BlueFish

Building resilience into Blue Growth in the Irish and Celtic Seas Fisheries and Aquaculture.

An Irish and Celtic Seas cross border operation.

Contents

INTRODUCTION

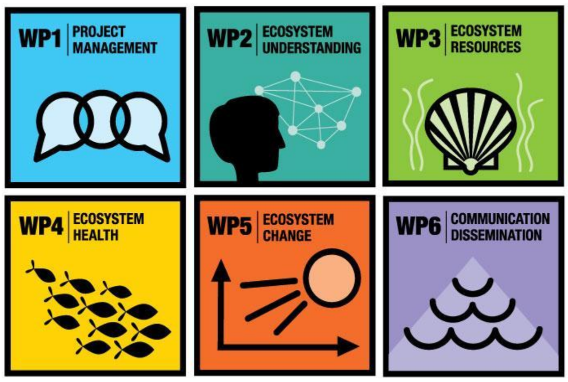
Climate change is already affecting the world's oceans and coasts, with European regional seas showing some of the most pronounced and rapid impacts. Oceans cover two thirds of the Earth's surface, are an essential component of the Earth's ecosystem, and are critical to sustainable development. Under predicted future scenarios, the functionality of shallow marine ecosystems is likely to change, with impacts on species of food or commercial relevance to coastal communities. The consequences of present and predicted climate effects on fish, shellfish and aquaculture in the Irish and Celtic Seas are poorly understood. Importantly, oceans contribute to poverty alleviation and are crucial for global food security and human health. The complexity of interactions between species and global climate change will require ongoing multidisciplinary, transnational investigation and understanding. A combined understanding of processes and effects in the Irish and Celtic Seas will be key to ensuring increased understanding and awareness of climate change effects, and aid in sustaining blue growth throughout the region. Changes on one coast can have direct and immediate effects on the other coast, underscoring how essential a cross-border approach is to addressing the issues presented by changing environments and a changing climate, on fish, shellfish and aquaculture activities within the joint maritime area of the Irish and Celtic Seas.

Building on the legacy, recommendations, and consortium expertise which resulted from the SUSFISH project (2009 - 2013), BlueFish aims to develop knowledge and understanding of the marine resources of the Irish and Celtic Seas, by addressing knowledge gaps regarding the effects on, and potential vulnerability of, selected commercial fish and shellfish due to predicted climate change.

The BlueFish Project brought together the Universities of Bangor, Aberystwyth, Swansea and Cork, the Marine Institute and Bord Iascaigh Mhara. It was co-funded by the Ireland Wales Territorial Co-operation Operation for the Irish and Celtic Sea, focusing on cross-border collaboration, climate change and community engagement.

This document briefly summarises the activities within each of the work packages prior to our closing conference for the BlueFish Project.

The BlueFish Operation would not have been possible without the funding received from the European Regional Development Fund, through the Ireland Wales Territorial Co-operation Programme 2014 – 2020. Our achievements would not have been possible without the support of several organisations cooperating with us in enhancing the marine and coastal environment, and through our engagement with coastal communities both in Ireland and Wales.



ACTIVITY 2.1 TROPHIC INTERACTIONS

PARTICIPANTS: P Daly, R Browne (BIM); L Le Vay, M Walton (BU)

AIMS: To understand trophic (and other) interactions between different species within the case study area of Berehaven, Bantry Bay. In particular to:

1. Map/define today's species/aquaculture interactions.
2. Model future aquaculture scenarios.
3. Highlight changes/threats to aquaculture and report on adaptation strategies.

MAIN ACHIEVEMENTS:

1. Tracing of trophic connections using stable isotopes indicated that nutrient inputs from salmon culture were of limited significance to mussel and algal growth. This did not alter according to proximity to the salmon culture units.
2. Harvesting of mussels resulted in the removal of nitrogen, equivalent to that released by the salmon farm. Hence, extractive aquaculture provides a means of offsetting nutrients released during fish production..
3. Kelp detritus was found to be a significant nutrient source for mussels (contributing 50-60% of their diet). Kelp contribution was inversely correlated with phytoplankton density, and therefore represents a vital food source in times when phytoplankton densities are low.
4. The dietary contribution of kelp detritus to mussels consistently varied according to location within Berehaven and was greater at stations where hydrodynamic models indicated faster water movement.
5. Findings indicate that climate change could have important effects on mussel carrying capacity if warming waters result in predicted decreases in kelp density.

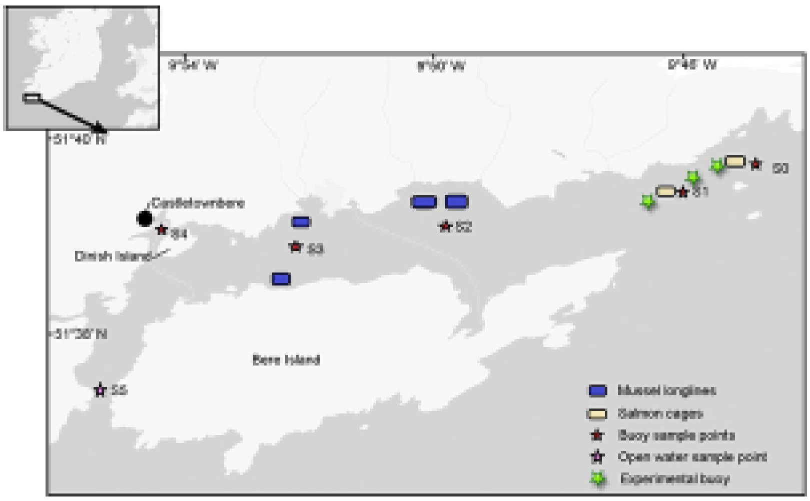


Figure 1: Location of sampling points and aquaculture installations within Bereshaven, between Bere Island and the BEARA Peninsula of mainland Ireland.

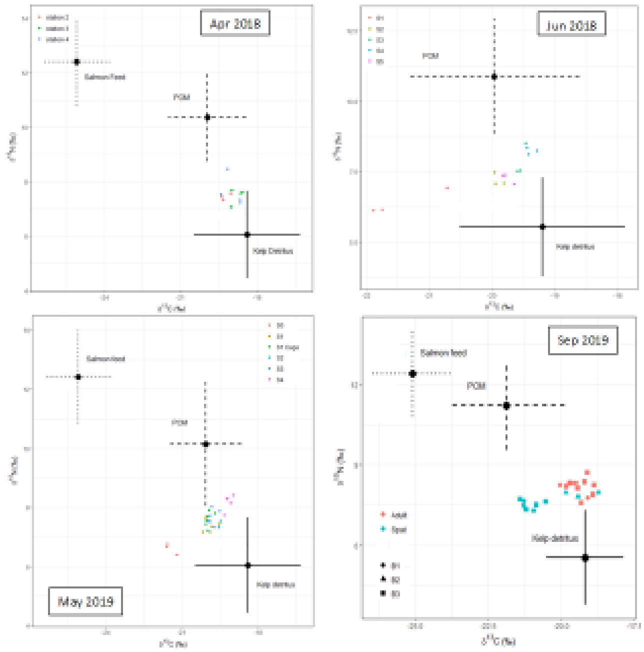


Figure 2: Stable isotope values (‰) of δ^{13}C and δ^{15}N of food sources and mussel samples from buoys within Berehaven.

Sample	Kelp detritus	POM	Salmon feed
April 2018	67.7% (41-80.4%)	21.9% (2-46.8%)	10.5% (0.6-27.7)
June 2018	65% (38.8-87.7%)	35% (12.3-61.2%)	
May 2019	43.7% (8.8-80.8%)	50.7% (13.1-86.9%)	5.6% (0.1-36.3%)
Sept 2019 (adult)	64.1% (52-77.7%)	24.9% (2.5-44.4%)	11% (0.5-26.8%)

Table 1: Mean dietary contribution and 95% confidence intervals from kelp detritus, particulate organic matter (POM), and salmon feed to the gill and mantle tissue of mussels.

RECOMMENDATIONS:

1. When determining the appropriate scale of licensed seaweed harvesting, consideration should be given to the trophic contributions of kelp detritus in regions where surface chlorophyll concentrations vary seasonally.
2. As rising sea temperatures are forecasted to decrease kelp density, efforts to increase the resilience of kelp systems to climate change should be prioritised.

OUTPUTS:

Meetings:

Including: Climate change conference, Rorvik, Norway, 2019; Integrate (Multi-trophic Aquaculture), NUI Galway, Ireland, 2019; BlueFish Science Meeting, Aberystwyth, Wales, 2019.

Coastal community engagement: Stakeholder meeting on the BlueFish project work and objectives at BIM, Regional Fisheries Centre, Castletownbere, Ireland, 2018; Coffee shop talk on the BlueFish project work and objectives, Westport, Co. Mayo, Ireland, 2019; Lunch and learn at BIM, Dun Laoghaire, Co. Dublin, 2019.

RESEARCH PUBLICATIONS

Walton, M., Browne, R., Malham, S., Le Vay, L. (in preparation for submission). The importance of kelp detritus as a food source for mussels.

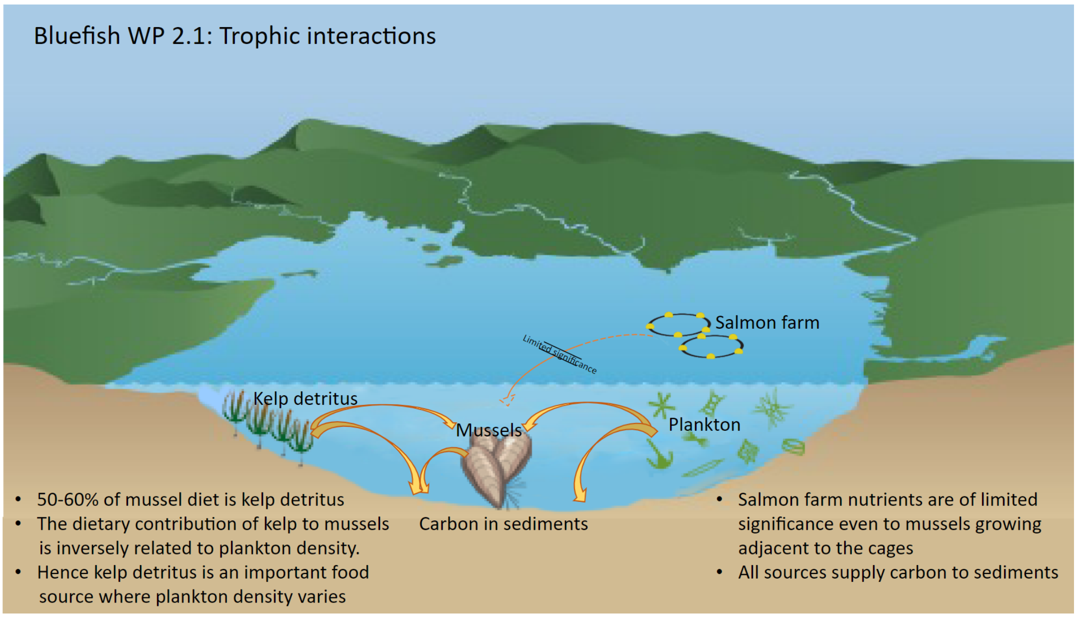


Figure 3: Trophic Interactions between different species within Berehaven, Bantry Bay

ACTIVITY 2.2. MAPPING PREDATORS

PARTICIPANTS: L Börger, E Shepard, S de Grissac (SU) M Jessop, EA Quinn (UCC)

AIMS:

1. To quantify how marine predators interact with fisheries in the Irish Sea.
2. To assess how climate change and changes in fisheries may affect the habitat and distribution of marine top predators.

MAIN ACHIEVEMENTS:

1. We developed a database of seabird movements in the Irish and Celtic seas, using data collected across 6 institutions. The database includes 871 individuals from 8 species, who made 3,650 trips at sea, and were tracked at 1,600,966 GPS locations (see summary image on the left below, coloured by species).
2. We have shown that the distribution of foraging fulmars at sea can be predicted from the distribution of fishing vessels (Figures 1 and 2), and that this is a more powerful predictor than any climatic or biological variable.

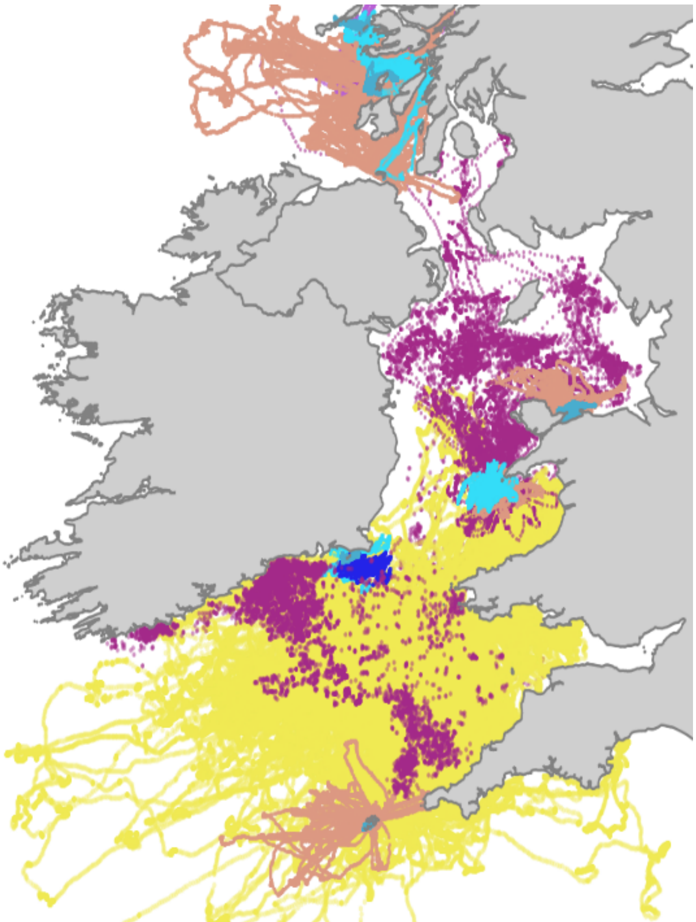


Figure 1. Distribution of fishing vessels and high frequency movement data of 8 species of seabird; fishing vessels shown in burgundy

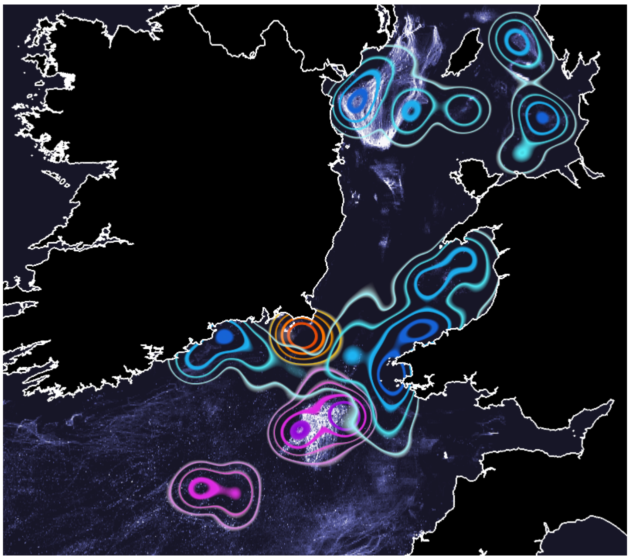


Figure 2. Distribution of fishing vessels and high frequency movement data of the Northern Fulmars and other seabirds. Black and white background represents fishing activity, from black (none) to white (intense); overlaying concentric shapes represent Fulmar (pink), Manx shearwater (blue) and Puffin (orange). Fishing areas with darker colours represent the core.

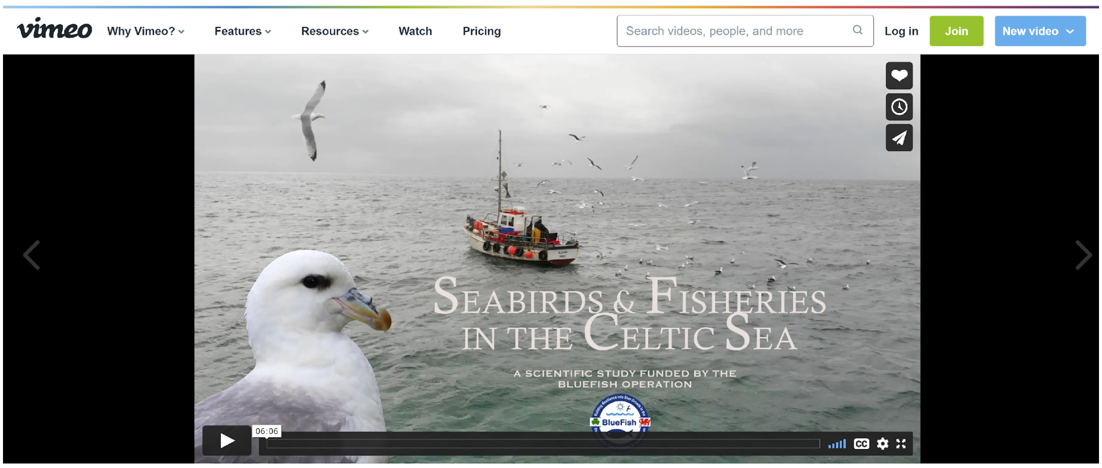
OUTPUTS:

Meetings: British Ecological Society, Birmingham, UK, 2018; Seabird Group Conference, Liverpool, UK, 2018; Ecology and Behaviour meeting, Toulouse, France, 2019.

Media: Examples include the production of a short public science film to highlight the interactions between fisheries and seabirds, taking the northern fulmar as an example (Vimeo and YouTube, 620 views). S de Grissac was also interviewed about her work on German radio and submitted an image (Figure 2) to the Research as Art competition run by Swansea University.

Coastal community engagement: As above, the BlueFish team produced a film about interactions between fulmars and fisheries in the Celtic Sea, which highlights the role of animal tracking in understanding the extent to which seabirds associate with fishing vessels.

The film is still available on YouTube (https://www.youtube.com/watch?v=EiecZf3LyqY) and Vimeo (https://vimeo.com/351864073/2d063b4895).



RESEARCH PUBLICATIONS

Darby, J.H., **de Grissac**, **S.**, Arneill, G., Pirotta, E., Waggitt, J.J., **Börger, L.**, **Shepard, E.**, Cabot, D., Owen, E., Bolton, M., Edwards, E., Thompson, P., **Quinn, J.**, **Jessop**, **M.** (in review). The foraging distribution of breeding northern fulmars is predicted by commercial fisheries. *Marine Ecology Progress Series.*

ACTIVITY 2.3. SHELLFISH AND CLIMATE CHANGE

PARTICIPANTS: NG King, SK Malham, J Thorpe (BU); NJ McKeown, I Skujina (AU)

AIMS: To understand how shellfish distributions will change in the NE Atlantic and identify physiological tipping points in key bivalve species. In particular to:

1. Use mechanistic niche modelling to predict where and when reproductive thresholds will be exceeded in the Pacific oyster, facilitating a future expansion.
2. Identify physiological tipping points in key intertidal species and use these to predict where population crashes may occur in the future.
3. Determine if marine heatwaves shift the associated bacterial community of species/populations prone to summer mortalities.

MAIN ACHIEVEMENTS:

1. We found that the Pacific oyster will undergo a range expansion in the NE Atlantic mediated by the thermal requirements of spawning and settlements being increasingly met (Figure 1). This will encompass the majority of the Northwest European Shelf by 2100 and result in earlier spawning dates.
2. Experimental stress assays identified the key physiological tipping points of the blue mussel, *Mytilus edulis*, to low tide stress. Comparison of these tipping points with intertidal logger data in the Menai Strait shows that they are exceeded during atmospheric heatwave events and mortalities may already be occurring (Figure 2).
3. Mesocosm experiments showed that the microbiome of the cockle, *Cerastoderma edule*, is unaffected by marine heatwaves.

RECOMMENDATIONS:

1. Pacific oyster, *Crassostrea gigas,* is farmed throughout the NE Atlantic and its naturalisation frontier will move increasingly north over the coming decades. Over the short term, farming triploids and eradications may prevent localised naturalisation. However, over the long term it is unlikely that local management strategies will prevent expansions. Here, a change in perceptions may be needed to effectively manage emerging populations.

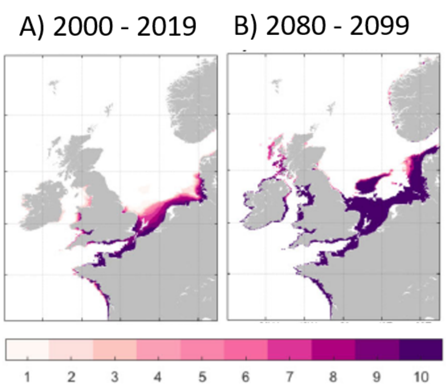


Figure 1: Proportion of years *C. gigas* settlement thresholds are exceeded for the present day baseline (2000 - 2019) and for the future (2080 - 2099) across the northwest European Shelf.

2. Heatwaves are set to become more frequent and intense. We recommend that surveillance of mortalities in the field and potential adaptive management solutions may be required to ameliorate mortalities.

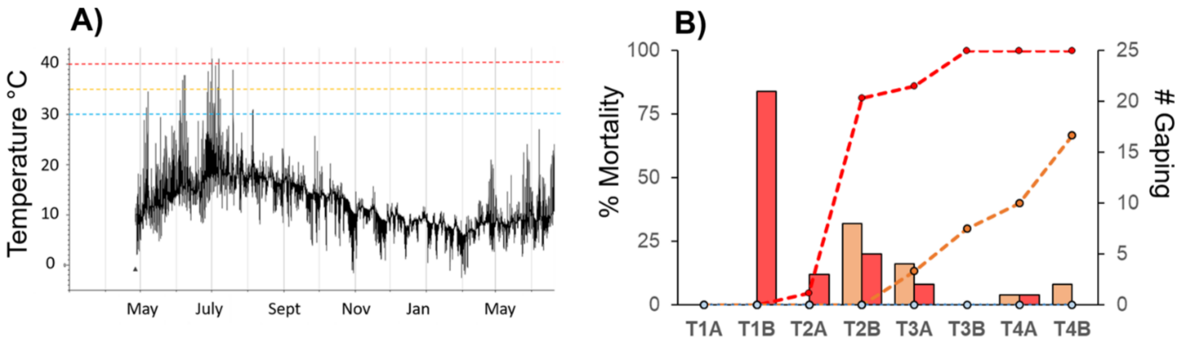


Figure 2: A) Intertidal logger data for the Menai Straits, Wales, during 2018. B) Gaping (bars) and cumulative mortalities of *M.Edulis* to daily 4-hour aerial stress assays.
Blue = 30°C Orange = 35°C Red = 40°C.

OUTPUTS:

Meetings: Naemo workshop, Oban, 2019; Joint ARCH-UK & BLUEFISH meeting, Fishmongers' Hall, London, 2018; Coastal adaptation workshop, Brazil, 2018.

Coastal community engagement: Festival of Discovery (2019).

RESEARCH PUBLICATIONS

King N., Wilmes S.B., Smyth D., Tinker D., **Robins P**., **Thorpe J**., Jones L., **Malham S.K**. (2020). Climate change accelerates range expansion of the invasive non-native species, the Pacific oyster, *Crassostrea gigas*. *ICES Journal of Marine Science*. **78**(1), DOI: 10.1093/icesjms/fsaa189

Jones, L. et al. (2020). Climate driven threshold effects in the natural environment. *Report to the Climate Change Committee*.

ACTIVITY 2.4 ECOSYSTEM GOODS AND SERVICES

PARTICIPANTS: P Connolly, F Donnelly, S Sugrue (MI)

AIMS:

1. To inform stakeholders, including policy and industry, about the goods and services provided by the Celtic Sea-Irish Sea ecosystem to the coastal communities of Ireland and Wales and to wider society.
2. To outline and demystify these goods and services using simple schematics developed by a professional artist.
3. To focus on the positive benefits that people derive from these goods and services.
4. To outline the impact of various climate change scenarios on these goods and services.
5. To use the schematics to inform the debate on improving security, well-being and health, in addition to adapting to climate change.

MAIN ACHIEVEMENTS:
The key objective of this activity was to fuse art and science, in order to demystify complex concepts and inform the debate in Irish and Welsh coastal communities, regarding the contribution of seas to improved security, well-being and health, as well as adaptation to climate change.

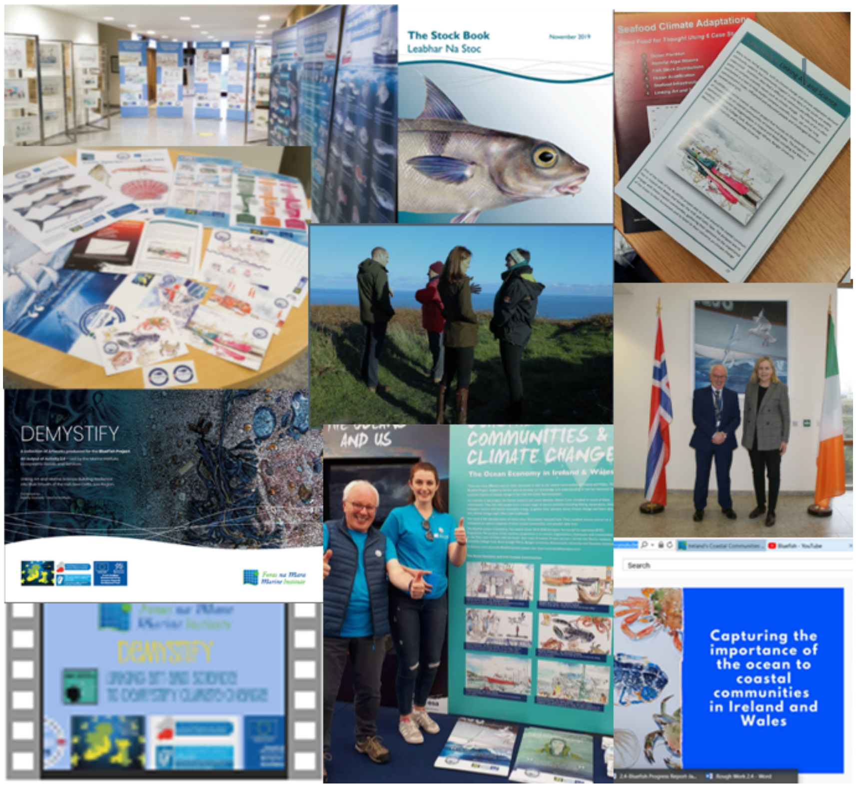
To achieve these aims, the MI brought together artists, marine scientists and environmental economists, and, thanks to close engagement with our project partners and coastal communities, a significant portfolio of multi-media artwork and infographics has now been developed.
The BlueFish Portfolio consists of approximately 60 pieces which have been commissioned to address each key component of the project. It is organised along the following distinct themes:

- Theme 1 - Understanding Ecosystem Goods and Services.
- Theme 2 - Coastal Community Engagement, Economic Impacts, Opinion and Societal Benefits.
- Theme 3 - Linking Art and Science. Interpretations of the Impacts of Climate Change.
- Theme 4 - Food Security, Well-being and Health.

OUTPUTS:
To maximize the project's reach, the portfolio of artwork has been used extensively to produce promotional and educational materials and media, for activities related to public engagement, stakeholder engagement, and policy work. All materials aim to inform and stimulate debate and discussion as to the possible impacts of climate change on Irish Sea/ Celtic Sea coastal communities.
The portfolio consists of original art-works complemented by an array of display banners, infographics, posters, postcards, an animation, and a compendium.

Infographic material includes the following large scale banners and exhibition stands:

- Irish Sea-Celtic Sea Ecosystem Goods and Services - How Will Climate Change Impact the Irish Sea-Celtic Sea Ecosystem? (Karen Nolan)
- BlueFish WP Icons (Karen Nolan/MI)
- Impacts of Climate Change on Coastal Communities of the Irish Sea (Rosin Cure/Sharon Sugrue/MI)
- Impacts of Climate Change on Coastal Communities of Celtic Sea (Rosin Cure/Sharon Sugrue/MI)
- Scenarios of Changing Estimated Economic Value of the Marine Ecosystem to Irish and Welsh Coastal Communities (MI/Economics for the Environment Consultancy/CountryScape/Rosin Cure)
- The Estimated Economic Value of the Marine Ecosystem to Irish and Welsh Coastal Communities
  (MI/Economics for the Environment Consultancy/CountryScape/Rosin Cure)
- Interpretations of Impacts of Climate Change (MI/Simon Royer/Cathy Bacon)
- Iconic Species of the Irish Sea (MI/Frances Ratcliffe)
- Iconic Species of the Celtic Sea (MI/Miranda Walker)
- Animation: “Demystify – Linking Art and Science to Demystify Climate Change” (MI and all artists)
- Exhibition Compendium: “Demystify – A Collection of Artworks Produced for The Bluefish Project” (MI and all artists)



FURTHER OUTPUTS:
Meetings: eNGO Meeting, MI Wilton Park House, Dublin, Ireland, 2019; The Skipper Expo International, Galway, Ireland, 2019; Food Web Workshop, Arklow Bank Marine Institute, Arklow, Ireland, 2019; EU day, 2018 & 2019; Presentation of BlueFish WP 2.4. to King Carl Gustaf and Queen Sylvia of Sweden, 2019; Meeting with the Norwegian Ambassador to Ireland, 2020; Coastal walk of Howth Head, with Their Royal Highnesses the Duke and Duchess of Cambridge and Dr. Paul Connolly, providing an opportunity to highlight the BlueFish Project, the importance of the ocean to livelihoods, and the impacts of a changing climate to the coastal communities of Ireland and Wales.
https://www.marine.ie/Home/site-area/news-events/press-releases/duke-and-duchess-cambridge-meet-marine-institute-during-first
Media: Marine Institute News & Events: "Artwork highlighting the importance of the ocean is unveiled at BlueFish Project meeting", 2018.
Marine Institute YouTube Channel - Video – Demystify.
https://www.youtube.com/channel/UCDHUpX9NzHO-pJtXZ90miEA
Oceans of Learning.
https://www.marine.ie/Home/site-area/areas-activity/education-outreach/irelands-coastal-communities
Oceans of Learning series celebrates Art of the Ocean.
https://www.marine.ie/Home/site-area/areas-activity/education-outreach/art-ocean
Coastal Community Engagement: Seafest, Cork, Ireland, 2019; Food Web Workshop, Arklow Bank Marine Institute, Arklow, Ireland, 2019.

PUBLICATIONS:
The Skipper Magazine article: "Capturing the Importance of the Ocean for Irish and Welsh Coastal Communities through Art", 2019.
DAFM/Seafood Climate Adaptation WG -BlueFish – Linking Art & science Case Study (6) Booklet.
DEMYSTIFY A collection of Artworks produced for the BlueFish Project - ISBN: 978-1-902895-68-0

ACTIVITY 3.1 SCALLOPS

PARTICIPANTS: O Tully, M Sheridan (MI); CL Szostek, LK Southworth, MJ Kaiser (BU)

AIMS: To improve knowledge of scallop stocks in the Irish Sea. In particular:

1. To describe and map the distribution of scallops from fisheries data.
2. To undertake surveys on commercial and research vessels, in order to gather catch data under varying environmental conditions.
3. To undertake fisheries independent surveys to estimate biomass and the relationship between biomass and seafloor sediments.
4. To enhance existing fisheries data collection programmes to provide new data on reproduction, and size and age structure.
5. To use historical fishing effort, catch, and environmental data, to model how variation in scallop catch rate is related to environmental parameters.

MARINE INSTITUTE - MAIN ACHIEVEMENTS:

1. The distribution of scallops, and spatial correlations between the species and differing sediment structures were identified.
2. A time series (2012-2019) of fisheries and environmental data was compiled for the modelling of catch rate data (indices of stock status).
3. Connectivity between stocks in the Irish Sea and Celtic Sea were identified through collaboration with Aberystwyth University (WP5).
4. Seasonal reproductive schedules for scallops in the Irish Sea and Celtic Sea were identified.
5. Modelling of scallop abundance indices and the effects of oceanographic variables were undertaken. This work will continue beyond Bluefish.

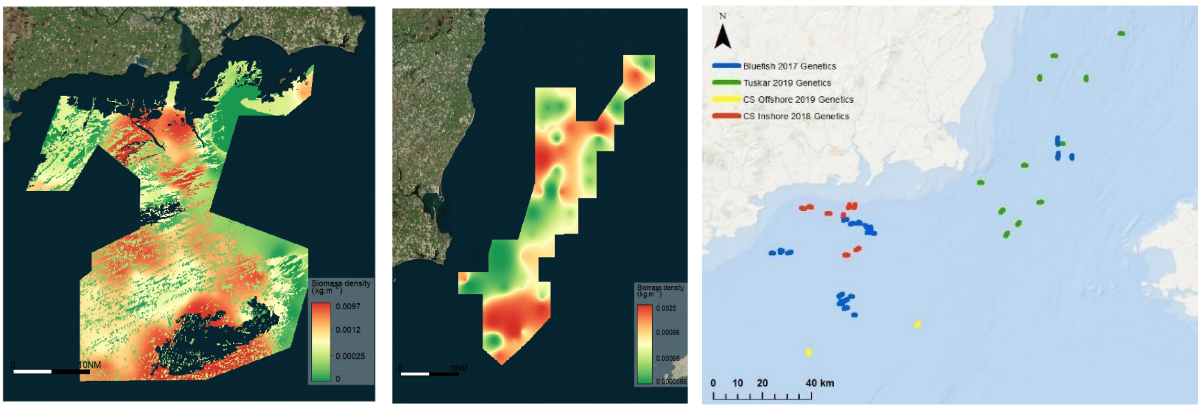


Figure 1: Scallop biomass in the Celtic Sea (left) and Irish Sea (middle), from surveys. Sampling points for genetic studies on connectivity between the two areas (right).

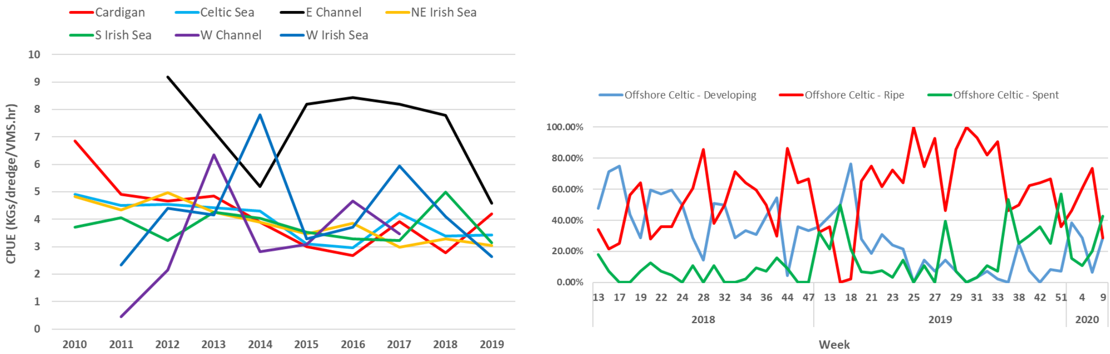


Figure 2: Scallop catch indices compiled for 2010-2019 (left) for modelling against oceanographic variables (temperature and bottom currents). Seasonal patterns of maturity for scallops in the Celtic Sea (right).

BANGOR - MAIN ACHIEVEMENTS:

1. Fisher surveys were completed and major factors influencing dredge efficiency were identified.
2. Scallop catch, as well as environmental and dredge accelerometer data, were collected on a commercial fishing vessel and the RV Prince Madog. Models indicate slight significance of the variable wave height, which indicates that sea condition is the main factor influencing catch rates. These results aligned with questionnaire responses.
3. Historical fishing effort, landings data, and environmental data were modelled to ascertain if catch per unit effort (CPUE) can be linked to specific environmental variables.
4. In conclusion, there are multiple factors that influence dredge catch efficiency (including the vessel, weather, and environmental variables). This makes it very difficult to ascertain the degree to which each individual factor influences catch rate and overall dredge efficiency.

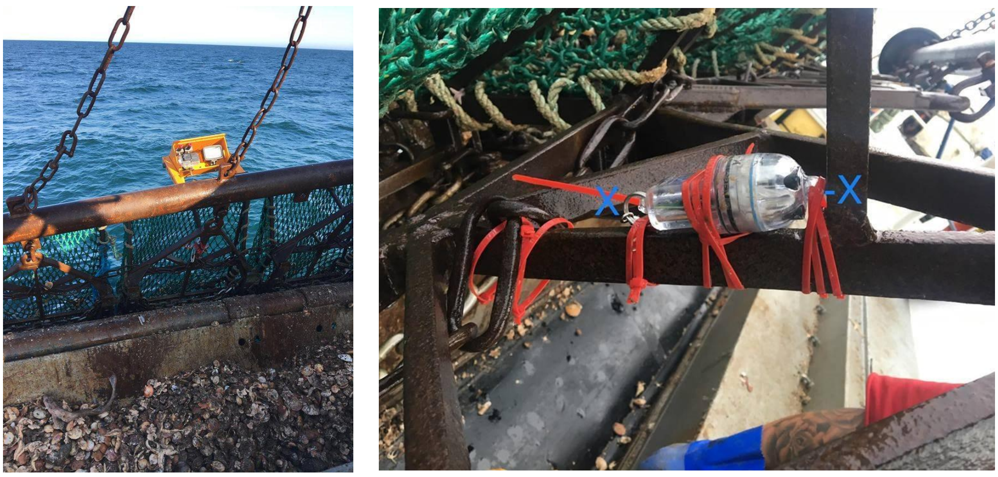


Figure 3: Left - GoPro cameras mounted on the dredge. Right - an accelerometer mounted inside a waterproof casing, on the top of a dredge.

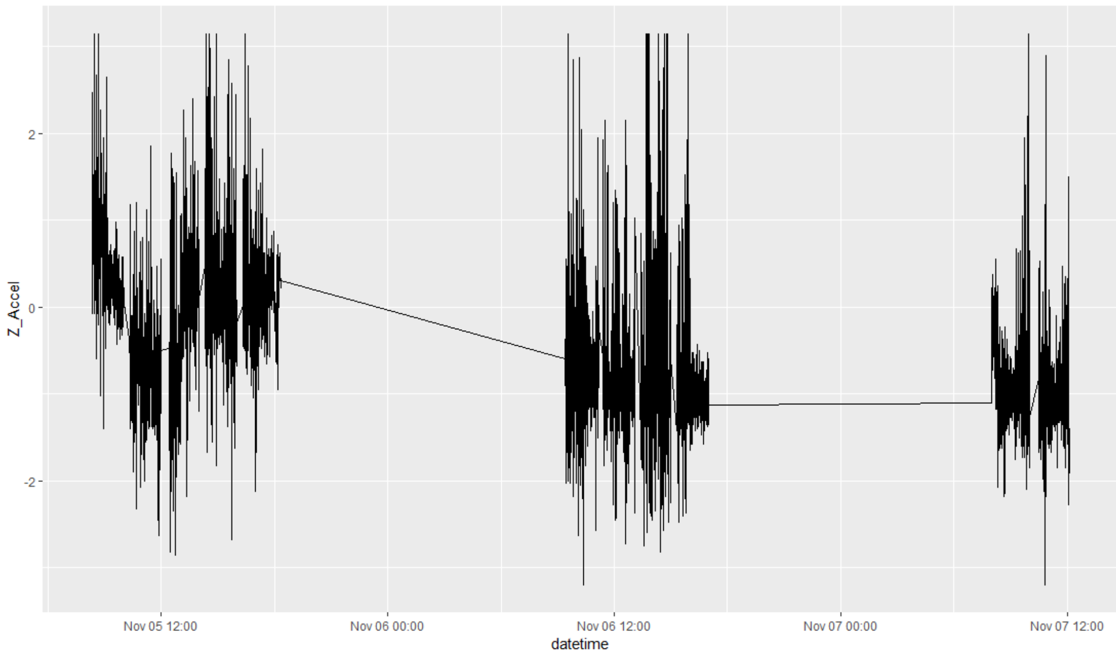


Figure 4: Data showing Z-axis of accelerometer readings from a scallop dredge during three separate fishing events. The length of the lines relates to the force exerted on the dredge as it bounces along the seabed.

Overall, further investigation into sea conditions is required to understand how they affect gear catch efficiency; this in turn can feed into more effective management of the fishery. Restricting fishing activity at times when sea state is high and catch efficiency is low could reduce the impact on the seabed and improve overall CPUE (catch per unit effort).

OUTPUTS:
Meetings: Inshore Celtic Sea survey assessment results were presented at the International Pectinid Workshop, Santiago de Compostela, Spain, 2019; Research was presented and discussed at the 2019 and 2020 ICES Scallop Assessment Working Group meetings (WGScallop), with details included in the annual WGScallop report, published by ICES.
Coastal community engagement: Festival of Discovery, 2019.

RESEARCH PUBLICATIONS
Data submitted to the first official ICES scallop data call in September 2020.
MSc Project completed in October 2019.

ACTIVITY 3.2 EUROPEAN SEA BASS (*Dicentrarchus labrax*)

PARTICIPANTS: N Ó Maoiléidigh, R O'Neill (MI); PW Shaw, NJ McKeown (AU); F Ratcliffe (SU); I McCarthy, P Robins, L Southworth (BU)

AIMS: The partners working within WP 3.2 undertook research to assess the potential impact of climate change on sea bass distribution within the Celtic Sea and Irish Sea regions. The main aims were:

1. To assess the potential impact of climate change on the distribution of sea bass within the Celtic Sea/Irish Sea regions through the use of biotelemetry and eDNA sampling.
2. To apply molecular techniques (metabarcoding of bulk and water samples), in order to identify larval fish spawning assemblages in Celtic and Irish seas and develop a non-neutral molecular marker (MHC) for assessing molecular selection signals and population connectivity of sea bass populations in the Eastern Atlantic.
3. To identify potential spawning grounds in the Irish Sea and Celtic Sea through the use of biotelemetry and retrospective particle tracking models.
4. To study the movement ecology of sea bass in the Irish Sea using stable isotope analysis and to examine the potential of otolith microchemistry as a method of identifying Welsh sea bass to its region of origin.
5. To identify the extent of interconnectivity of sea bass stocks from various locations in the Celtic Sea/Irish Sea region through the use of genetic techniques.

MAIN ACHIEVEMENTS - MARINE INSTITUTE

- A total of 324 fish were tagged as part of the BlueFish project: 21 with acoustic tags (with three additional specimens being detected which were tagged as part of previous research), 9 with PSATs, and a further 294 with plastic identification tags only.

Figure 1: A wildlife Computers MiniPat PSAT tag used to track large adult fish offshore.

- Analysis of the acoustic detection data compared with the environmental data found that tagged fish were more likely to be present in warmer, more saline water
- This may suggest that under current climate change predictions, temperature increases may not affect sea bass presence/distribution. However, the predicted increase in annual rainfall (and the resulting lowering of salinity in estuarine systems) may negatively impact on the species' presence in Irish inshore waters.

- Further research is required to investigate these potential impacts on the more vulnerable early-life stages of the sea bass.
- While most acoustically tagged fish displayed a high level of residency to the area in which they were tagged, some specimens undertook significant migrations – including one individual which travelled from the south-east to north-west of Ireland and back, twice.
- Fish tagged with PSATs revealed a high level of interconnectivity between Ireland and Wales, with migrations to coastal waters on both sides of the Irish Sea observed.
- The first sea bass to be PSAT tagged on the west coast of Ireland also revealed a fascinating migration, for what is currently a very poorly understood stock.

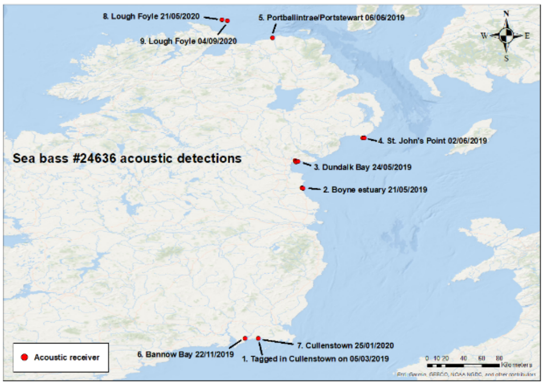


Figure 2: Detections of acoustically tagged fish 24236 around the Irish coastline.

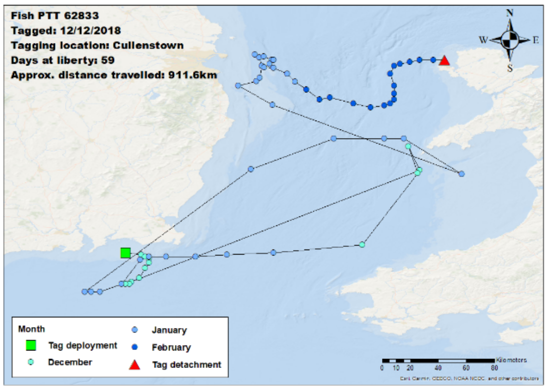


Figure 3: A modelled migration pathway for PSAT tagged fish 62833 (tag washed up on shore in Anglesey in northwest Wales).

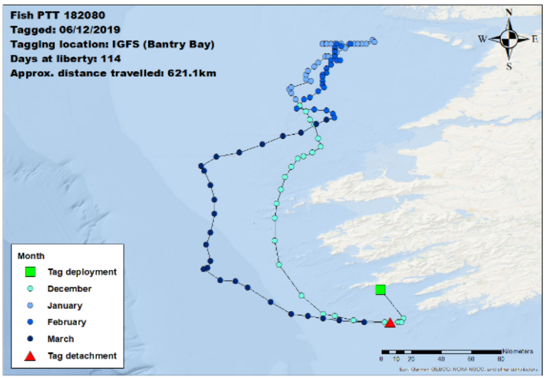


Figure 4: Modelled migration pathway of a PSAT tagged sea bass off the west coast of Ireland.

MAIN ACHIEVEMENTS – BANGOR UNIVERSITY

- Particle track models have indicated regional spawning, with sea bass in South Wales utilising known spawning areas in the Bristol Channel and Celtic Deep, inshore and close to all nursery areas sampled. With warming waters due to climate change, it is possible that some sea bass could now be spawning further north in the Irish Sea.
- Our study of the movement ecology of sea bass in the Irish Sea, using stable isotope analysis, showed overlap in the isotopic niche widths of sea bass from South Wales and South East Ireland. This suggests more connectivity between these fishes - i.e., it is likely that these fish are feeding within isotopically similar areas at sea, most likely within the Celtic Deep and northern Celtic Sea.
- Otolith microchemistry used to identify Welsh sea bass to their region of origin indicated considerable variability in the core otolith chemistry of adult fish. It also suggested that adult fish caught in Mid or South Wales were not necessarily derived from nursery areas exclusively within these two regions. Thus, core otolith microchemistry cannot be used to accurately indicate the region of origin of juveniles.

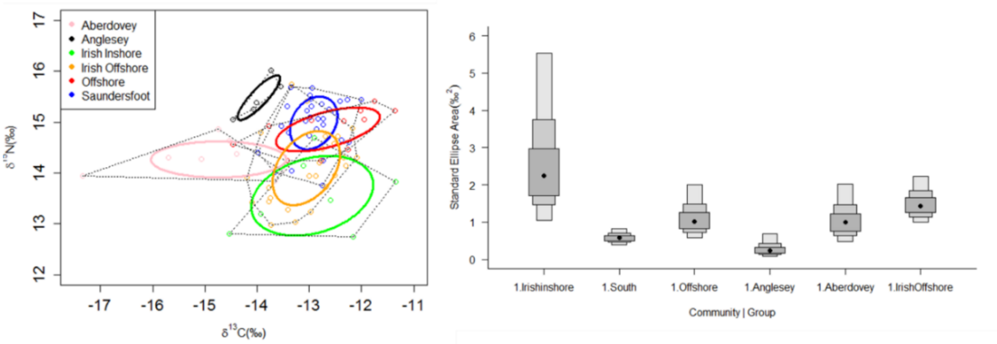


Figure 5: Isotopic biplot (left) and isotopic niche width (right) for sea bass sampled from Wales and southeast Ireland.

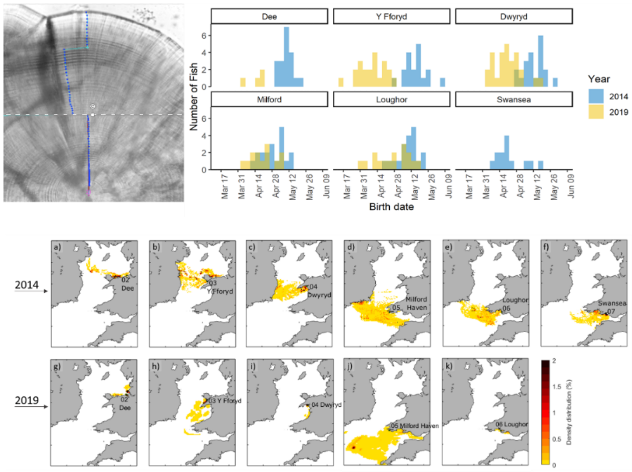


Figure 6: Regional sea bass spawning areas in Irish Sea based on particle track models.

MAIN ACHIEVEMENTS – SWANSEA UNIVERSITY

- We developed a protocol for identifying and quantifying mixed samples of fish larvae using bulk tissue metabarcoding, which resulted in a feasible, efficient alternative to morphological methods.
- We compared water samples to bulk tissue metabarcoding for fish larvae communities. Both sample types detected a core of 12 taxa, with an average agreement in detections of 75% at sampling site level. This demonstrates that eDNA metabarcoding provides a rapid and feasible monitoring method for the management of key taxa.
- We characterised molecular selection, recombination and regional differentiation at the MHC class I peptide binding region for the first time in wild-caught sea bass individuals, and demonstrated the potential of this marker to differentiate between regional populations of sea bass.

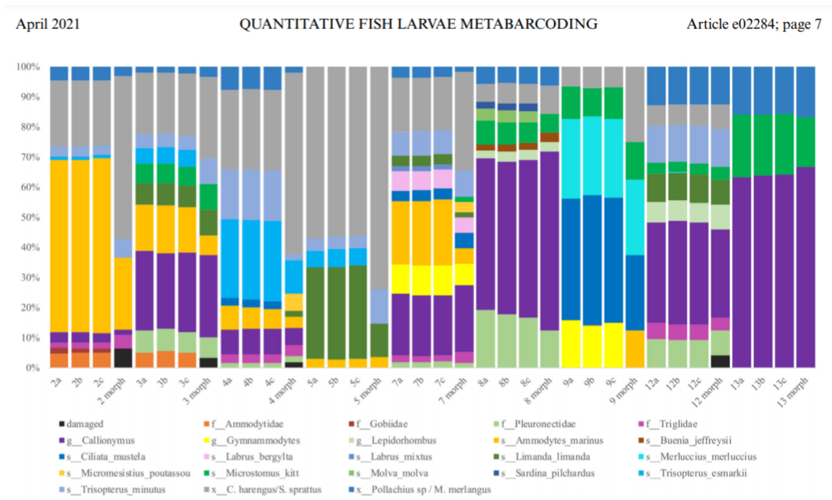


Figure 7: Comparison of relative read abundances (three replicates per haul, a, b, c samples) and morphological taxonomic assignments, corrected by Sanger sequencing ('morph' samples).

OUTPUTS:

Meetings: BlueFish bass research has been promoted at meetings with scientists and bass fishers on complementary projects (EMMF-funded projects Fisher-Scientist Project and Sea Bass Fisheries Conservation).

Conferences attended: FSBI conference, 2018: Poster presentation titled 'Adaptive responses of sea bass to environmental change'. FSBI conference, 2019: full length oral presentation titled 'Spatial distribution analysis of fish larvae in the Celtic and Irish seas using environmental DNA'. Environment Evidence, 2019 – Marine Evidence conference - Environment Platform Wales: full length oral presentation titled 'Rapid methods for quantitative fish larvae community assessment using metabarcoding'.

Coastal community engagement: Swansea Science Festival, 2019; Festival of Discovery (BU), 2019 - outreach events which introduced children and adults to the research being undertaken as part of the BlueFish project.

RESEARCH PUBLICATIONS

Ratcliffe, F.C., Uren Webster, T.M., Rodriguez-Barreto, D., O'Rorke, R., Garcia de Leaniz, C., Consuegra, S. (2021). Quantitative assessment of fish larvae community composition in spawning areas using metabarcoding of bulk samples. *Ecological Applications,* **31**(3). DOI: 10.1002/eap.2284

Ratcliffe, F.C., Uren Webster, T.M., Garcia de Leaniz, C., Consuegra, S. (2021). A drop in the ocean: Monitoring fish communities in spawning areas using environmental DNA. *Environmental DNA*, **3**(1), 43-54.

As part of acoustic monitoring, detections of fish from other acoustic tracking projects were recorded by the Marine Institute. This resulted in the MI being named as authors on the paper –

Davies, P., Britton, R.J., Nunn, A.D., Dodd, J.R., Crundwell, C., Velterop, R., **Ó'Maoiléidigh, N., O'Neill, R**., Sheehan, E.V., Stamp, T., Bolland, J.D. (2020). Novel insights into the marine phase and river fidelity of anadromous twaite shad *Alosa fallax* in the UK and Ireland. *Aquatic Conservation*, **30**(7), 1291-1298. DOI: 10.1002/aqc.3343

In prep:

Ian McCarthy (BU) is currently preparing two papers based on the stable isotope and spawning location work.

The Marine Institute is currently preparing two papers based on the potential effects of climate change on estuary habitat usage by European sea bass and also on the movement behaviour of tagged sea bass along the Irish coast.

ACTIVITY 3.3 SHELLFISH SEED

PARTICIPANTS: P Daly, T O'Carroll, B Dallaghan, R Browne, A Andrews, J Gallagher (BIM); PW Shaw, I Skujina, NJ McKeown (AU); S Albuixech Marti, G Kett (UCC); P Robins (BU)

AIMS:

1. To map shellfish beds (mussels) through surveys and existing data (BIM, BU).
2. To undertake predictive modelling (3D particle track) of planktonic larval movement linking to WP5 (BU, BIM).
3. To identify and assess site-specific environmental parameters, anthropogenic impacts, and biological factors that influence mussel reproduction, zooplankton dispersal, and seed performance (BIM, BU, UCC).
4. To undertake a genetic study to see relatedness of mussel populations, assessing larvae and spat (pre- and post-settlement) (AU, BIM).
5. To disseminate this information to Irish and Welsh SMEs and stakeholders via reports, workshops, a dedicated website, and the linked websites of BIM and others.

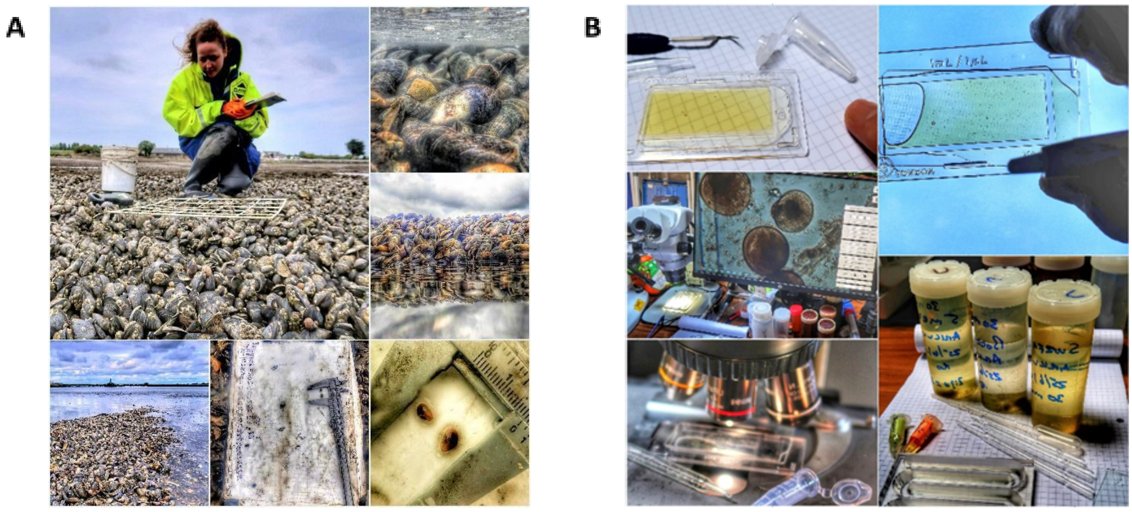


Figure 1: A) Mussel mapping. B) Microscopic examination of bivalve larvae.

MAIN ACHIEVEMENTS:

1. Over several years we mapped and measured the mussel population structure of different intertidal mussel beds along the Irish Sea (Figure 1a).
2. We undertook larval monitoring. Zooplankton samples were collected by pumping at discrete depths in Wexford, Arklow and Malahide (Figure 1b).
3. Bivalve larval samples were collected throughout the year at various geographical locations. The resultant larvae were microscopically examined for size, and a selection were isolated for genetic analysis by AU.
4. Mussel larvae, reared at the Bantry Research Station under different temperature, salinity and pH regimes, were assessed to gauge the impacts of these treatments.

5. Drogue studies (three drogue releases and recoveries) assessed the potential movement of mussel larvae. Two drogues journeyed to the UK, while one navigated its way around the Isle of Man, making its way to Drogheda.
6. Spat collectors were deployed in three embayments and monitored for settlement. There was only limited recruitment witnessed on one intertidal collector.
7. Condition Index (monitored at Rogerstown, Malahide and Dun Laoghaire) and Gonad Index measurements were collected. A report on gonad development has been produced along with the preparation of micrographs.
8. Physicochemical measurements were recorded where larvae were collected and counted at different depths (1, 5 & 10m).
9. Historical and current environmental information relevant to the project was collated.
10. Technical reports were produced and stakeholder engagement was undertaken.

Figure 2: BlueFish Shellfish Seed

RECOMMENDATIONS:

1. Promote the success of intertidal mussel populations by enhancing recruitment through active management where needed.
2. Study the ecology of intertidal substrates where mussel settlement occurs to assess methodologies for improving their resilience to climate change impacts and encouraging biodiversity.
3. Enhance the potency of mussel larvae and their retention in embayments in order to improve recruitment.
4. Improve early-stage predator protection of settled spat.
5. Monitor and evaluate mature intertidal mussel beds annually to establish their health and any changes. These mussels are essential for the stability of the environment and the success of other organisms.
6. Establish and document localised anthropogenic impacts on shellfish stocks and seek to manage them appropriately.
7. Improve the understanding of mussel larval drift and recruitment by evaluating the significance of different geographically dispersed broodstock populations.
8. Investigate the potential of natural shellfish beds to mitigate CO_2 levels.

OUTPUTS:

Meetings: Included: Climate change conference, Rorvik, Norway, 2019; Integrate (Multi trophic Aquaculture), NUI Galway, Ireland, 2019; BlueFish Science Meeting, Aberystwyth, UK, 2019.

In addition, we reported to regional and technical BIM staff about findings and opportunities.

Coastal community engagement: Stakeholder meeting on the BlueFish project work and objectives, BIM, Regional Fisheries Centre, Castletownbere, Ireland, 2018; Coffee shop talk on the BlueFish project work, Westport, Co. Mayo, Ireland; Lunch and Learn, BIM, Dun Laoghaire, Co. Dublin, Ireland, 2019.

ACTIVITY 4.1 INVASIVE SPECIES

PARTICIPANTS: KE Costello, G Kett, SA Lynch, R McAllen, RM O' Riordan, SC Culloty (UCC); EA Quinn, S Malkin, AF Rowley, CJ Coates (SU)

AIMS:

1. Carry out a desk study on the importance of marine bivalves in invasive host-parasite introductions and review invasive species currently present in the Irish Sea region.
2. Investigate the role of invasive tunicates/sea squirts as reservoirs of molluscan pathogens.
3. Identify regional differences in zooplankton-associated bacterial communities and aquaculture pathogens across two shelf seas (Irish and Celtic).
4. Assess the potential for invasive species introductions/prevention and secondary spread using vessel movements in maritime ports in the Irish and Celtic Seas.
5. Conduct a desk-based study on the disease ecology of the invasive slipper limpet, *Crepidula fornicata.*
6. Determine the pathogens/parasites associated with *C. fornicata* across two sites in Wales, one important for native oyster restoration (Swansea Bay) and one for commercial activity (Milford Haven).

MAIN ACHIEVEMENTS:

1. Both desk studies on the role of marine bivalves in invasive host-parasite introductions and on pathogen/parasite diversity, prevalence and disease ecology in *C. fornicata*, have been completed at UCC and at SU, respectively.
2. Field surveys have been carried out by both partners to (a) assess the role of tunicates as reservoirs of infection, and (b) identify the pathogens/parasites of *C. fornicata*.
3. Offshore plankton sampling with the Celtic Voyager and bacteria-zooplankton bioinformatic analyses have been completed.
4. A meta-analysis of shipping data to assess potential routes of entry of invasive species to Irish ports and the Irish Sea region has been carried out.
5. Identification of key factors attributed to the invasion success of *C. fornicata* in the region has been carried out.

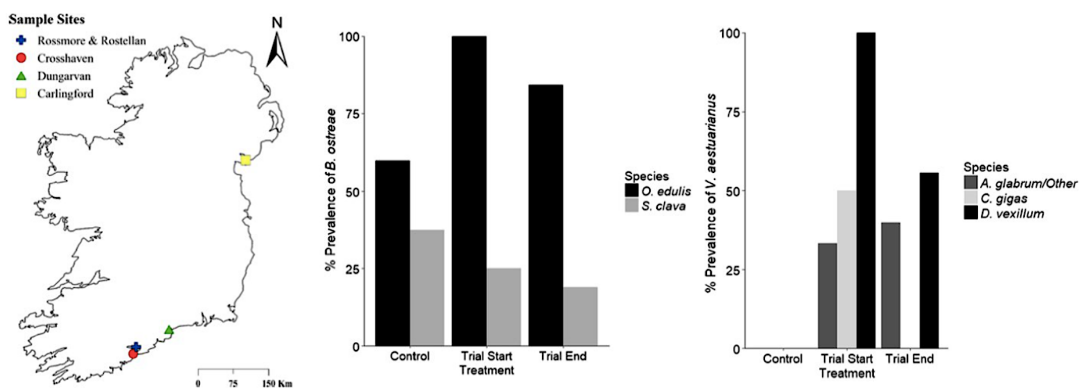


Figure 1: The role of invasive tunicate/ sea squirt species as carriers/ reservoirs of molluscan pathogen groups.

KEY FINDINGS:

1. Movement of farmed shellfish stocks enables invasive species and their associated parasites to move and subsequently colonise further sites.
2. Invasive species can maintain pathogens that impact commercial bivalves including flat oysters, Pacific oysters (Figure 1), and cockles.
3. Nearshore meteorological extremes (e.g. marine heatwaves due to climate change) may have an impact on larval settlement, establishment, and subsequent reproductive output of certain invasive species.
4. Distinct microbial communities associated with zooplankton in the Irish and Celtic Sea regions have been identified. This information may be used to determine the potential for pathogen dispersal in these areas and facilitate efficient site selection for future bivalve culture sites, both nearshore and offshore.
5. High connectivity observed in shipping routes between Ireland and international ports in which particular invasive species are confirmed, suggesting that preparation for their arrival is warranted. The potential for secondary spread of invasive species is high.
6. A multi-resource screen of 1,800 slipper limpets revealed a lack of susceptibility to bacteriosis, and the absence of *Vibrio* bacteria known to be pathogenic to humans and commercial shellfish.

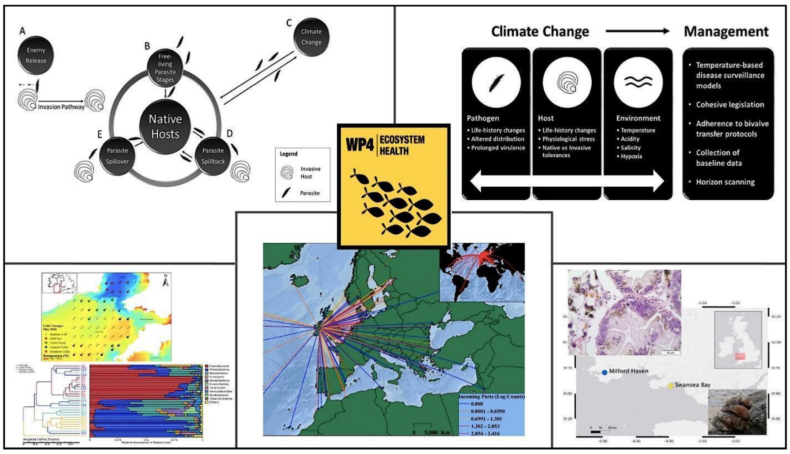


Figure 2: Infographic providing an overview of the findings of WP 4.1 'Invasive Species'.

OUTPUTS:

Meetings: European Association of Fish Pathologists (EAFP) 3rd UK and Ireland Branch meeting, EAFP international meeting, Wales Ecology and Evolution Network, 2019.

Coastal community engagement: Seafest, 2018 and 2019; Swansea Science Festivals, 2018 & 2019.

RESEARCH PUBLICATIONS:

Costello K.E., Lynch S.A., McAllen R., O'Riordan R.M., Culloty S.C. (2021). The importance of marine bivalves in invasive host-parasite introductions. *Frontiers in Marine Science* **8**, 609248.

Costello K.E., Lynch S.A., McAllen R., O'Riordan R.M., Culloty S.C. (2021). The role of invasive tunicates as reservoirs of molluscan pathogens. *Biological Invasions* **23**, 641-655.

Lynch S.A., Coughlan A., O' Leary B., Morgan E., Culloty S.C. (2020). Northward establishment of the Mediterranean mussel *Mytilus galloprovincialis* limited by changing climate. *Biological invasions* **22**, 2725–2736.

Lynch S.A., Lepée-Rivero S., Kelly R., **Quinn E**., Coghlan A., Bookelaar B., Morgan E., Finarelli J.A., Carlsson J., **Culloty S.C**. (2020). Detection of haplosporidian protistan parasites supports an increase to their known diversity, geographic range and bivalve host specificity. *Parasitology* **147**, 584-592.

O'Riordan R.M., Culloty S.C., McAllen R., Gallagher M.C. (2020). The biology of *Austrominius modestus* (Darwin) in its native and invasive range. *Oceanography and Marine Biology: An Annual Review* **58**, 1-7.

Quinn E.A., Malkin S.H., Rowley A.F., Coates C.J. (2020). Laccase and catecholoxidase activities contribute to innate immunity in slipper limpets, *Crepidula fornicata. Developmental & Comparative Immunology* **110**, 103724.

ACTIVITY 4.2 COCKLE HEALTH

PARTICIPANTS: JE Ironside, I Skujina (AU), S Marti Albuixech, SA Lynch, SC Culloty (UCC)

AIMS:

1. Assess the diversity, prevalence, and distribution of parasites in Irish Sea cockles.
2. Determine if parasite/pathogen species co-occur in cockles and what factors drive or inhibit parasite/pathogen assemblages.
3. Investigate potential for transmission of parasites and pathogens between cockles and birds.

MAIN ACHIEVEMENTS:

1. A novel parasite of the cockle *Cerastoderma edule* was discovered and named *Marteilia cocosarum* (Skujina et al. 2021). This parasite is widespread in Wales but was not detected in Ireland (Fig. 1). It is closely related to *Marteilia cochilia*, a parasite associated with mass mortality of cockles in Spain.
2. The roles of biological, environmental and anthropogenic factors in parasite/pathogen distribution and coinfection in *C. edule* throughout the year were analysed. A novel geographical range of two haplosporidian species, *Minchinia tapetis* and a *Minchinia mercenariae*-like parasite in *C. edule* was detected along the Irish and Celtic Seas, showing a positive two-way association between these species (Fig. 2).
3. Identical strains of *Vibrio splendidus* were found in *C. edule* and shorebird faecal samples (Fig. 3), suggesting that shorebird consumption of local cockles could act as a potential source or mode of transmission of this *Vibrio* species.
4. We recommend monitoring of *Vibrio* spp. to assess the impact of climate change impacts on *Vibrio* and cockle interactions.

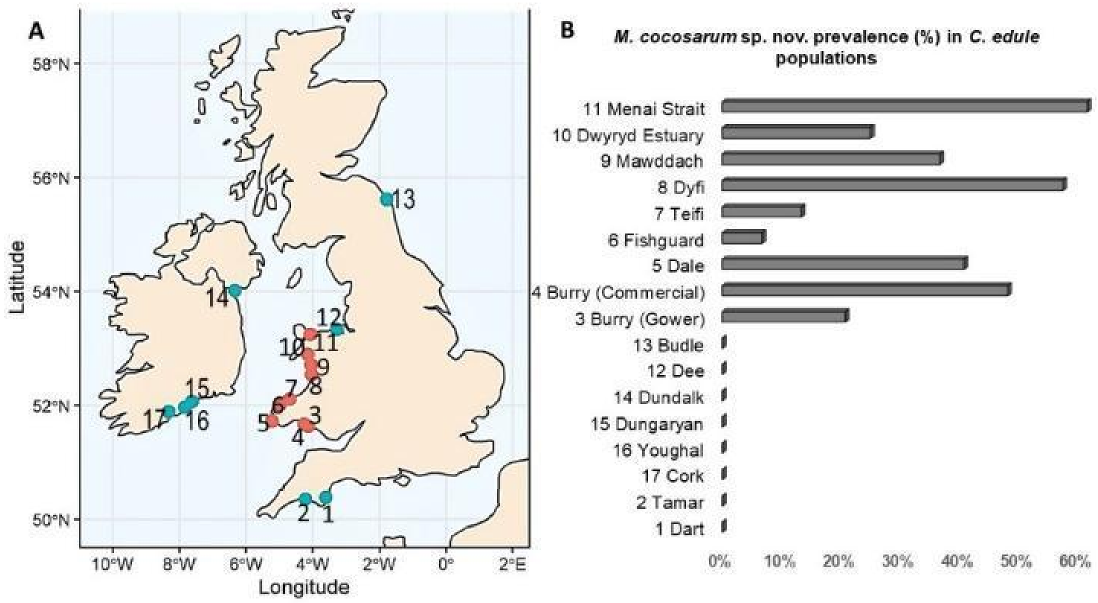


Figure 1: Distribution (A) and prevalence (B) of *Marteilia cocosarum* in *C. edule* populations.

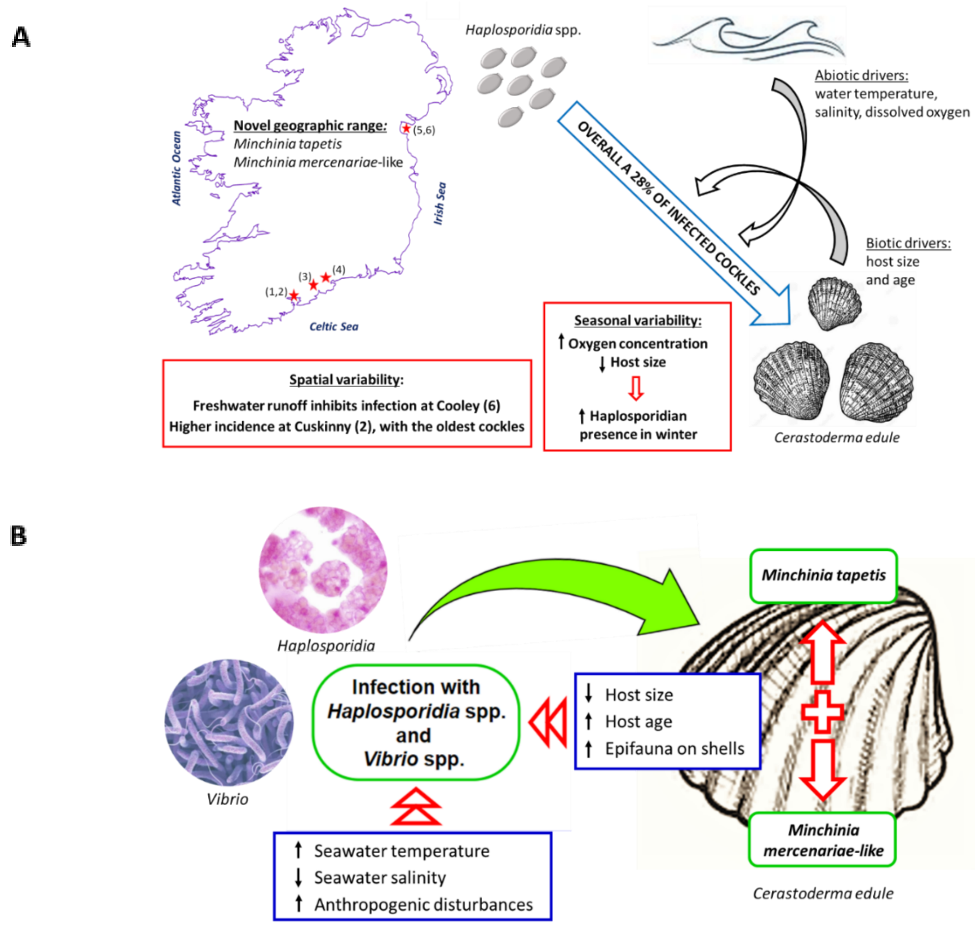


FIgure 2: Factors driving (A) distribution and (B) co-occurrence of two haplosporidian parasite species in *C. edule* in Ireland.

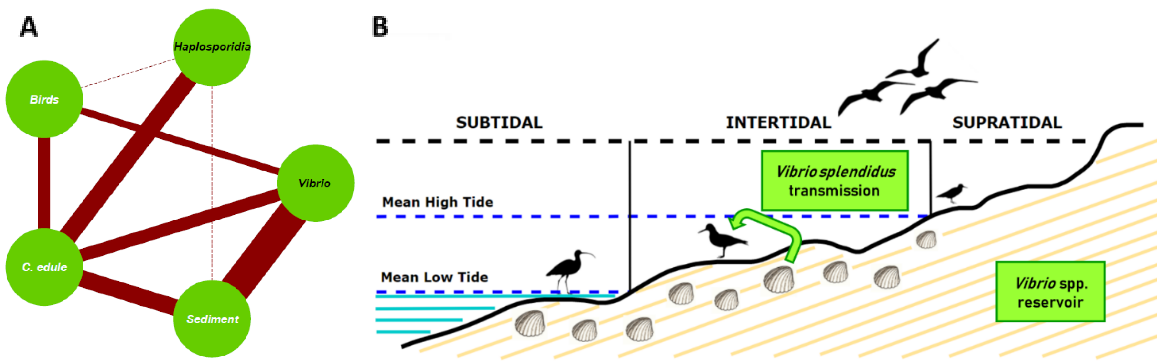


Figure 3: Parasite/pathogen transmission between cockles and birds: (A) Network association plot displaying the links between *C. edule*, shorebirds and sediment; (B) *Vibrio* transmission between sediment, *C. edule*, and their shorebird consumers in the tidal zone.

OUTPUTS:

Meetings: Oral presentations at: Aquaculture Europe 2020 (online); Irish Society for Parasitology Annual Meeting 2021; 3rd Ecology and Evolution Ireland Conference, Irish Ecological Association, 2021; Environ 2020 "Ireland's Water, Energy & Environment in a Climate & Biodiversity Emergency"; 19th European Association of Fish Pathologists Meeting 2019; 52nd Annual Meeting of the Society for Invertebrate Pathology 2019; European Association of Fish Pathologists UK & Ireland Branches Third Meeting "Connecting Academia with Industry for Improved Aquatic Animal Health" 2018.

Coastal community engagement: SeaFest Ireland's national maritime festival, 2019 and 2018; Native Scientist outreach activity aimed at promoting STEM and language education among school pupils, 2018.

RESEARCH PAPERS PUBLISHED

Albuixech-Marti, S., Lynch, S.A. & Culloty, S.C. (2020). Biotic and abiotic factors influencing haplosporidian species distribution in the cockle *Cerastoderma edule* in Ireland. *Journal of invertebrate pathology.* **174**, 107425. DOI: 10.1016/j.jip.2020.107425

Skujina, I., Hooper, C., Bass, D., Feist, S. W., Villalba, A., Carballa, M. J., Iglesias, D., Cao, A., Ward, G.M., Ryder, D.R.G., Bignell, J.P., Kerr, R., Macariea, N.A., Prentice, M., King, N., Thorpe, J., Malham, S.K., McKeown, N.J., Ironside, J.E. (2021). Discovery of the parasite *Marteilia cocosarum* sp. nov. in common cockle (*Cerastoderma edule*) fisheries in Wales, UK and its comparison with *Marteilia cochillia*. Submitted to *Journal of invertebrate pathology*

ACTIVITY 4.3 DISEASE CONNECTIVITY

PARTICIPANTS: CJ Coates, AF Rowley, FM Batista, CE Davies, JE Thomas, S Malkin, H Emery (SU); SA Lynch, SC Culloty (UCC); SK Malham (BU)

AIMS: To determine where the reservoirs of shellfish diseases in the Celtic and Irish Seas are found. In particular:

1. To develop methods to study disease agents in both host and environment.
2. To assess the potential role of shore crabs *Carcinus maenas* in harbouring pathogens of other shellfish including crustaceans of commercial interest (e.g., edible crabs *Cancer pagurus*).
3. To examine the temporal distribution of 'molecular signatures' of pathogens and parasites of molluscs and crustaceans in the water column.

MAIN ACHIEVEMENTS:

1. Shore crabs harbour a wide range of parasites and pathogens including *Hematodinium* (an important disease-causing agent of crustaceans worldwide), fungi, *Sacculina*, and bacteria including Vibrio species (Davies et al. 2019, 2020a; Rowley et al. 2020; Edwards et al. 2019; **Figure 1A-D; Figure 2**).
2. We discovered two novel parasites of shore crabs and named these *Haplosporidium carcini* and *H. cranc* (after the Welsh for crab) (Davies et al. 2020b; **Figure 1E**).
3. We successfully developed methods to look for molecular signals of pathogens of shellfish (crustaceans and molluscs) in the environment and hence to predict how diseases are spread (to be published).
4. We recommend the need for long term datasets of disease prevalence in crustaceans and molluscs to understand how climate change will affect both hosts and pathogens.

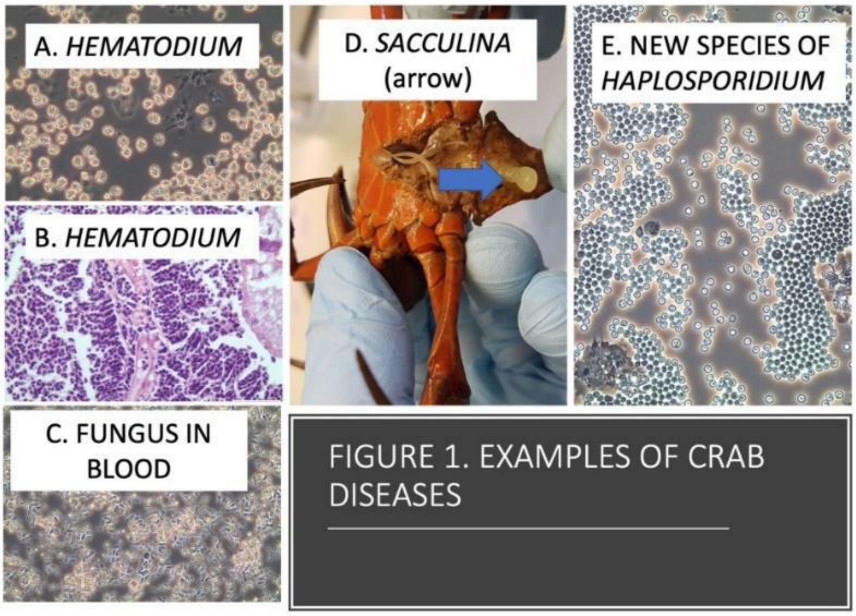


Figure 1: Examples of crab diseases

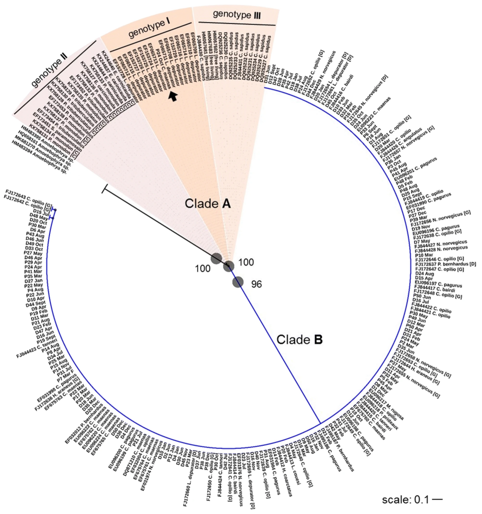


Figure 2: Consensus phylogram of the ITS1 and partial 18S rRNA gene regions from *Hematodinium*-infected crustaceans (maximum likelihood estimation, 1000 bootstrap replicates). Sequences from *Hematodinium*-positive crabs from every month of the year-long survey are distributed within Clade B, thereby suggesting that the parasite most likely infecting shore crabs in our samples is the generalist *Hematodinium* sp. found in other commercial species in the Celtic and Irish seas including edible crabs. (From Davies et al. 2019).

OUTPUTS:

Media: Examples include: 2020: Charlotte Davies interviewed by ITV Coastal and Country about Bluefish (@itvcoastcountry); 2018: Research As Art - Swansea University winner exhibited in London and Texas, USA (>40,000 views online).

Meetings: Including: 19th Int. Conference on Diseases of Fish and Shellfish, Porto, 2019; Joint ARCH-UK & BLUEFISH meeting attended by industry and government bodies, Fishmongers' Hall, London, 2018.

Coastal community engagement: Swansea Science Festival 2018 & 2019 – Swansea University, Waterfront Museum, saw between 5-7,000 visitors each day; Super Science Sundays, touch-tank displays and community empowerment, e.g., local Beavers Scouts and invitations to schools.

Figure 3: Photographs of public engagement activities.

RESEARCH PAPERS PUBLISHED:

Davies, C.E., Batista, F.M., Malkin, S.H., Thomas, J.E., Bryan, C.C., Crocombe, P., **Coates, C.J., Rowley, A.F**. (2019). Spatial and temporal disease dynamics of the parasite *Hematodinium* sp. in shore crabs, *Carcinus maenas*. *Parasites & Vectors* **12**, 472. DOI: 10.1186/s13071-019-3727-x

Edwards, M., **Coates, C.J., Rowley, A.F**. (2019). Host range of the mikrocytid parasite *Paramikrocytos canceri* in decapod crustaceans. *Pathogens* **8**, 252. DOI: 10.3390/pathogens8040252

Davies, C.E., Malkin, S.H., Thomas, J.E., Batista, F.M., Rowley, A.F., Coates, C.J. (2020a). Mycosis Is a disease state encountered rarely in shore crabs, *Carcinus maenas*. *Pathogens* **9**, 462. DOI: 10.3390/pathogens9060462

Davies, C.E., Bass, D., Ward, G.M., **Batista, F.M., Malkin, S.H., Thomas, J.E**., Bateman, K., Feist, S.W., **Coates, C.J.**, **Rowley, A.F**. (2020b). Diagnosis and prevalence of two new species of haplosporidians infecting shore crabs *Carcinus maenas*: *Haplosporidium carcini* n. sp., and *H. cranc* n. sp. *Parasitology* **147**, 1229-1237. DOI: 10.1017/S0031182020000980

Rowley, A.F., Davies, C.E., Malkin, S.H., Bryan, C.C., Thomas, J.E., Batista, F.M., Coates, C.J. (2020). Prevalence and histopathology of the parasitic barnacle, *Sacculina carcini* in shore crabs, *Carcinus maenas. Journal of Invertebrate Pathology* **171**, 107338. DOI: 10.1016/j.jip.2020.107338

Coates, C.J., Söderhäll, K. (2020). The stress-immunity axis in shellfish. *Journal of Invertebrate Pathology* 107492. DOI: 10.1016/j.jip.2020.107492

Coates, C.J., Rowley, A.F., Whitten, M.M.A. (2021). Host defences of invertebrates to pathogens and parasites. In: **Rowley, A.F., Coates, C.J.**, Whitten, M.M.A. *Invertebrate Pathology*, Oxford University Press (in press).

Coates, C.J. (2021). Host defences of invertebrates to non-communicable disease. In: **Rowley, A.F., Coates, C.J.**, Whitten, M.M.A. *Invertebrate Pathology*, Oxford University Press (in press).

Bass, D., **Rowley, A.F., Coates, C.J. (2021).** Diagnostic approaches in invertebrate pathology. In: **Rowley, A.F., Coates, C.J.**, Whitten, M.M.A. *Invertebrate Pathology*, Oxford University Press (in press).

Lynch, S.A., Rowley, A.F., Longshaw, M., **Malham, S.K**., **Culloty, S.C**. (2021). Diseases of molluscs. In: **Rowley, A.F., Coates, C.J.**, Whitten, M.M.A. *Invertebrate Pathology*, Oxford University Press (in press).

Rowley, A.F. (2021). Bacterial diseases of crustaceans. In: **Rowley, A.F., Coates, C.J.** and Whitten, M.M.A. *Invertebrate Pathology*, Oxford University Press (in press).

ACTIVITY 4.4 EMERGING PATHOGENS IN THE IRISH SEA

Participants: NG King, SK Malham, J Thorpe (BU); R Browne (BIM); NJ McKeown, I Skujina (AU)

AIMS: Characterise emerging pathogens of human and shellfish health in the Irish Sea. In particular:
1. Quantify *Vibrio* occurrence and abundance at shellfish farms in the Irish Sea.
2. Scan farms for known pathogenic species of *Vibrio* of concern for both human and animal health.
3. Characterise offshore dynamics of *Vibrio* and bacteria more generally in the Irish Sea.

MAIN ACHIEVEMENTS:
1. *Vibrio* displayed clear summer and winter blooms in shellfish farms (Figure 1).
2. Up to 50% Pacific oyster mortalities were observed in Dungarvan Bay in summer 2019, which coincided with elevated nutrients and high seawater temperatures (Figure 2).
3. The oyster pathogen *Vibrio aestuarianus* was found during this event and was likely the disease-causing agent responsible for the observed mortalities.
4. No *Vibrio* pathogens of human health concern (*V. parahaemolyticus, V. vulnificus* and *V. alginolyticus*) were found in any samples.
5. Offshore research cruises identified zooplankton as a clear offshore vector of *Vibrio* in the Irish Sea (Figure 3).

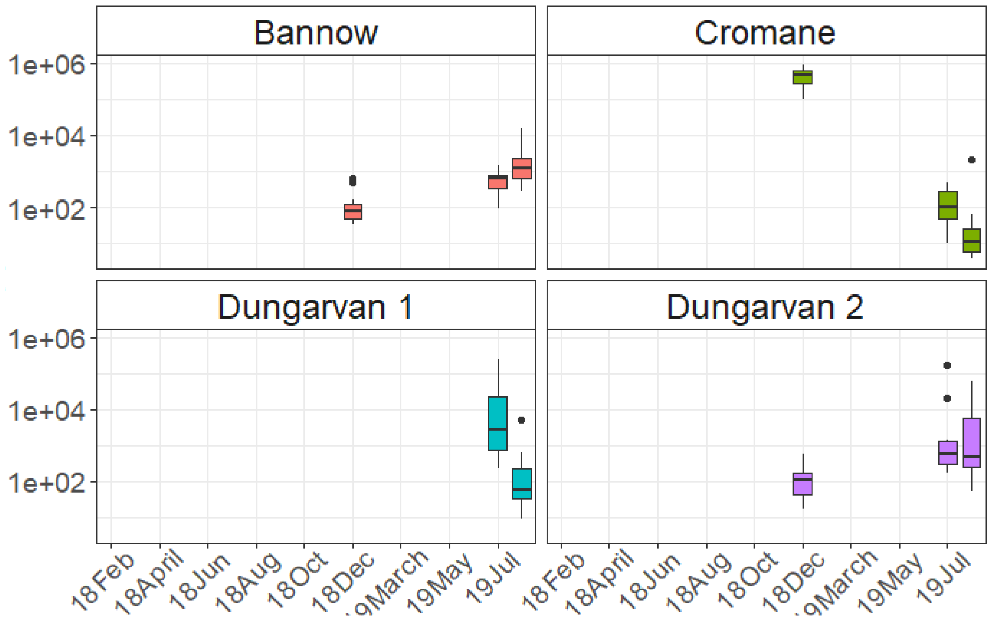


Figure 1: Abundance (copy number) of *Vibrio* bacteria in Pacific oyster, *C. gigas*, tissue in oyster farms in the Irish Sea.

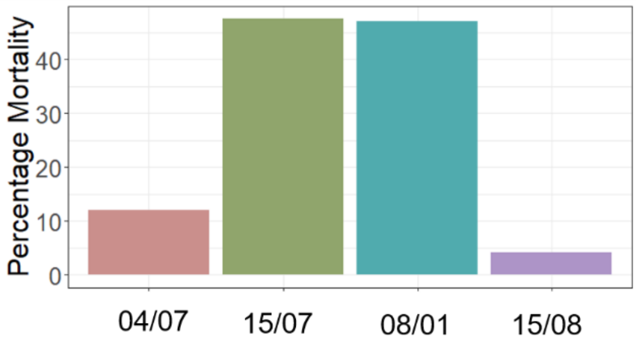


Figure 2 Percentage mortalities of Pacific oysters at Dungarvan Bay in 2019 (left) and photo (credit, Ronan Browne BIM) of algal blooms on oyster trestles during the same period (right).

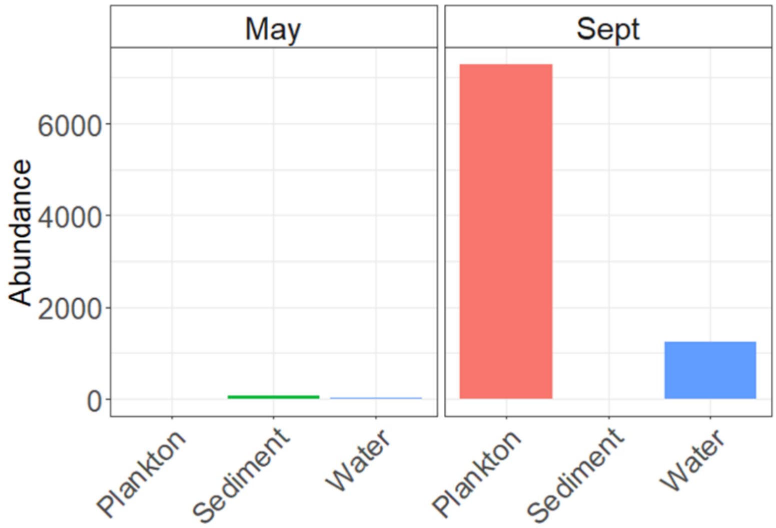


Figure 3: Vibrio abundance associated with environmental sample type in offshore sites in the Irish Sea.

RECOMMENDATIONS:

1. Managing local point stressors such as nutrient loading may be effective in reducing mortalities of oysters as climate change advances.
2. Monitoring zooplankton for *Vibrio* may serve as an effective early warning system for future monitoring programmes.

OUTPUTS:

Meetings:

Shellfish Association of Great Britain annual meeting, 2019 – "Vibrio, shellfish and climate change"
NAEMO meeting, Oban, 2020 – "Climate change and its impacts on shellfish health and distributions".

Coastal community engagement: Festival of Discovery, 2019

RESEARCH PUBLICATIONS

King et al., *in prep*. Vibrio blooms and mortalities of Pacific oysters in the Irish Sea.
King et al., *in prep.* Shallow sea front drives selection in seawater bacterial communities.
King et al., *in prep.* Characterising spatial and temporal variation in oyster microbiomes.
King et al., *in prep.* Marine heatwave and nutrient loading impacts on oyster microbiome communities.

ACTIVITY 5.1 MODELS AND SCENARIOS

PARTICIPANTS: PW Shaw, NJ McKeown, I Skujina (AU); P Robins, SB Wilmes (BU)

AIMS: to use ecological niche modelling of species distributions and 3D particle modelling of individual (adult or early life history stage) dispersal to assess how species distributions and dispersal dynamics may change, and how connectivity between populations of the same species may change, in response to changing environments. In particular:

1. Optimisation of ecological niche models for application to Bluefish target species (seabass, scallop, blue mussel, brown crab).
2. Incorporation of existing Met Office (and other) models, and development of a novel Irish/Celtic Sea–specific 3D oceanographic model, for particle tracking studies of species dispersal within the Irish Sea, Celtic Sea and interacting neighbouring areas, utilising species-specific propagule data.
3. Generate novel data on genetic connectivity of target species (seabass, scallop, blue mussel) to assess present realised connectivity among populations within the Irish and Celtic Seas.

MAIN ACHIEVEMENTS:

1. Target species distribution changes in relation to future climate scenarios were tested using both traditional (Maxent) and novel (Mahalanobis distance) approaches to distribution modelling. Three broad patterns of species response to predicted changes in environmental conditions over the next 80 years (2020-2100) were observed:
   1 – No substantial change, with both distribution and abundance in UK waters remaining similar (e.g. blue mussel *Mytilus edulis* – see Fig.1);
   2 – No change in spatial distribution but a reduction in abundance in UK waters, particularly southern Irish Sea and Celtic Sea, suggesting a decline in suitable habitat (e.g. cockle *Cerastoderma edule*, scallop *Pecten maximus* (see Fig.1), brown crab *Cancer pagurus*, lobster *Homarus gammarus*);
   3 – Change in species distribution (shifting north), with either the species becoming less abundant / absent in SW UK waters, including the Irish Sea (e.g. seabass *Dicentrarchus labrax*), or becoming more widespread and abundant in UK waters (e.g. Mediterranean mussel *Mytilus galloprovincialis* – see Fig.1)
2. Ocean models were either developed or acquired: (1) Met Office AMM15 3D model; (2) Met Office AMM7 UKCP18 climate model; (3) BU ROMS 3D ocean model; (4) Telemac unstructured-grid 2D coastal models developed for north Wales and southern Ireland. Models provided 2D and 3D simulated ocean velocities to drive Particle Tracking Models (in Python and Matlab programmes) that simulate larval transport. Models fitted closely with observational data and simulated drifter trajectories.
3. Species larval dispersal throughout the Irish and Celtic Seas was simulated for a subset of 7 years (2008-2014). The influence of larval behaviour (i.e. fixed depth in the water column) on dispersal was evaluated, and connectivities examined between known populations. The influence of the seasonal/interannual development of the Celtic Sea tidal mixing front was also evaluated, given the front can act as a barrier to larvae between the Irish and Celtic Seas. Potential future changes in larval dispersal were evaluated using Met Office AMM7 projections (2000 -2099), focusing especially on likely changes in frontal structure (e.g. the Celtic Sea Front, which is a key driver in cross-shelf dispersal). Present-day and future sea surface temperature variability (AMM7 UKCP18) were compared to evaluate the likelihood of shifts in species distributions, as well as the potential future viability of shellfish farming in the UK.

4. Genetic data were collected for three Bluefish target species (mussel, scallop, seabass) to assess distribution of genetic diversity and levels of reproductive connectivity among geographical areas, which could be related to predicted habitat suitability and species dispersal assessed by hydrographic models. Results demonstrated that in each case, species-specific interactions of species biology, dispersal, habitat suitability, and response to area-specific hydrographic conditions produced population structures that could not be predicted by any one approach. For example, traditional species-specific genetic markers indicate that mussel populations around SW Ireland / UK comprise a mix of *M.edulis*, *M.galloprovincialis* and ME/MG hybrids, whereas populations in the Irish Sea are almost exclusively pure *M. edulis* (see Fig.2A), which conforms with a degree of hydrographic isolation. However, genetic tests using a new combination of mtDNA and nDNA genetic markers show that mussel populations in the Irish Sea show genotypic profiles shared with ME, MG and ME/MG hybrids in southwestern waters, and a lack of genetic structuring throughout the region (see Fig.2B&C), indicating substantial gene flow between the Irish Sea and surrounding waters, and genetic mixing of the two species. This suggests that climate change will not lead to a gradual replacement of the blue mussel by the Mediterranean mussel, across this area, but more likely will increase mixing of the two species. By contrast, scallop populations display extensive gene flow across the area (Fig.3A&B), but also display evidence of fine-scale genetic patchiness owing to ephemeral recruitment processes and potential larval cohesion (clusters in Fig.3C), possibly related to annual shifts in the position and strength of the Celtic Sea Front. While such recruitment processes may drive fine-scale spatial/temporal shifts in genetic composition, this is occurring against a pattern of high connectivity which confers robustness on intergenerational scales.
5. Overall, the data for sea bass, scallop, and mussels, highlight that stock connectivity transcends geopolitical boundaries and confirm that these resources require cross-border management. We recommend that longer-term datasets are collected for these and other exploited species in the Irish Sea, to ascertain source-sink dynamics of stocks and consequently identify important seed source areas that can be prioritised for protection and management.

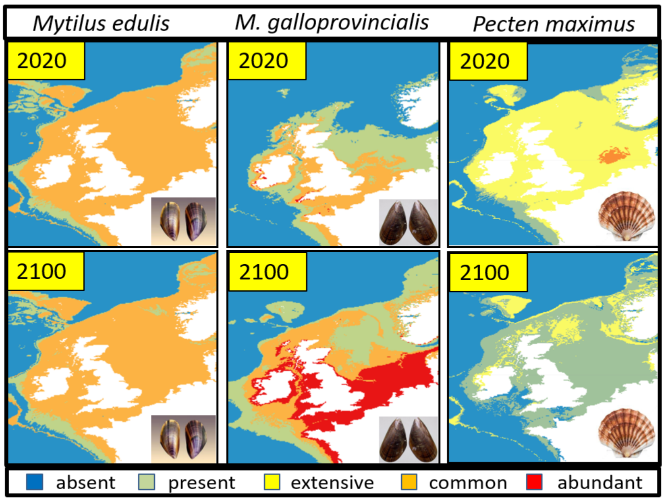


Figure 1: Predicted changes in habitat suitability, and resulting potential changes to distribution and abundance (from unsuitable = species absent; to highly suitable = species abundant), in UK waters for three target species (blue mussel *Mytilus edulis,* Mediterranean mussel *Mytilus galloprovincialis*, and king scallop *Pecten maximus*), illustrating different patterns of response to changes to sea surface temperatures and habitat conditions from 2020 to 2100.

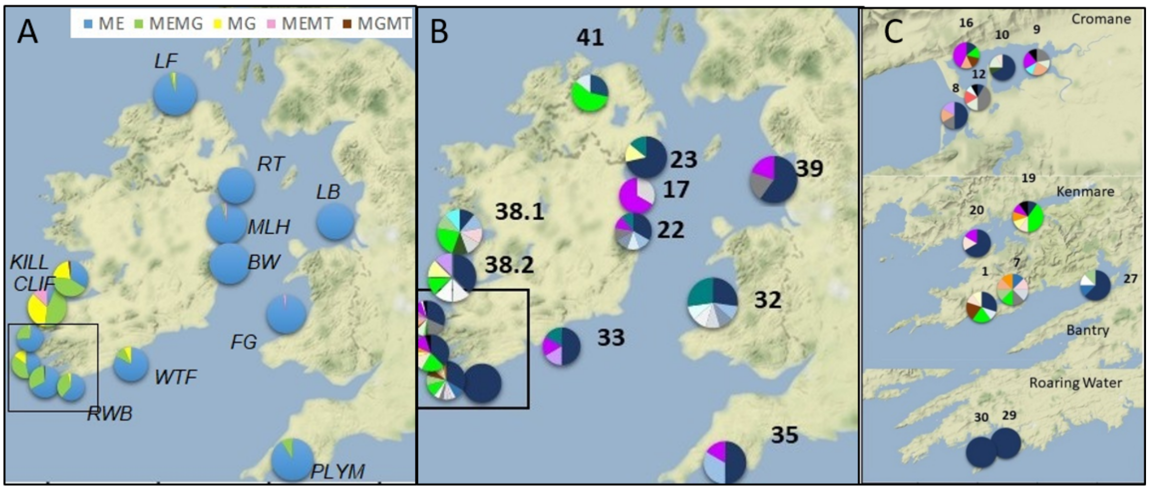


Figure 2: Genetic population structure of mussels in the Irish and Celtic Seas: A – distribution of pure *Mytilus edulis* (ME), *Mytilus galloprovincialis* (MG) and ME/MG hybrids; B - distribution of mtDNA COI haplotypes; C – distribution of mtDNA COI haplotypes within SW Ireland focus area on mussel aquaculture.

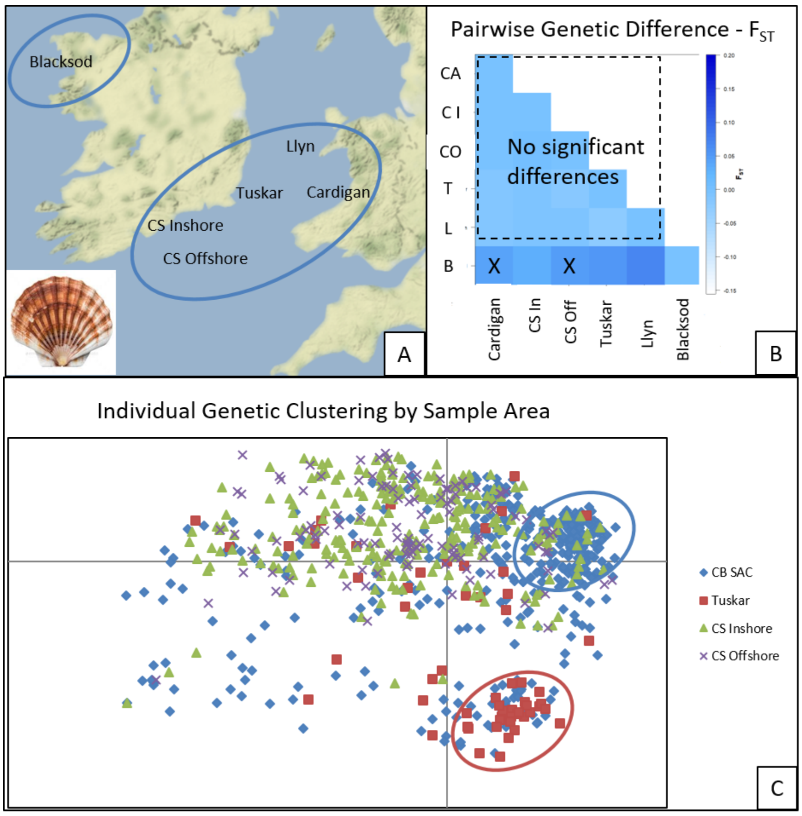


Figure 3: Genetic population structure of king scallop (*Pecten maximus*) in the Irish and Celtic Seas: (A) main scallop beds studied; (B) genetic differentiation among scallop beds tested using 11 nDNA microsatellites; (C) genetic clustering of individuals from scallop beds in southern Irish Sea and western Celtic Sea.

OUTPUTS:

Meetings: Including: "Ocean Sciences 2018", Portland, Oregon; 5th International Marine Connectivity Conference (iMarCo2019), Aveiro, Portugal, 2019; EGU meeting, Vienna, 2019; Joint ARCH-UK & BLUEFISH meeting, Fishmongers' Hall, London, 2018.

Coastal community engagement: Cardigan Bay Fisheries Local Action Group "Day on the Quay" events in Aberdyfi, Barmouth & Aberystwyth, 2018 & 2019 – touch tank and presentations to public; Europe Day outreach events in Aberystwyth & Bangor, 2018 & 2019.

Stakeholder engagement:

6-monthly meetings with, and advice provided to the Welsh Government Marine & Fisheries Section (2017-2021), and meetings with Welsh Government Chief Scientists Office (2019-2020); quarterly meetings with and information / advice provided to Cardigan Bay Fisheries Local Action Group (2017-2021).

Figure 4: Stakeholder engagement activities.

RESEARCH PAPERS PUBLISHED:

Atkinson, J., **King, N.G.**, **Wilmes, S.-B.**, Moore, P.J. (2020) Summer and Winter Marine Heatwaves Favour an Invasive Over Native Seaweeds. *Journal of Phycology*, **56**, 1591-1600.

Coscia, I., **Wilmes, S.B.**, **Ironside, J.E.**, Goward-Brown, A., O'Dea, E., Malham, S.K., McDevitt, A.D., **Robins, P.E.** (2020). Fine-scale seascape genomics of an exploited marine species, the common cockle *Cerastoderma edule*, using a multimodelling approach. *Evolutionary applications*, **13**(8), 1854-1867.

Hold, N., **Robins, P.**, **Szostek, C.**, Lambert, G., Lincoln, H., Le Vay, L., Bell, E., Kaiser, M. (2021). Using bio-physical modelling and population genetics for conservation and management of exploited species. *Fisheries Oceanography,* available online.

King, N.G., **Wilmes, S.-B.**, Smyth, D., Tinker, J., **Robins, P.E.**, **Thorpe, J.**, Jones, L., **Malham, S.K.** (2020). Climate change accelerates range expansion of the invasive non-native species, the Pacific oyster. *ICES Journal of Marine Science*, in press.

McKeown, N.J., Watson, H.V. ,Coscia, I., Wootton, E., Ironside, J.E. (2018). Genetic variation in Irish Sea brown crab (*Cancer pagurus L.*): implications for local and regional management. *Journal of the Marine Biological Association of the United Kingdom*, 1–8.

Wilmes, S.B., Perks, E., Winterbourne, B., **King, N., Malham, S**., **Robins, P.** Tidal effects on temperature extremes experienced by mussels. In preparation for submission to *Atmosphere*.

Wilmes, S.-B., Ward, S. L., Gimenez, L., O'Dea, E., Malham, S., Tinker, J., Robins, P. E. The role of a shelf sea front in determining shellfish population connectivity in the present day and future. In preparation for submission to *Limnology and Oceanography*.

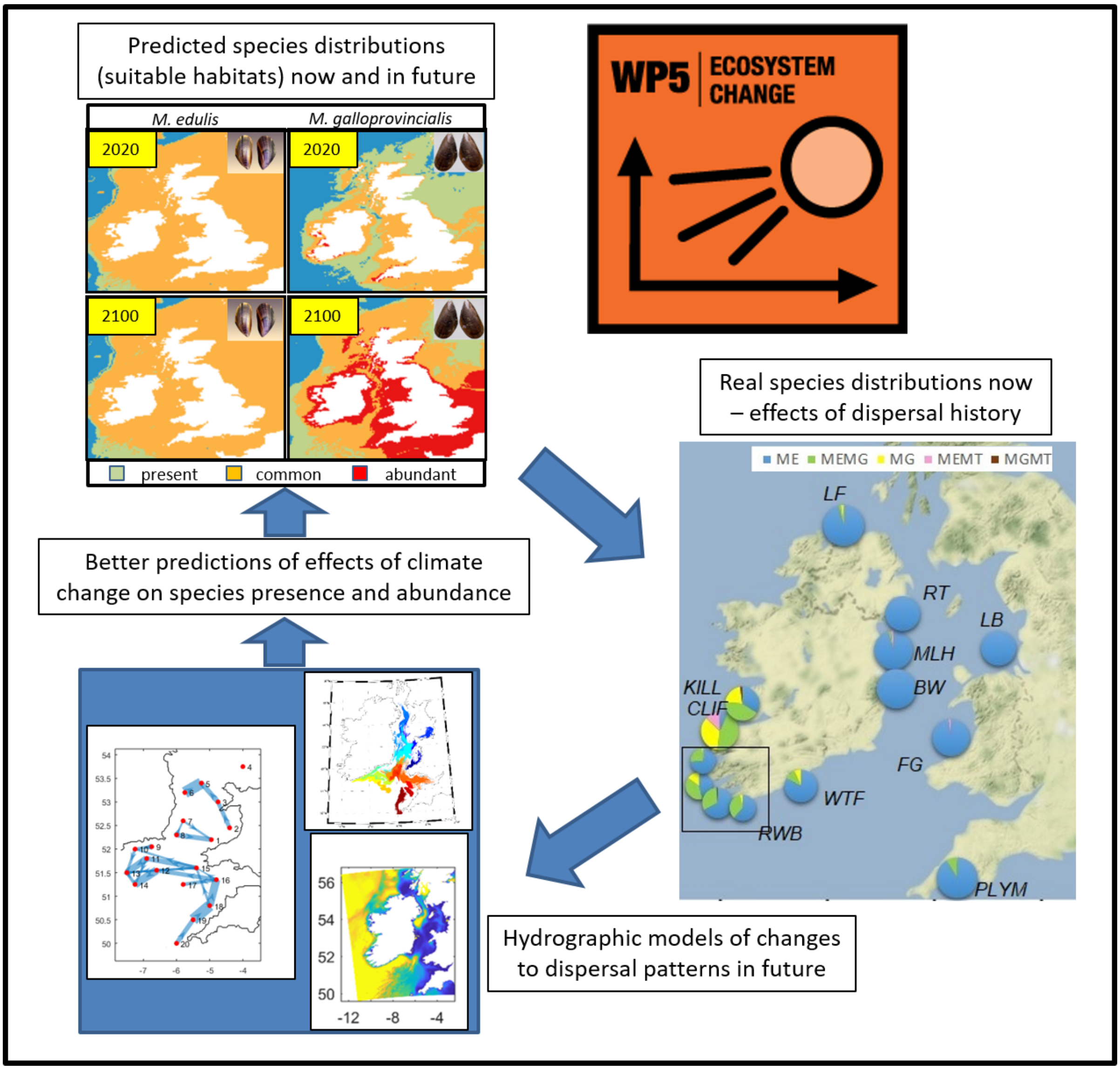


Figure 5: Infographic for WP5 Ecosystem Change: models and scenarios.

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