately 8^{o}C (typical winter temperatures). Higher salinities up to 20ppt are required to maintain survival as temperatures increase to 20^{o}C (Figure 52, Figure 53). Temperatures higher than 20-22^{o}C leads to some mortality even when salinities are above 20ppt.

The GAM can predict mortality rates due to exposure of oysters to various regimes of temperature and salinity over a given duration.

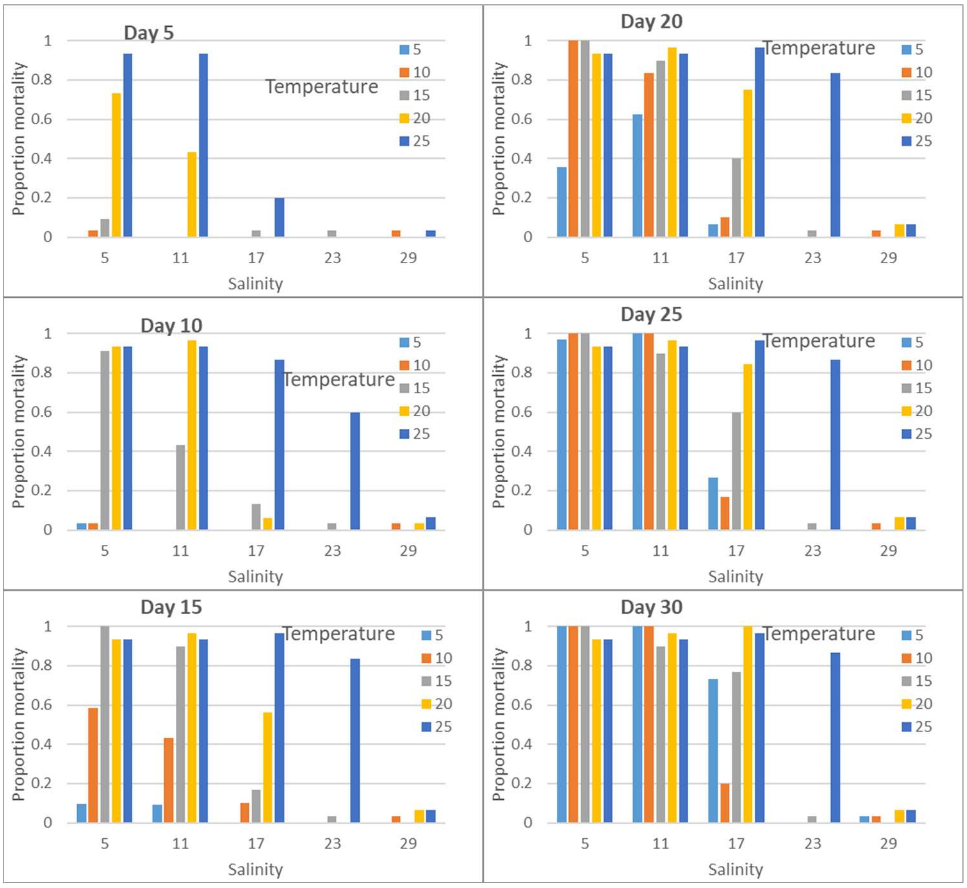


Figure 52. Summary data on mortality rates across combinations of temperature and salinity at 5 day intervals between 5 and 30 days.

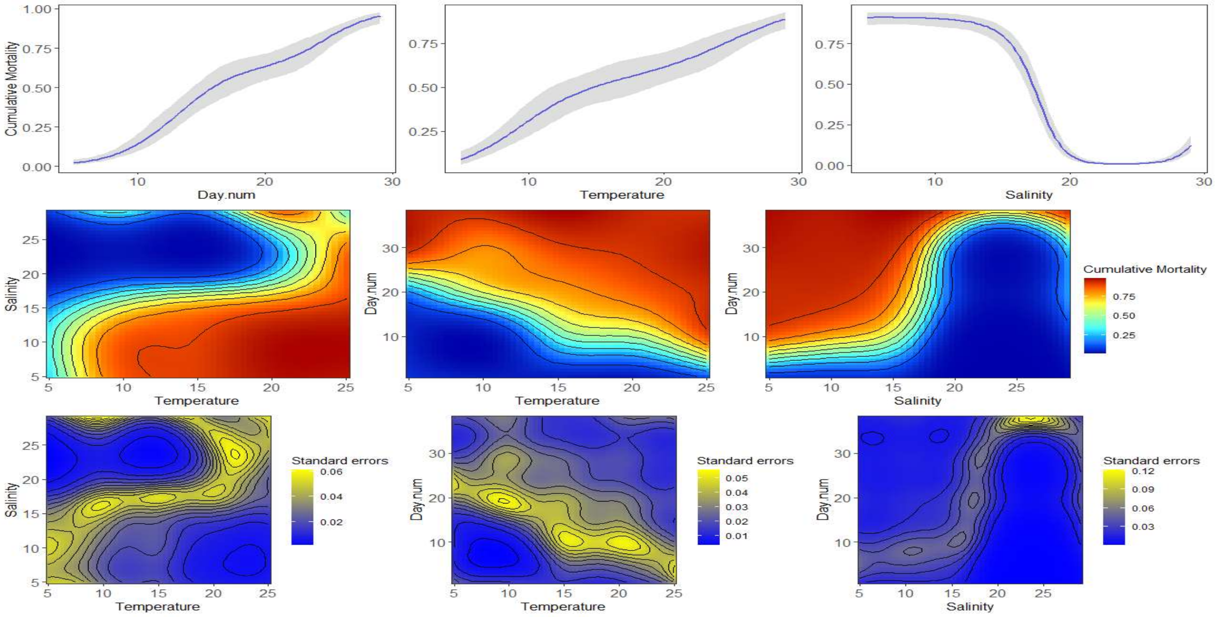


Figure 53. GAM prediction model for cumulative mortality of oysters in prolonged exposure to a range of temperatures, salinities and combinations of (interaction of) temperature and salinity. The lower panel shows the uncertainty of the modelled estimates.

Mortality rate (NNI prediction)

The natural neighbour predicted daily mortality model was applied to near-seabed, temperature and salinity 2012-2021 time series in Galway Bay derived from a hydrodynamic ROMS model with grid size of 70m^2. Figure 54 shows an example of its application to the Mulroog West site (53.178°N, 8.957°W) which was used separately to monitor survival of oyster spat transplanted from spatting ponds as described above. As expected, highest mortality events are predicted each year in wintertime, when rainfall and freshwater discharge into the bay are higher, causing sudden drops in salinity. In such events, oysters have very limited capacity to adapt to the rapidly changing environmental conditions.

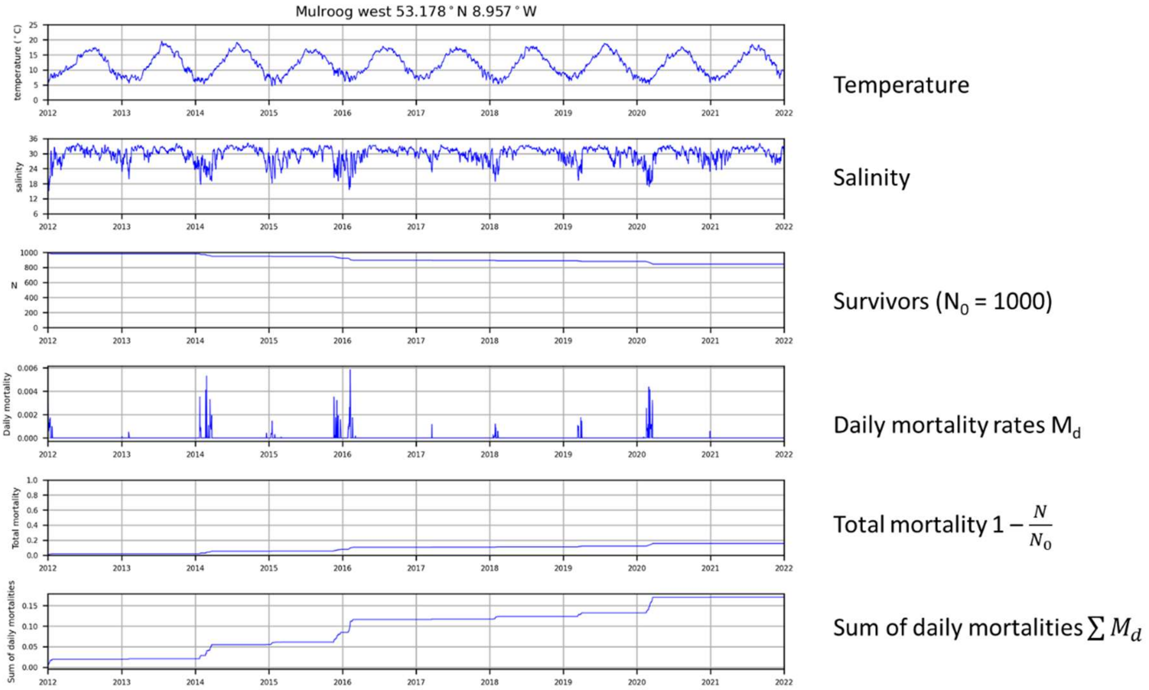


Figure 54. Sample location modelled trends in temperature and salinity in Galway Bay and predicted daily mortality rates due in this case to low salinity conditions and cumulative mortality over time from lethal combinations of temperature and salinity

Habitat suitability and risk

By applying the NNI predictions for mortality to the whole Galway Bay model domain, the 2-D distribution of total predicted mortalities across the bay over years is obtained (Figure 55). The distribution of total mortalities reveals the impact of freshwater sources, and the interactive effect with temperature, on oysters in Galway Bay. Estuarine areas under the influence of river inflows are high risk areas for oyster although these areas historically contained oyster beds that were fished commercially. The frequency and duration of lethal combinations of temperature and salinity is irregular (Figure 54) but is frequent enough to cause significant effects over the life cycle of a cohort of oysters over a number of years.

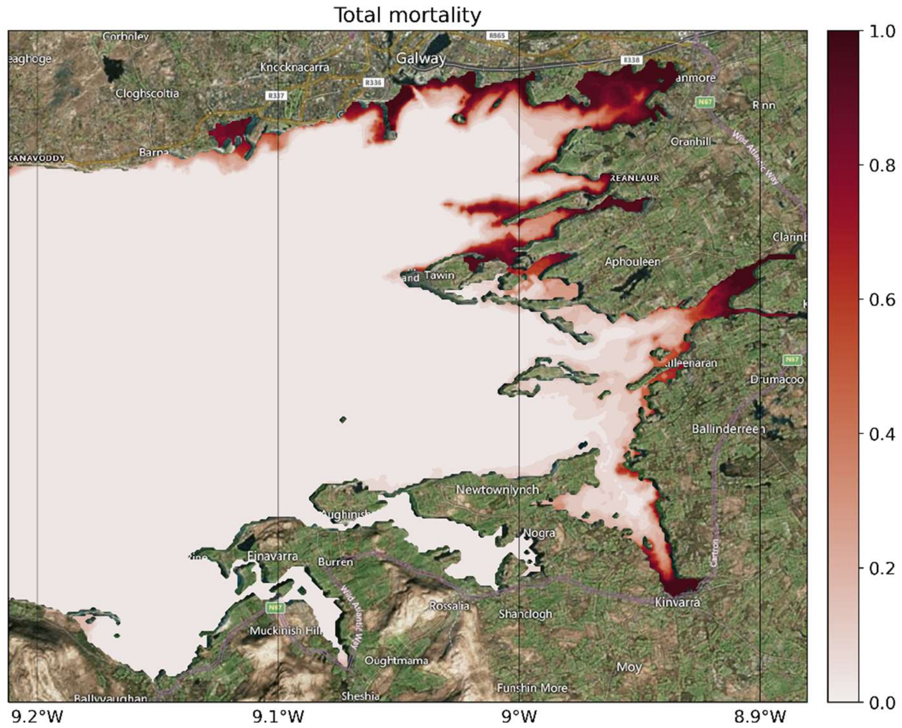


Figure 55. Predicted mortality rates of oysters from experimental data on mortality at different combinations of temperature and salinity and modelled estimates of temperature and salinity on a 70m^2 model grid in inner Galway Bay

Filtration rate

Fluorescence, measured in the experimental containers with a probe, was correlated with phytoplankton cell count density estimated by microscopy (Figure 56). The rate of reduction in fluorescence per hour standardized to 1kg of oysters was highest at salinity of 29ppt and temperatures 5-15°C (Figure 57 and figures in Annex II). Reduction in fluorescence (feeding), as measured over repeated observation periods of 7hrs, occurred in all experimental conditions including those conditions (low salinity and high temperature) that were eventually lethal to oysters indicating that oyster valves were open. Within each salinity treatment filtration rates were generally lower at temperatures of 20-25°C than at temperatures of 5-15°C.

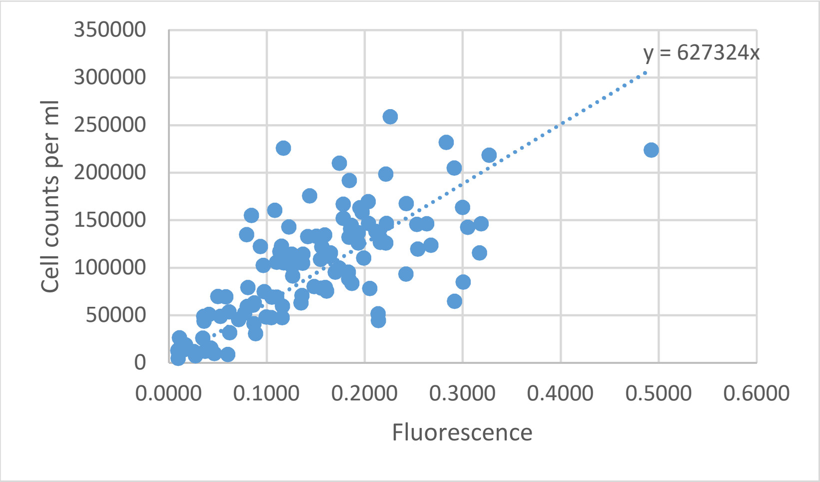


Figure 56. Relationship between fluorescence and phytoplankton cell counts from samples extracted from experimental chambers holding oysters at different combinations of temperature and salinity

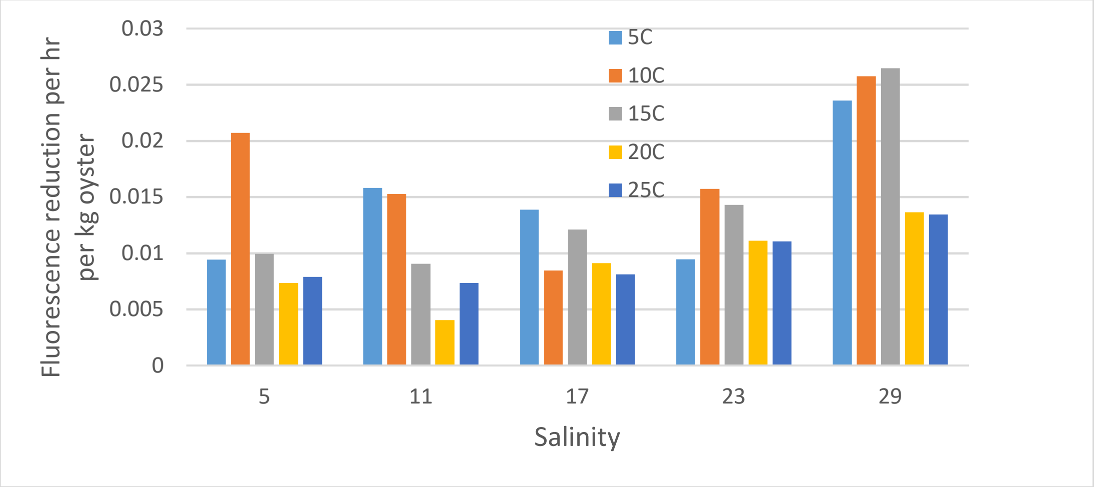


Figure 57. Rate of reduction in fluorescence (as a proxy for oyster filtration rate) at 5 combinations of salinity and temperature

Discussion

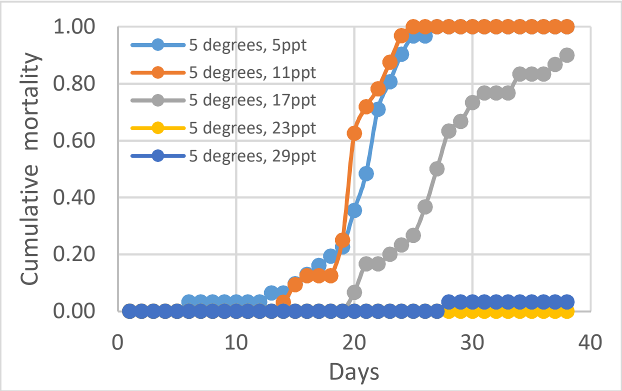
Temperature, salinity and the interactive effects of temperature and salinity within the range of conditions found in inner Galway Bay have significant effects on oyster survival and feeding rate. Although the frequency of unfavourable combinations of temperature and salinity is irregular and many of these events are short lived and will not cause significant mortality, one prolonged event is sufficient to cause severe consequences for oyster populations or on an individual age class of oysters that might survive over 10 years in the system.

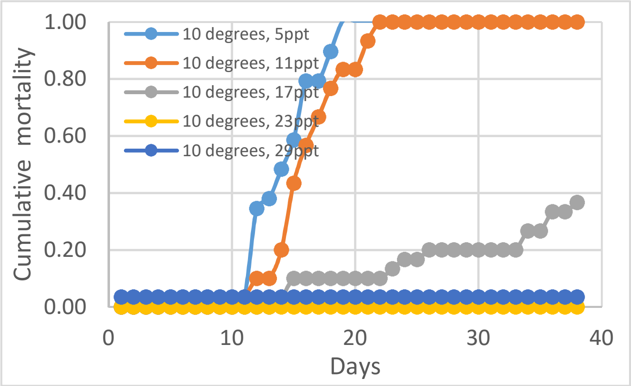
Sub-lethal effects such as reduced feeding rate and presumably knock on effects on scope for growth also occur at low salinities and at high temperatures. In the experimental conditions used here feeding continued at a reduced rate under conditions that were eventually lethal. Oysters did not completely close their valves, therefore, to protect themselves from osmoregulatory stress even at low temperatures when metabolic rate and ammonia production would have been low. This undoubtedly exacerbated the mortality rate under these conditions.

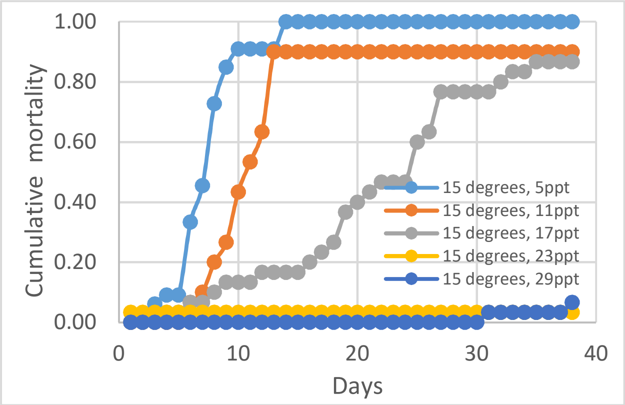
The predicted impact of salinity and temperature on oysters shown here is a partial habitat suitability assessment for oysters in Galway Bay. Additional environmental parameters such as food availability (chlorophyll), sediment stability (bottom shear stress), sedimentation rates (siltation of settlement surfaces) and larval retention modelling need to be considered in a comprehensive oyster habitat suitability assessment which could be extended to dynamic energy budget modelling that can be used to model lifetime feeding, growth and reproduction and responses to changes in biotic and abiotic conditions (van der Meer 2006).

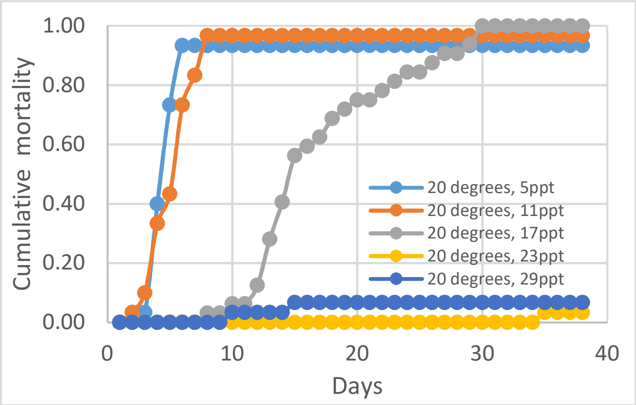
Annex I

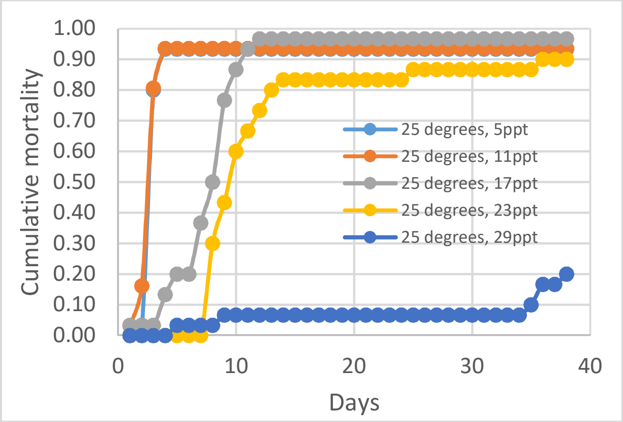
Cumulative mortality of oysters over time (0-30 days) held at 25 combinations of temperature and salinity





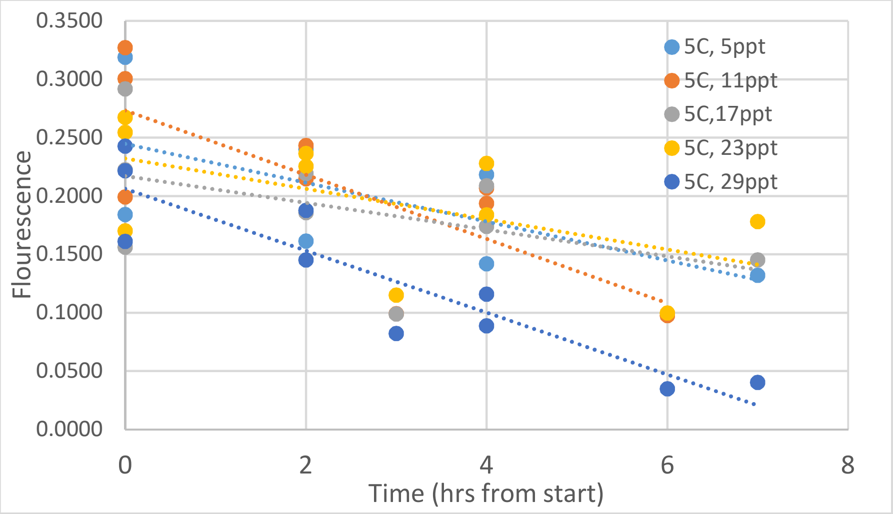


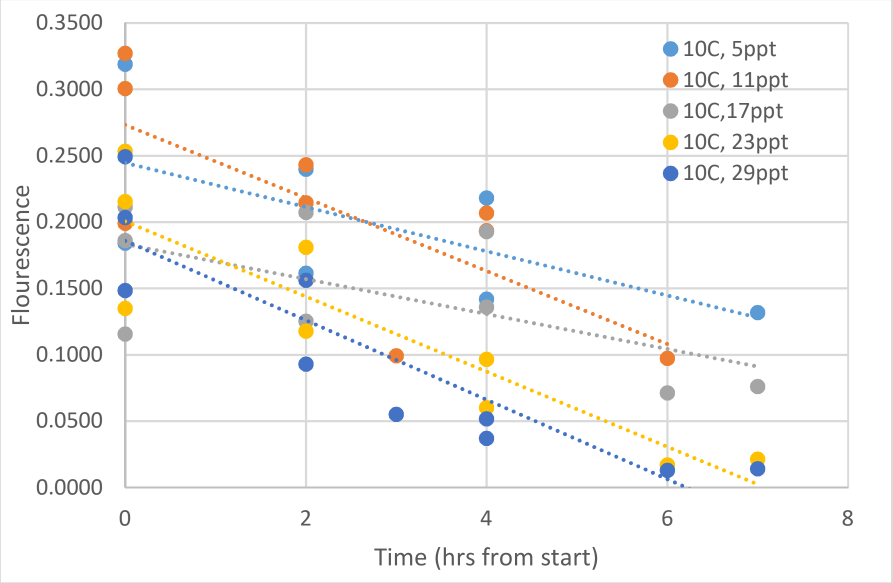


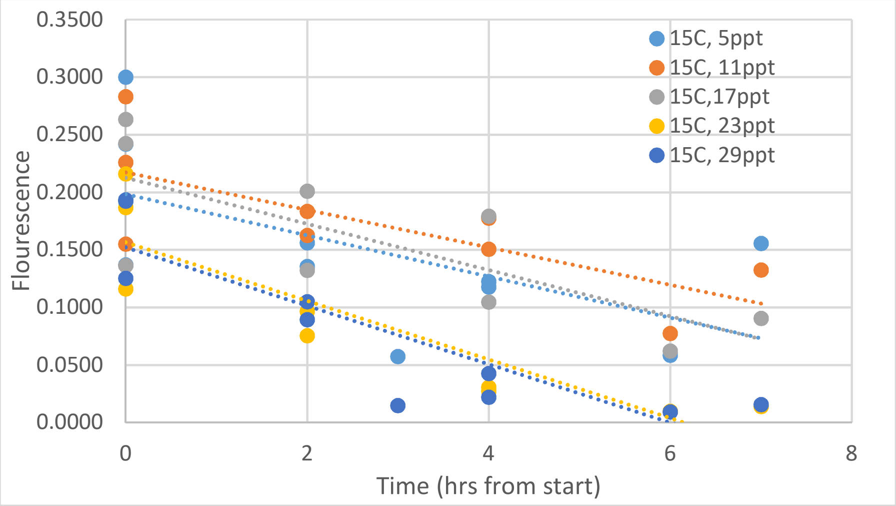


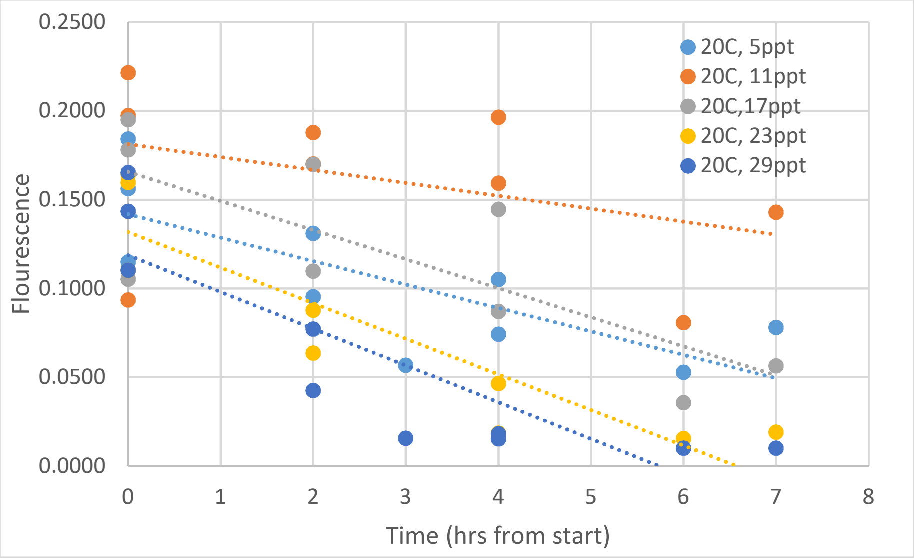
Annex II.

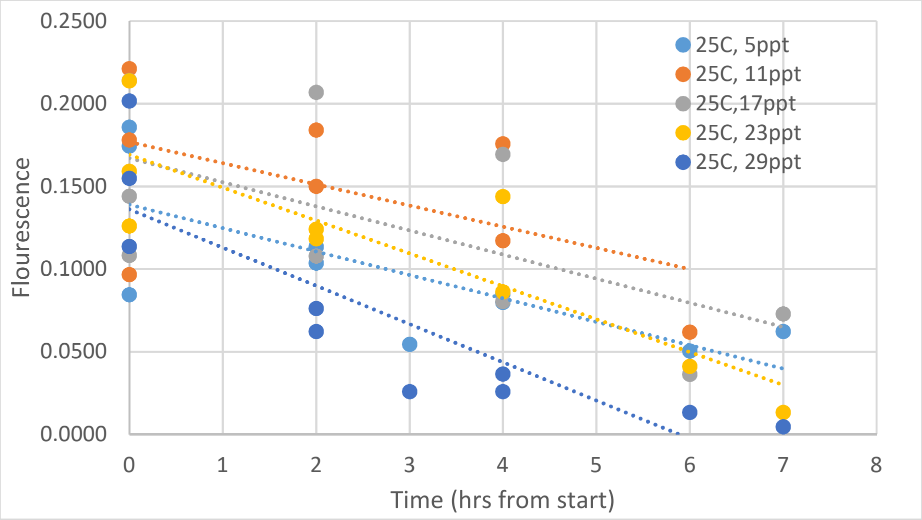
Changes in fluorescence over time (0-7hrs) due to feeding activity of oysters held in 25 combinations of salinity and temperature.








0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
Flourescence
0
1
2
3
4
5
6
7
8
Time (hrs from start)
20C, 5ppt
20C, 11ppt
20C,17ppt
20C, 23ppt
20C, 29ppt


0.2500
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Flourescence
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7
8
Time (hrs from start)
25C, 5ppt
25C, 11ppt
25C,17ppt
25C, 23ppt
25C, 29ppt

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