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Methods for studying coastal bivalves in a changing world:

A review and implications for management.

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Abstract

Anthropogenic activities such as pollution, CO_2 emission, and overfishing, are among leading reasons for global environmental change and negative impacts on the marine environment including loss of biodiversity. Marine bivalves are an example of species that suffers from such consequences while they have high value in both aquaculture and marine ecosystems. With the existence of many threats including overharvesting, invasive species, parasites, and diseases, coastal bivalves such as flat oysters (*Ostrea edulis*) and blue mussels (*Mytilus spp*) are in many places endangered. The existing knowledge gaps in the historic and current distribution, however, makes quantifying the effects of these threats difficult and conservation management challenging. With the global dispersal of the invasive Pacific oyster (*Crassostrea gigas*) which is perceived as a threat to many coastal ecosystems, it has become even more important to increase our knowledge of native species to be able to devise successful management strategies and safeguard their future existence. There are, for instance, no standardized protocols for designing and performing mapping and monitoring surveys of coastal bivalves in Scandinavia. To start filling these gaps a literature review was conducted to get an overview of field techniques used in surveys of coastal bivalves and evaluate which method is suitable for different study aims. In addition, a pilot study was carried out to test the reliability of remotely operated vehicle (ROV) for mapping occurrences of coastal bivalves. The bivalve studies were categorized in four main groups; 1) mapping current geographic distribution and detecting potential high-density areas, 2) finding their origin and determine connectivity between populations, 3) monitoring programmes for estimating population parameters such as recruitment, mortality, population density, size structure, and health status, and 4) studies focusing on predicting future distribution patterns. Fishing, manual surveys, and various types of video recording equipment are all common field techniques for collecting data on coastal bivalves. However, as expected, there is not any "one-size-fits-all" method that could be used in all types of surveys since each one has its advantage and disadvantages depending on habitat characteristics and study aims. Therefore, a flow chart was created to guide researchers and managers to choose the best suitable field technique based on environmental conditions. Missing metadata such as substrate and water depth in many studies impairs our ability to compare results between different surveys. Therefore, a protocol for monitoring and mapping surveys was developed to improve collaboration and data integration between managers and the scientific community. This will assist in the important development of increasing our efforts in terms of regular mapping and monitoring programmes of coastal bivalves to stay informed about their status in the marine ecosystem.

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Contents

1. Introduction

Biodiversity brings many benefits to our lives, including ecosystem functions and services that have a direct effect on humans' well-being (Isbell et al., 2017). However, according to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services anthropogenic activities like pollution (including eutrophication, marine plastics, etc.), overharvesting, and climate change are causing a massive decline in biodiversity inside of the marine environment (Worm et al., 2006, Gamfeldt et al., 2014). Losing species in the marine environment can decrease the productivity of the oceans it can also (Gamfeldt et al., 2014).

Coastal bivalves are highly beneficial for the marine ecosystem due to their useful functions such as filtering the water, stabilizing the shoreline, providing nursery grounds for other species, etc. (Windle et al., 2019). Bivalve aquaculture production has been increasing over the last decades and it has fewer environmental impacts than other aquaculture industries (Gallardi et al., 2014). Global bivalve production has a huge potential to become one of the main food sources for humans in the future (Gallardi et al., 2014). Additionally, bivalves are also a great asset in monitoring programmes that aim at detecting polluted areas (Waykar and Deshmukh, 2012). They can mitigate negative anthropogenic impacts such as marine eutrophication; the estimated global removal of nitrogen (49000 tonnes per year) and phosphorus (6000 tonnes per year) by filter-feeding farmed bivalves are worth 1.20 billion US dollars (Olivier et al., 2018). For instance, a spatial model has been presented to reduce eutrophication in the Baltic sea based on blue mussel farms' nutrient mitigation (Holbach et al., 2020).

1.1 Native coastal bivalves

Among native bivalves, blue mussel species (*Mytilus* spp) and flat oysters (*Ostrea edulis*) have a high ecological role due to their benefits in coastal regions such as increasing water quality and human consumption. During the last decades, the flat oyster population has declined across the world and they have been listed as a threatened species by the OSPAR Commission (OSPAR, 2009)

Blue mussels are distributed in North America, Europe, and other temperate waters around the world. They usually can be found in intertidal areas while attached to solid substrates such as rock (Gazeau et al., 2010). Thus, despite being one of the most cultured bivalves worldwide the potential for further development of cultivation is high (Pettersen et al., 2010).

In addition to being a valuable food resource, blue mussels are used for monitoring microplastic pollution due to their filter-feeding capacity (Kazour & Amara, 2019). Their broad spatial distribution and high tolerance to varied environmental conditions make them ideal for biomonitoring programmes and integrated data from both native and transplanted populations can bring an accurate assessment of environmental pollution around the globe (Kazour & Amara, 2019).

Oyster species can often be found on intertidal and subtidal substrates in enclosed, wave-sheltered coastal and estuarine areas (Stagličić et al., 2018). The flat oyster is a sessile, filter-feeding bivalve that can be found in a variety of sediments ranging from mud to gravel (Airoldi & Beck, 2007). They can be found from the subtidal zone up to 80 meters in depth (Perry & Jackson, 2017). The flat oyster stock declined due to decades of extreme exploitation and other environmental factors such as pollution and infection diseases (Laing et al., 2006).

1.2 Threats to coastal bivalves

1.2.1 Overharvesting

Oyster harvesting has been an important economical and productive component for communities all around the world. Before their dramatic decline of flat oysters in the twentieth century, the flat oyster was abundant in most of Europe. The history of human consumption of flat oysters goes back to the pre-Viking era in Shetland (Shelmerdine & Leslie, 2009). Romans also put a high value on oysters and fished them from European and Mediterranean coastlines (Airoldi & Beck, 2007). In the mid-1800s in Europe, intensive exploitation of wild flat oysters decreased their population density (Smyth et al., 2020). Therefore, many different projects are working on restoring the flat oyster population. For instance, The Native Oyster Restoration Alliance (NORA) has developed guidelines for flat oyster restoration in Europe (Pogoda et al., 2019). Current NORA groups working in different aspects including identifying suitable sites for restoring flat oyster populations (Pogoda et al., 2020).

1.2.2 Climate change

Climate change and ensuing ocean acidification are among the major threats to marine life, and bivalves are no exception. Ocean acidification can not only affect flat oyster's immune system it also has detrimental effects on their fertilization success (Sezer et al., 2018).

Climate change not only has abiotic effects on the physiology of native bivalves it can also create opportunities for non-native species. For instance, increased temperatures research shows that climate change has a benefit for invasive species since temperature change can help them to establish easier in the new environment than local species which have adapted themselves to the previous conditions for a long time (Nehls et al., 2006). For example, temperatures above 20 degrees and salinity of 20 PSU are believed to be vital factors for the establishment of the invasive Pacific oyster (*Magallana*/*Crassostrea gigas*) in a new habitat (Wrange et al., 2009).

1.2.3 Parasites and disease

Many flat oyster populations are still threatened by parasites and disease. The intracullar parasite *Bonamia ostreae* infects flat oyster's haemocytes (Morga et al., 2009) and is a serious threat to both wild populations and farmed stocks. Both juvenile and adult oysters can be affected, however, mortality has mostly occurred in 2 years or older oysters (Morga et al., 2009). Studying many populations of flat oysters and their genome sequence raised the hypothesis that there is a possibility of specific genome regions in flat oysters being resistant to *Bonamia* infection (Vera et al., 2019).

Rickettsiales — which is an alphaproteobacterial disease— has infected flat oyster populations in some regions in Italy, raising the concern about the spread of the infection to other regions (Tinelli et al., 2019). Since flat oysters have been eaten raw by many people, the health risk is a critical concern thus it is crucial to monitor these population conditions and maintain their health (Tinelli et al., 2019).

Marteilia spp. are protozoan parasites that infected bivalves such as flat oysters and blue mussels globally. For instance, they can cause bivalves to lose their lose pigmentation in their tissue which can lead to an economical loss for farmers (Carrasco, Green, & Itoh, 2015).

Although major infection events in both non-native and native bivalves were created by parasites that could only target one of them, some studies have identified mutual parasites which can cause infection in both groups. For instance, protozoans parasites of the genus Perkinsus are causing intense mortality in marine mollusks worldwide and creating major economic loss (Cascas et al., 2008).

1.2.4 Invasive species

Invasive Alien Species are species that can establish themselves outside of their natural habitat. The absence of predators or parasites alongside the lack of proper competitors can help invasive species to establish and expand in the environments. After the establishment of an invasive species if it remains unaffected by enemies or new environmental conditions, its dominance can become permanent (Reise et al., 2017). Deliberate introductions by humans may be followed by establishment of feral populations and further dispersal to new areas. For instance, the Pacific oyster (*Magallana/Crassostrea gigas*) is one of the most common invasive marine species in Europe especially in Scandinavian waters (Faust et al., 2017). A historical review of the Pacific oyster invasion showed that sea-based farming of this species made the invasion inevitable (Reise et al., 2017) and after the deliberate introduction combination of factors that accelerate establishment of invasive populations and their dispersal to new areas caused the invasion. There is a concern that they can outcompete local bivalves and in turn, harm corresponding ecosystem services. However, a recent study revealed that there is no difference in nutrient cycling rates between these species and thus Pacific oysters could then compensate for the ecological benefits of the native bivalves (Zwerschke et al., 2019).

Controlling invasive species in marine life has been a challenge for management due to the connectivity between marine ecosystems on a broad spatial scale. Therefore, some studies have suggested a series of actions such as removing the species physically, protect or restore the invasion areas, applying biological control through alien parasites and alien consumers, etc. (Giakoumi et al., 2019). Generally, early detection of invasive species increases the success of management actions (Simberloff et al., 2012).

1.3 Pacific oyster — ally and threat at the same time

Pacific oysters were first introduced to Europe more than 100 years ago. Since then, it has been spread around the Wadden Sea, the Black Sea, Mediterranean Sea, and Scandinavia for aquaculture. Feral populations have been created at almost every introduction site (Laugen et al., 2015). Larval dispersal through ocean currents is hypothesized to have spread Pacific oysters to western Sweden around 2006-2007 (Laugen et al., 2015). After being detected along the Norwegian Skagerrak coast in 2005, the species has dispersed and established populations from the Swedish border to the archipelago north of Bergen (Dolmer et al., 2014, Laugen et al unpublished data). Pacific oysters are resilient species that can adhere to different types of substrate and are capable of tolerating a wide range of environmental conditions. For instance, their survival temperature range is between sub-zero to +30°C (Strand et al., 2012). However, in some cases, they have experienced intense mortality due to severe ice winters (Strand et al., 2012), and more so at higher latitudes. There is a negative relation between Pacific oyster presence and higher latitudes due to colder temperature. The Pacific oyster can produce 50-200 million eggs per individual during spawning season (July-August in the northern hemisphere) and then the released gametes fertilize in the water masses (Laugen et al., 2015). After that, the larvae are free to follow water currents and then can disperse to new places (Laugen et al., 2015).

Due to their sharp edges, Pacific oyster shells can cause problems for recreational activities such as swimming and snorkeling (Laugen et al., 2015). Fouling of boat engines, piers, and other underwater constructions have also been reported and cause a generally negative attitude towards the species in coastal areas. They could be also a possible threat to blue mussels and flat oysters due to their invasions to new areas. New evidence, however, suggests that coexistence is possible (Reise et al., 2017, Simberloff et al., 2012). The main cause of their successful co-existence is still not clear, but the winter mortality of Pacific oysters can have a key role in it (Dolmer et al., 2014). Pacific oysters can also affect the parasite infection level in native mussels, however, other biotic factors such as individual sizes or alternative hosts presence may influence infection rates (Goedknegt et al., 2019).

The multiple environmental and anthropogenic threats to coastal bivalves, the lack of knowledge about current and historical distribution of native bivalves, and uncertain effect of the massively invasive Pacific oyster reveal an urgent need to develop robust management strategies, including closing knowledge gaps.

2. Aims of the thesis

To develop successful management strategies we urgently need to improve our ecological knowledge of coastal bivalves. Firstly, the lack of knowledge about their historic and current distribution hinders our efforts to validate any citizen science concerns about decline in key species. Secondly, the lack of monitoring programmes hampers our knowledge about current and future threats. Thirdly, the lack of consistent management strategies for the invasive Pacific oyster in Scandinavia potentially threatens both local bivalve species as well as a potential source of income in coastal communities. Finally, the lack of common survey methods and protocols within and between management areas makes cooperation and data sharing challenging. There is a thus an urgent need for common protocol mapping and monitoring programmes for coastal bivalves. Therefore, this thesis will improve the current knowledge gaps, organized around the following specific aims.

1. To get an overview of currently available survey methods — including recent technological developments through aerial and underwater drones — for mapping and monitoring coastal bivalves, I did a comprehensive review of scientific literature as well as relevant grey literature.

2. To improve survey protocols and advice to policy-makers and conservation management I reviewed the advantages and disadvantages of each method in relation to survey objectives.

3. To produce common guidelines for studying coastal bivalves, I created decision flowcharts and protocols for the most important types of mapping and monitoring studies by reviewing and improving available survey protocols and consulting with other researchers.

4. To assess the usability of remotely operated vehicles (ROVs) in mapping surveys I conducted a pilot study testing two different types of ROVs in terms of performance in different habitat types, depths, and currents.

3. Methods

3.1 Literature review

For the literature review, I searched for original research papers published in peer-reviewed scientific journals from 2006 to 2020 through Web of Science. I used the following search words: bivalves, oyster, mussel, density, mapping, monitoring, modelling, distribution, Crassostrea gigas, Ostrea edulis, and Mytilus edulis. In addition, several reports about coastal bivalves and theses at the bachelor and master level were provided by my supervisor. Those reports were mainly in Scandinavian languages, so they were first translated to English through Google translate. In all articles and reports, I searched the title, abstract, method sections for methodological details on field methods and modelling approaches. This led me to 67 articles that include field sampling activity (Appendix 1) and 9 articles that used different modelling techniques (Appendix 2). Then I extracted information on 1) the year and location of study 2) species 3) main goal of the project 4) collecting techniques, 5) modelling techniques, 6) abiotic data such as water depth and substrate (if it was presented) 7) biological data (density and individual size measurement). The review was organised under headings corresponding to four main research questions that are highly relevant for governance and management; 1) Where are they? (mapping the current distribution of coastal bivalves), 2) Origin: Where do they come from? 3) Monitoring: How are they doing? 4) Predicting: where are they going?

3.2 Decision flow chart and survey protocols

To create a decision flowchart that can be used to decide among different sampling techniques, I analyzed the different sampling techniques and protocols. I also consulted with experienced researchers from the Scandinavian Network of Oyster Knowledge (SNOK) to gain insights into what they consider to be the most important data to be included during fieldwork. Then I created a flowchart as a guideline to choose the most suitable collecting method based on the aim of the study, previous knowledge, and habitat characteristics. I also created protocols for mapping and monitoring programmes as a proposal for common survey methods for future studies (Appendix 4 & 5).

3.3 Testing ROVs as a tool for bivalve mapping

To test the reliability of ROVs in detecting surveys, a pilot study about using an underwater drone in mapping surveys by visiting 15 locations from Egersund to Bergen in the Norwegian coastline in July 2020. During the fieldwork, I checked coastal bivalves' presence/absence by using a remotely operated vehicle (ROV). The initial plan was to test 2 ROVs during fieldwork while the first one was a simpler underwater drone and the second one was a more advanced version. For assessing the effectiveness of the ROV, 3 main factors (Speed, reliability, accessibility) were examined to assess the potential of video recording equipment in the mapping survey. For more detail, see Box 1.

4. Review of methods for studying coastal bivalves

Of the 67 studies that used actual bivalve collection (take samples to the lab, take samples without removing them from the habitat or taking footage of them), 47 studies used the manual survey as the collecting method. Only 9 studies used photography or video recording techniques and 14 studies used fishing techniques (some studies used multiple techniques). Overall, results show that manual survey is the most common method in studying coastal bivalves.

There were fewer studies that focused on modelling future distribution or predict the areas with a high density of bivalves. Among 9 modelling studies, only 1 study did not include Pacific oysters in the research (Appendix 2).

4.1 Where are they? Mapping the current distribution of coastal bivalves

In times of global change, mapping the occurrence of bivalves is of major importance (Shelmerdine & Leslie, 2009). For instance, early detection of non-native species such as the Pacific oyster can facilitate removal programmes to reduce possible destructive effects on native populations. Bivalve reefs can be found in very different environmental conditions (e.g., brackish to saline, subtidal to intertidal, etc.) thus doing a proper habitat mapping and population assessment can be challenging (Ridge et al., 2019).

Generally, mapping species distributions is a two-step process. The first step is developing efficient tools and methods to predict their occurrences, and the second is using appropriate and efficient field protocols for verifying or falsifying these predictions. This could be challenging especially in terms of rare or invasive species.

4.1.1 Make predictions and choose sites for further investigations

One simple way to gain information about the presence of species is to utilize the potential of citizen science. Web portals such as www.oysterregistration.azurewebsites.net where everyone can report species observations can help researchers identify areas for further investigation (Malmedal & Ersland, 2021). However, such resources are not always considered to be the most reliable option for scientific studies, and verification of data is necessary.

Ecological niche modelling combine known species observations with layers of abiotic data to determine suitable habitats for a given species (Laugen et al., 2015) and thus can be used to predict species distributions outside the currently known distribution. It could help researchers to predict future presence of the species while considering abiotic factors temperature change in the future.

After making model predictions, choosing which locations to visit prior biological knowledge about suitable habitats can be used to narrow down field efforts. Presence of protected areas (national parks and other types of protection) and randomly generated points based on known criteria about preferred habitat (depth, substrate, wave exposure, etc.) are additional ways researchers can choose suitable sites for mapping

4.1.2 Determine presence/absence of coastal bivalves

Water depth is the most important factor for deciding the field technique for verification/falsification of our previous prediction. Thus, field techniques for mapping studies have been categorized into shallow and deep-water depth.

Shallow waters

Detecting reefs and sandbanks oyster or mussel banks by using the GIS method based on environmental data such as depth and aerial photography is another tool to help identify potential areas for large-scale oyster or mussel banks (Blomqvist & Hafok, 2013). For shallow waters (0-0.5 meters) researchers either conduct a manual survey using waders/dry suits and aquascope to search for bivalves or use aerial drones for searching the area. If the location consists of a dense bivalves population, it would be harder to count every individual to gain an accurate density. In shallow areas that have a high density of coastal bivalves, researchers either conduct transects or randomly place square frames into the water to assess the area by using aquascope and take samples for size measurements (length, width, height). This method can be used in both presence/absence surveys and measuring the density. It is also easier to distinguish between live and dead oysters since researchers can take a closer look at the samples. On the downside, based on the density and size of the area these techniques can be time-consuming.
With the boost of new technology, video recording equipment increase researchers' options for species distribution mapping. For instance, recent studies showed that unoccupied aircraft systems (UAS) can reliably be used in the mapping of oyster reefs (Windle et al., 2019, Ridge, et al., 2019). Using aerial drones in a systematic pattern can cover large areas of shallow-water areas. Besides in some areas which are hard to get access to by foot, aerial drones are one of the most effective techniques to search the area. By using UAS not only do we modernize mapping studies but we can also improve our knowledge about the reef without causing any

environmental destruction to it (Windle et al., 2019). However, in terms of measuring individual sizes (length, width, height), since you don't have actual access to the species it is only possible to categorize their size as small, medium, and big by video analyses.

Deep waters

For identifying bivalves in deeper waters (more than 0.5 meters), there are different field techniques including manual surveys (aquascope from boat, snorkeling, diving) and video-based surveys. Due to the challenges of measuring the dimension of bivalves in deep waters (length, width, height), most methods are unable to have precise data about individual sizes.

Using aquascope from a boat

In some cases, researchers try to detect bivalves by searching through aquascope from a boat while the boat goes in a straight line. The success of this technique is highly dependent on the clearance of the water. For instance, areas covered in high density of algae can create an obstacle for a clear view for detecting the bivalves.

Snorkeling

Snorkeling is an effective method of sampling in areas deeper than 1 meter. Usually, several hand gestures are established among snorkelers so they can give a signal to others when it is needed. The signals are used for showing basic things like live or dead bivalves. In a systematic pattern, snorkelers create a transect to survey the area. They are also capable of carrying calipers so they can measure the bivalves if it was possible. For example, if there is a bivalve reef, then the snorkeler can measure the dimensions of individual bivalves. In this scenario, someone needs to be near them and take note of the measurements. This method has been used mostly in mapping projects in which surveys start from shallow areas and continue to deeper waters. It is effective in areas such as lagoons and reefs where you can search for any bivalves attached to the reefs. This method is limited since it is hard to do accurate measurements or counting of the species.

Diving

Sampling in more than 5-meter depth requires diving. The diving method is similar to snorkeling, however, diving allows the researcher to access deeper waters and stay underwater longer than snorkeling. Furthermore, while snorkeling only requires minimal equipment (goggles, snorkel, fins, wetsuit), diving requires a more extensive set of equipment. Having access to more than 5-meter depth is the strongest point of this method but it is challenging to do accurate measuring due to problems of taking notes or communicate with other team members. Diving also generally requires professional diving certificates and may thus be impractical.

Remotely operated vehicle (ROV)

Depending on the size of the ROV, it needs 0.6 - 1 m depth for operation. In terms of surveying areas, researchers establish a base location which sometimes could be a boat or even on the shore since the drone contains a long cable (Box 1). With a systematic pattern for the drone, the operator starts to survey the area. The process can be handled by 2 people while one is the main operator and the other one writes down the environmental conditions. This technique can be used only in field studies with the main focus on mapping and regular monitoring programmes to detect bivalves or estimate their density. Some ROVs such as the Deep Trekker can go up to 60 meters in depth which can be useful to search very deep areas. On the downside, the equipment is expensive and it is not capable of measuring the dimension of bivalves. The water condition has a high effect on the final result of the process since you need clear water to be able to achieve decent quality records.

GoPro camera

Another widely used equipment in mapping and monitoring studies is GoPro cameras. These cameras can be attached to the end of the boat and record the bottom of the sea while the boat goes in straight transects. It can also be dragged by a different object such as sticks to take a picture or video record a reef for mapping purposes. Although due to some limitations it is not possible to use towed video recording techniques in every location, it has been used successfully for estimating flat oyster population size (Thorngren et al., 2019). GoPro cameras mounted on poles have been developed to survey otherwise difficult-to-reach Pacific oyster habitats such as vertical pier walls in the harbors along the coasts of southern Sweden (Martinez-Garcia et al 2018, Ahlers et al., 2020; Forsberg et al 2021). This equipment is significantly cheaper than ROVs and they can also be attached to the snorkelers or divers to take a video while they are doing their sampling. On the other side, these cameras cannot record a decent video/picture quality from distance.

Box 1. Mapping coastal bivalves using Remotely Operated Vehicles: a pilot study

As a sub-project in my thesis, I tried to detect marine bivalves by using a remotely operated vehicle (ROV). I visited 15 locations on the Norwegian coast from Egersund to Bergen from the 7th of July till the 16th of July 2020. Survey locations were derived from three sources 1) areas included in a 2017 survey from the Institute of marine research (Jelmert et al., 2020), 2) areas predicted by a model created by Danish Hydrological Institute (Birkeland et al., 2018), and 3) locations from artskart.no. For more details about each survey location, see Appendix 3.

The original plan was to test two different ROVs for the study a simple affordable drone (Chasing Dory TX) and a more advanced — and also more expensive — drone (Deep Trekker DTG 3). However, due to poor performance of the Chasing Dory TX in the first 2 locations, only the Deep Trekker was used during subsequent field work (Figure 1). The main problems of the Chasing Dory were short cable, weak engine, and poor video quality. The usability of the ROV was assessed in terms of accuracy in detecting bivalves, time spent, and accessibility to surveying areas. All surveys were performed in a systematic pattern to reduce overlap and missed areas.

The results showed that the ROV was effective in determining presence of coastal bivalves. However, it was not possible to measure their dimensions (length, width, height) and their survival status in a reliable way. In terms of time consumption, the overall time of preparation of ROV was around 3 min and an average of 17 min to cover 100 m2. Although the ROVs speed was not affected by current speed, the presence of macroalgae in the area could have a direct effect on the overall time spent by getting stuck in the engines and thus interrupting the operation. Time records demonstrate that every cleaning process that contains pulling the ROV out and cleaning the engines takes approximately 2 minutes which clearly increases the overall time of the survey.

The result showed that the major advantage of using ROV is accessibility. ROV was suitable for use in some areas where the location was too muddy to survey by foot. In such areas, ROV could do a quick survey to check the presence or absence of bivalves. The minimum required depth for this particular ROV was 60 cm.

Overall, using ROV for mapping coastal bivalves seems to be a promising technique especially in colder seasons with fewer algae density in the area. Since this sub-project had focused only on presence/absence surveys, further studies are recommended to develop methods for using ROVs for measuring population density, individual sizes, and mortality, under varied environmental conditions.

Figure 1. On the left, the preparation of the Deep trekker for operation. On the right, a picture of blue mussel bed taken by ROV in Torvastadvegen, Norway.

4.2 Origin: Where do they come from?

Important aspects of the study of coastal bivalves include investigating the origin of populations of native and invasive species through studies of connectivity (gene flow) between populations linked to source-sink dynamics, as well as oceanographic modelling to corroborate genetic data.

4.2.1 DNA methods for detecting the genetic origin

DNA markers and genome sequencing reveal that origin of the Pacific oyster population in Sweden, Denmark, and a Norwegian population are sharing the same origin (Faust et al., 2017). Furthermore, the evidence showed that Swedish and Danish Pacific oyster populations are more similar to each other than the Norwegian population (D'Auriac et al., 2017). By identifying marine invasive species routs we would improve our understanding of the invasion (Faust et al., 2017). By collecting random samples of coastal bivalves from varied locations and conducting genetic studies we are not only able to study genetic diversity of each coastal bivalve population, but we are also capable of using this technique to know the starting point of the Pacific oyster invasion. For instance, researchers stated that the Pacific oyster population in Sweden is most likely originated from Denmark and the invasion would still happen even if the native population of Pacific oysters in Sweden were removed by anthropogenic activities (Faust et al., 2017). These studies show the importance of invasive species management in terms of preventing the spread of such species to other regions.

4.2.2 Larval dispersal modelling to detect dispersal pathway

Genetic studies have compared the Pacific oyster populations in Norway, Sweden, and Denmark and simulate larval drift to predict the future status of factors such as survival and their distribution based on climate change development in the future (D'Auriac et al., 2017). Oceanographic modelling technique based on current movements is also able to simulate Pacific oyster larval dispersal in Scandinavia (Laugen et al., 2015). This technique can be an extremely useful tool in areas with high density of Pacific oysters since it can help management to detect dispersal patterns. Researchers suggest that oceanographic modelling can be used for detecting suitable habitats and potential areas with an established population of Pacific oysters (Birkeland et al., 2018). However, in my pilot study (Box 1) most of the locations that were based on this modelling technique either had no Pacific oysters or had low density (Appendix 3). Although predictions based on this modelling technique is helpful it should be checked out to verify or falsify after the predictions.

4.3 Monitoring: How are they doing?

While mapping studies can give us valuable information about the presence of bivalves in different regions, they do not necessarily tell us about the ecological status of the populations. By choosing ecologically important populations for regular surveys, we can run monitoring programmes to keep track of population parameters such as recruitment, mortality, population density, and size structure to be aware of any potential changes over time.

4.3.1 Large-scale bivalve bank dynamics

Oyster reefs have numerous benefits for the marine ecosystem including stabilizing shorelines, enhancing water quality, and providing habitat for other marine organisms (Grabowski et al., 2012). To monitor large-scale bivalve banks researchers, use photography and GIS-based methods while snorkeling-based techniques are also an option for monitoring these areas with focusing more on topography.

Unmanned Aerial System (UAS)

Aerial photos are one the efficient way to take the footage to map a large spatial area. The footage derived from Unmanned Aerial System (UAS) is useful survey flat regions covered by sand and mud. Data can be used in other computer programmes like GIS while having a higher resolution than satellite images (Windle et al., 2019). The downside of this technique is that the study area must be in low tide while the drone is taking a picture and other conditions such as current speed must be low to not have a negative impact on the reef's visibility (Windle et al., 2019).

GIS-based methods

A Geographical Information System (GIS) based method includes the geographical data that could be used to map and evaluate bivalve's habitat. It also contains chemical, physical, and biological data (Mckindsey et al., 2006) which help to create oceanographic and geographic models. By using varied data sources including underwater footage, sediment sampling, remote sensing, multibeam sonar, and oceanographic data GIS technique is capable of collect information about the spatial pattern of bivalve banks (Crawford et al., 2006)

4.3.2 Investigating the genetic/ecology of coastal bivalves

Due to climate change, invasive species such as Pacific oysters have dispersed and are predicted to continue spreading to new areas around the globe. The impact of invasive species is heavily dependent on the ecosystem that they are occurring in. However, if we want to have a better understanding of a specific species' invasion consequences, we must study them in various environments (Zwerschke et al., 2018). In many places including the Barents Sea, there is a lack of data about bioindicator's response to different anthropogenic stressors (Nahrgang et al., 2013). For example, when it comes to predicting the future status of any species, factors such as environmental changes and interaction between species would be under investigation. Evidence showed that hybrid Mediterranean mussel (*M. galloprovincialis*) larvae are more tolerant to temperature change than blue mussel larvae. Thus if temperature rise continues there is a strong chance of a shift in dominance in areas with the co-existence of these species (Boukadida et al., 2020).

To distinguish different tolerances of environmental stress between populations, wild and farmed Pacific oysters were compared in their ability to tolerate different temperatures and salinities (Yang et al., 2016). The findings indicated that farmed populations have a lower ability to cope with temperature rise than wild populations (Yang et al., 2016). In another study case, 1-year-old Pacific oysters from the subtidal and intertidal region were collected to be exposed to air to see if the Pacific oyster population can evolve themselves to adapt to the dry environment or not. The results showed that hypoxia stress will have a more adverse effect on subtidal oysters in the long term than intertidal oysters (Meng et al., 2018).

These sorts of studies increase our understanding of different ecological aspects of coastal bivalves that could help managements to be alert about the potential threat and take the necessary actions to prevent further damage.

4.3.3 Population dynamics

Early detection of changes in recruitment, mortality, population density, and size structure is among the goals for monitoring bivalve populations. For instance, to continue receiving the social and economic benefits of flat oysters, it is highly important to take action for their recovery by monitoring natural beds and a deeper understanding of the possible threats to the population (Vera et al., 2019).

Like mapping programmes, choosing field techniques for sampling bivalves in monitoring programmes also depend on environmental condition like water depth. In shallow waters (0-0.5 meters) researchers use manual surveys through transect lines with the help of square frames to study the area. In deeper parts of the sea (more than 0.5 meters) or in very muddy places which are hard to walk, transects can be done through snorkeling, diving, video recording tools such as ROV and GoPro cameras, and fishing. However, in deep waters, it would be only possible to estimate the density of bivalves since measuring the individual sizes would be not an option.

Both researchers and managers claim that due to their capacity for rapid growth, the invasive Pacific oysters could eliminate the local species like flat oysters. Monitoring programmes can investigate such areas regularly to detect any potential threat and inform the management to take an action. The outcome of recent monitoring studies in Telemark, Norway revealed that there is a more dense Pacific oyster population in bedrock and boulders that are near to tidal zone (Tangen, 2017). This sort of information can help to narrow down the searching areas in the case of detection surveys.

Based on factors such as the location or aim of the project different sampling techniques can be used in measuring the population density. Manual surveys are the traditional collecting method for measuring the size and density of the coastal bivalves population. For instance, there are annual surveys in Denmark which aim to monitor and map the density of Pacific oysters which started in 2017 by doing manual surveys in the same locations each year (Tangen et al., 2020). In the data set of field studies, researchers include both individual information about the species and numerous environmental factors for further studies. Factors such as substrate, tidal level, water depth range, current speed, etc. are part of the dataset that leads to further studies about habitat choice preference or modelling studies that can predict the species distribution in the future.

Manual survey (transect lines) in shallow waters

This technique is one of the most proper methods which gain accurate data about the species dimension (length, width, height). It has been used in monitoring programmes that need regular surveys to assess the density of the species in the area. Team members conduct transects with the help of metal squares to search for bivalves. In addition to individual sizes, researchers also can measure the mortality rate by counting the dead bivalves. It is also common to take note of abiotic factors such as substrate and water depth to have more accurate knowledge about the study area. The downside of this technique is its extremely time-consuming process and it usually needs more team members for high-density locations.

Fishing

Since commercial fishing has an impact on the biodiversity of marine species in any area, one way to study the potential changes is the impact assessment of fishing (Nielsen et al., 2018). These projects can assess the stock size of the population which can lead to the conclusion that either the population is declining or not. In addition, it will be a useful guideline for management to set a limit on how much harvesting should be allowed to prevent any damage to the native population.

Using fishing techniques for sampling marine species is one of the well-known methods. There are varied fishing techniques for catching bivalves from the sea such as fishing net, gear, dredges, water pump, etc. In the field studies, the main usage of this technique is to assess the impact of fishing by comparing the species stock on regular basis. For instance, there are annual studies in Nissum Bredning, Denmark that assess the impact of fishing for flat oysters, Pacific oysters, and starfish. By comparing data from commercial fishing they can assess species stock size and predict the future of the population in that specific area (Nielsen et al., 2019).

The positive side of this sampling technique is the easy access. It is also less time-consuming than other techniques that require more fieldwork. On the other hand, most times there is less information about the species habitat or sampling site. Lack of environmental factors such as water depth, substrate, habitat type is a major downside.

4.3.4 Parasites and disease

Monitoring programmes related to food safety in commercially important species are common, but they are usually focused on preventing human disease and death and not necessarily to investigate the health of the bivalve stocks themselves. Other monitoring programmes keep track of the parasites *Marteilia* and *Bonamia* to prevent dispersal between different geographic regions. The surveillance programme by IMR detected *Marteilia* sp. in the blue mussel population in Norway but no detection of *Bonamia* spp. in the flat oyster population (Mortensen et al., 2021). This finding shows the importance of the flat oyster population in Norwegian waters since it could be highly valuable for aquaculture and restoration purposes (Mortensen et al., 2021). *Polydora websteri* is a shell-boring invasive parasite that is detected recently in the pacific oyster population all around the globe (Waser et al., 2020, Martinelli et al., 2020). The spread of these parasites can have a huge negative economic impact on the aquaculture industry and it would be much harder to control the infection after spreading in many places. The parasite has recently been detected in Bohuslän, Sweden (Wrange et al, unpublished data), and mapping its occurrence along the coasts of the Skagerrak is urgently needed.

In 2014 there was a high mortality rate in the Pacific oyster wild population on the Swedish west coast and Southern Norway due to infection of Ostreid herpesvirus (OsHV) for the first time in Scandinavia (Mortensen et al., 2016). Although all class sizes of Pacific oysters were affected by the virus, flat oysters and blue mussel populations were remained unaffected (Mortensen et al., 2016).

In case of any suspicious mortality event, researchers try to collect samples from the area to perform analyses for detecting the reason. For instance, due to mortality events in the flat oyster population around Europe, different samples of the flat oyster population were collected in the Solent, United Kingdom for genome sequencing to detect parasite *Bonamia exitiosa* in adults and larvae of flat oysters. Although the parasite was detected in some samples, the result showed that the parasite failed to establish itself in the area. The study recommended continuing monitoring the infection since it can prevent the flat oyster restoration process in Europe (Helmer et al., 2020). A similar study was performed in France to analyze the impact of OsHV-1 in experimental conditions to study the transmission and development of the infection in Pacific oysters (Schikorski et al., 2011).

Due to the bivalve's high value in both aquaculture and marine ecosystem, it is highly recommended to do regular monitoring programmes to detect such diseases for keeping the coastal bivalve population safe. This sort of programme usually involves randomly picking bivalves in sampling locations and opening shells to do a visual inspection or send samples to a laboratory for genetic analyses. Although detecting parasites in the bivalve's natural habitat by opening the shells is a time-consuming process there are no other alternative field methods.

4.4 Predicting: where are they going?

Modelling studies can be a very useful tool for predicting coastal bivalves' future distribution. There are many different approaches in each modelling technique for example, on the individual scale, most of the modelling approaches detect the relation between environmental conditions and populations to predict the population's future response. Another aspect is a regional scale which is more focused on larval dispersal and habitat connectivity on the spatial scale (Thomas et al., 2020).

Niche modelling

Ecological niche modelling is another method to predict the population's future distribution. By having data about the presence or absence of species such as coastal bivalves you can predict their distribution and know where to find them (Leidenberger et al., 2015). Based on the niche modelling concept species are capable of establishing their population only in a suitable ecological environment. Therefore, by knowing which environmental conditions they prefer we can detect and predict their geographic area (Peterson, 2003).

Habitat modelling

Another modelling technique is habitat modelling which can predict the presence or absence of species based on environmental conditions such as bottom substrate or water depth. This can be a great asset for any mapping or monitoring programmes by suggesting the best locations for conducting surveys (Pearce & Ferrier, 2000, Bergström et al 2021).

Individual-based modelling

Individual-based modelling (IBM) has become one of the useful tools to study the interaction between individuals and environmental factors such as temperature or salinity (Thomas et al., 2020). Contemporary climate change and non-indigenous species are often considered as a major threat to global biodiversity since climate change can directly affect species, such as Pacific oysters, and allow them to spread to new areas that were not reachable in the past. Therefore, IBM can predict Pacific oyster's invasion patterns by using abiotic factors such as temperature and help management to take early action before their establishment.

5. Implications for research and management

5.1 Choosing the proper sampling technique

There are different field techniques to collect coastal bivalves based on the aim of the study. Each technique can collect different information about individuals in the field such as individual measurements (length, width, height) or their vital status. Many study cases use just one type of collecting technique while in some studies researchers used a mixture of techniques to achieve the aim of the study. Each sampling method has its advantages and disadvantages so there is no superior method in the field that can handle all kinds of situations. Thus, before choosing the proper field technique, variables such as the scientific or management goals, available time and financing, and habitat characteristics, must be accounted for. By considering these factors we can achieve the best result which is collecting the bivalves in minimal time alongside the all necessary data in the field. It is especially important to use the proper method in mapping and monitoring studies since these type of studies requires the most data. For instance, counting live/dead bivalves, shell dimensions (length, width, height), water depth, etc. is extremely important for mapping and monitoring purposes. Suboptimal data collection reduces the efficiency of analyses and models. A flow chart was therefore created to help to choose the proper sampling method in the field based on the environmental conditions (Figure 2).

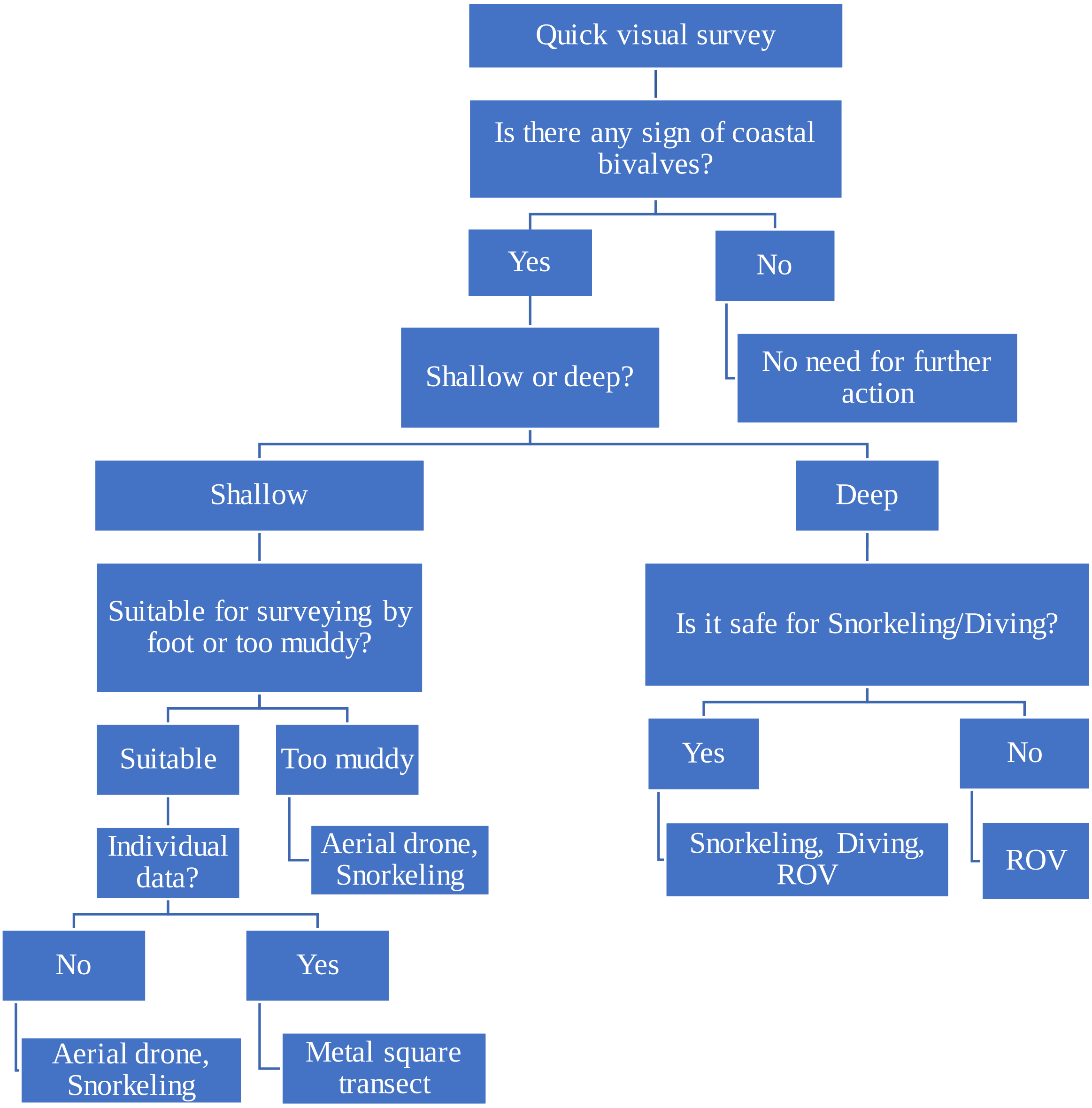

Figure 2. Guideline for choosing the suitable sampling method of coastal bivalves.

5.1.1 Aim of the research project

In most laboratory studies there is no need to know about the environmental conditions of the sample's habitat. Therefore, simple collecting or fishing techniques are sufficient since usually there is no need to know all environmental details of the samples. However, this is not the case for studies that include field work. In this category, the efficient sampling methods are the ones that contain not only geographical data but also all necessary environmental factors such as water depths and substrate of the site. For instance, the sampling technique for studying winter mortality in coastal bivalves must be able to distinguish between live and dead bivalves. Therefore, it would be better to use manual survey techniques to check the status of the species.

Although video recording techniques can survey faster, it is extremely difficult to know species vital status (Henriksen, 2008).

5.1.2 Time and financing

One of the most important aspects of choosing a sampling method is directly related to the study's time plan and total budget. If time for field work is limited, video recording techniques (UAS, ROV, mounted Go-Pro camera) can be used to quickly record large areas and recordings can be examined later. However, the most time-efficient recording equipment is also the most expensive.

5.1.3 Environmental conditions

Last but not least, taking habitat characteristics into account is crucial as not every method is suitable for every condition. For example, in deeper waters (below 60-80 cm), manual surveys using waders and aquascopes become impossible and snorkeling, diving, or video recording techniques are required. However, the safety of the team members must always be taken into account, and UAS and ROVs can be suitable tools for general occurrence mapping. For shallow areas, on the other hand, snorkeling and using ROVs is of limited benefit, and manual surveys using line transects or square-based density estimations are preferable. Mudflats — even in shallow areas — often requires snorkeling, use of stand-up-paddleboards, or some kind of video recording to prevent sediments from clouding the waters and reduce visibility.

Thus it is recommended to check the environmental condition before any sampling process to prevent any obstacles and dangers. Environmental factors such as water depth, tidal conditions, substrate, wind speed, algae density, etc. must be considered when choosing sampling technique.

5.2 Slowing down the invasive species

Invasive species can reduce native biodiversity and significant amounts of taxpayer dollars and conservation management's time are dedicated to actions against them. For instance, in several counties along the Norwegian Skagerrak coast cleaning programmes are conducted by management through voluntary activities to reduce Pacific oysters invasion (Naustvoll et al., 2019). While no proper Before-After-Control-Impact (BACI) study to date has been carried out, a survey by IMR (Naustvoll et al., 2019) suggests that clearing action has a positive effect on limiting the density of Pacific oysters but it should be repeated regularly every 2-3 years to maintain the result. Although these actions are recommended for slowing the Pacific oyster invasion, it is critical to study the area before any clearing action to establish baseline information about population density through a BACI-design study. Without baseline information, it is not possible to draw conclusions about how effective the clearing actions are. A BACI study also includes regular monitoring after clearing action to determine how often the process must be repeated to keep the unwanted species away or at a low level.

5.3 Suggestions for improving survey protocols

There is a huge gap of knowledge when it comes to our understanding of the condition of our coastlines. Europe is not the only place in the world that has limited data about its coastline to predict the future trends of marine life. Alaska in the USA which contains an extensive coastline suffers from the same issue (Hartwell et al., 2019). Studying the marine environment through monitoring regularly can help us to gain more necessary information about organisms and environmental factors to be able to detect and prevent potential dangers (Hartwell et al., 2019). However, it is important to notice which type of information is necessary to know for having a better understanding of our coastlines and species status. Factors such as substrate, tidal level, water depth range, current speed, etc. are part of the dataset that leads to further studies about habitat choice preference or modelling studies that can predict the species distribution in the future.

One of the main obstacles to tracking the recovery process of flat oysters is the lack of enough quantitative baseline data about the species density and age or size structure. By having more accurate stock data it would be easier to compare the species density to its past and have a better understanding of their restoration progress (Allison et al., 2019).

In many mapping and monitoring projects, the main focus is on counting or detecting live bivalves without any attention to the number of dead individuals. In most cases when researchers study the distribution of the coastal bivalves and detecting their presence in new areas, they only focus on the live bivalves. Facts such as parasite infection and extreme changes in the environment can create many dead oysters or mussel shells in the area. Thus it is important to pay attention to not only live individuals but also the dead ones. There are few studies about mortality rate and its relations to different reasons and that is why it is important to add the counting of dead bivalves in the field studies. It is highly recommended to count both live and dead bivalves in any mapping and monitoring study.

Overall, there is a clear lack of additional variables collected in many studies which is an obstacle for other researchers to use the data. As mentioned earlier it is important to take note of environmental factors such as water depth in terms of re-using that data for other studies like predicting the distribution of coastal bivalves. In many cases, there is for instance no information about water depth, and additional relevant information is too vaguely described or not included at all. This hampers the use of currently available studies for future research projects such as environmental niche modelling to predict future distribution. For instance, although Pacific oysters and flat oysters can be found in the same area there is a crucial difference in terms of their maximum water depth since flat oysters live sub-tidally while Pacific oysters live intertidally (Dolmer et al., 2014). If a mapping study shows the presence of a flat oyster population alongside the abiotic factors like depth of the water, it could easily determine that the Pacific oyster population can also be found there or not. In addition, having more accurate environmental data about species habitats can create many opportunities to improve our knowledge about important species like Pacific oysters in terms of ecological aspects such as their habitat preference.

Another variable often left out of reports is the substrate of the study's habitats. This missing information makes it difficult to create a proper habitat classification for bivalves. Habitat modelling can be a great asset for researchers to boost their knowledge in terms of the geographical location of bivalves all around the globe. By having a unified structure in our metadata we can tackle various issues regarding the future of coastal bivalves. For example, in terms of the Pacific oyster invasion, we can predict which areas are more likely to experience their presence in the future just by having accurate information about substrate in areas where they have been found previously.

Some environmental variables are important to include in the sampling process, while others are not as relevant to include. Abiotic factors such as water temperature or salinity will differ depending on the time of the day. If the study specifically needs to consider such factors it should be recorded several times every day. Some studies conclude that there is a positive relation between salinity and oyster's individual sizes by just getting one water sample from different locations and compare the salinity levels and individual sizes (Lourdes et al., 2018). Since salinity can differ during the day it must be examined 2-3 times per day and this process must be continued over a longer period to conclude any potential relation between salinity and ecological aspects of bivalves. Ideally, a network of measuring stations that automatically record abiotic factors such as temperature, salinity, and water currents, should be set up throughout marginal seas such as the Baltic Sea, Øresund, Kattegat, Skagerrak, and the North Sea, to help us predict the future of our local marine ecosystems.

5.4 Video recording equipment

With technological advances, there are new opportunities that have emerged for studying coastal bivalves. These new pieces of equipment can be highly reliable since the collected data can be reused and re-examined in the future if it is needed. Aerial drones are a promising approach for mapping oyster reefs in different areas while remaining environmentally friendly and not disturbing the study organisms. However, there are still a few challenges in their way to becoming the most useful tools in mapping surveys.

Aerial drones have been successfully used for presence/absence surveys but since bivalves are fixed in a specific angle it is hard to distinguish their vital status (Nielsen et al., 2019). Therefore, they are not the best option for studying the mortality rate in the area and that is why it is important to define the aim of the project before choosing the methodology of the survey. The same issue goes with the ROV and GoPro camera. In addition, it is not possible to measure the accurate dimension of the bivalves. The best solution for this problem is to categorize them into 3 size ranges (small, medium, large). There are advanced accessories for some ROVs that add the ability of measurement with help of a laser scaler but that could only measure length if the bivalve is settled at the proper angle.

Another usefulness of the drones for mapping approaches is to use the data in various softwares that can handle GIS data to calculate the extent (area) and biomass of the oyster reefs in the area (Nielsen et al., 2019). However, there is a negative relation between area size and the accuracy of the result (Nielsen et al., 2019). Thus, it is recommended to consider this method for only small regions to have higher accuracy in the result.

5.5 Combination of mapping/monitoring studies with modelling techniques

It is important to have a better interaction between mapping/monitoring techniques and modelling approaches for better resolution in predicting the dispersal of individuals. This would help to detect early changes in biodiversity and prevent invasive species like Pacific oysters from threatening the local species (Stelzer et al., 2013). By collecting all necessary data for modelling studies through any mapping or monitoring projects we can tackle this sort of issue that is causing danger to native coastal bivalves.

For instance, modelling studies implied that neither water temperature increase nor ocean acidification changes by the year 2100 will affect Pacific oysters and these species will remain competitive in dominance (Pack et al., 2020). This kind of information is useful for management to predict the future state of blue mussels and flat oysters population since they are continuously in danger of invasion.

Modelling studies' benefits are not limited to only Pacific oyster invasion or prediction about where we can find coastal bivalves. For instance, the particle tracking model (PTM) has tried to find any possible connection between blue mussel populations and offshore energy installation. The result predicted that without artificial shallow hard substrate commonly referred to as “ocean sprawl”, the blue mussel population would not survive in North Sea offshore areas (Coolen et al., 2020). Therefore, modelling approaches are also capable of detecting the potential environmental threat for coastal areas and generating a warning to take action for maintaining marine biodiversity.

5.6 Protocols for mapping and monitoring surveys

In terms of any mapping or monitoring study, it is useful to have a unified protocol that guides researchers to know how they should perform the survey and what type of method and environmental factors they should consider. By having a similar format in research projects we will be able to use the data more efficiently to improve our understanding of coastal bivalves' status, mortality rate, growth rate, and tracking the Pacific oyster invasion. Furthermore, every mapping or monitoring study can help management to know the status of the coastal area and pave the way for other scientists to use the data in modelling studies. Therefore, two separate protocols for mapping and monitoring coastal bivalves have been created to guide future studies (appendix 4, appendix 5).

6. Conclusion

Nowadays many governments, habitat managers, and non-governmental organizations realized the destructive consequences of oyster reef reductions. Thus, a consensus exists among concerned stakeholders to support the restoration of oyster reefs to prevent any further damage. Proper monitoring can be an effective way to help us to achieve this goal in the future (Smyth et al., 2020). It is vital to increase our knowledge about the abundance and distribution of oyster reefs in terms of promoting their recovery process (Allison et al., 2019). Coastal bivalves have high value in both aquaculture and marine ecosystem so it is important to have a regular monitoring programme, especially in high-density areas.

The lack of information about historical data on bivalves makes predicting the future spreading patterns and prevent threats such as overfishing challenging. It is vital to know how current harvesting levels impacts current bivalve stocks to be able to set reasonable quotas for an outtake. Both Norway and Sweden — with a few implemented no-take zones and national parks — currently allow more or less unrestricted outtake of flat oysters without any knowledge about the standing biomass for this species. It is thus recommended to increase efforts to estimate native bivalve stock size for flat oysters as soon as possible given that The stocks in Northern Scandinavia are for the time being the last parasite-free natural stocks.

The Pacific oyster has colonised Skagerrak coastlines since 2006. The species may cause negative as well as positive effects and is also of high commercial value. Consequently, management of the species is challenging. Developing a dynamic management model for this species — with different management actions in different geographical regions based on their invasion status could improve the current management of the species and optimise resources dedicated to natural resource management and conservation management in the region.

There are lots of other bivalve species that are not mentioned in the thesis and there is not much information about them. By detecting and identifying their high-density regions we would be able to have better management of the coastal ecosystem. There is a critical need to keep monitoring and protecting these populations to continue receiving their ecosystem services in the future.

References

Aamodt, H. (2021). *Kartlegging av stillehavsøsters Crassostrea gigas i Karmøy kommune* [Bachelor's thesis]. Nord University.

Ahlers, N., Meier, F., Ottosson, T., & Tsouka, F. (2020). *Changes in the occurrence and establishment of the Pacific oyster (Crassostrea gigas) in Scania* [Student report]. Lund University.

Airoldi, L., & Beck, M. W. (2007). Loss, status and trends for coastal marine habitats of Europe. *Oceanography and Marine Biology*, *45*, 345–405. https://doi.org/10.1201/9781420050943.ch7

Allison, S., Hardy, M., Hayward, K., Cameron, T. C., & Underwood, G. J. C. (2020). Strongholds of *Ostrea edulis* populations in estuaries in Essex, SE England and their association with traditional oyster aquaculture: Evidence to support an MPA designation. *Journal of the Marine Biological Association of the United Kingdom*, *100*(1), 27–36. https://doi.org/10.1017/S0025315419001048

Anglès D'Auriac, M. B., Rinde, E., Norling, P., Lapègue, S., Staalstrøm, A., Hjermann, D., & Thaulow, J. (2017). Rapid expansion of the invasive oyster *Crassostrea gigas* at its northern distribution limit in Europe: Naturally dispersed or introduced? *PLoS ONE*, *12*(5), 1–19. https://doi.org/10.1371/journal.pone.0177481

Barillé, L., Le Bris, A., Méléder, V., Launeau, P., Robin, M., Louvrou, I., & Ribeiro, L. (2017). Photosynthetic epibionts and endobionts of Pacific oyster shells from oyster reefs in rocky versus mudflat shores. *PLoS ONE*, *12*(9), 1–22. https://doi.org/10.1371/journal.pone.0185187

Bergström, P., Thorngren, L., Strand, Å., & Lindegarth, M. (2021). Identifying high-density areas of oysters using species distribution modelling: Lessons for conservation of the native *Ostrea edulis* and management of the invasive Magallana (Crassostrea) gigas in Sweden. *Ecology and Evolution*, *March*, 1–11. https://doi.org/10.1002/ece3.7451

Birkeland, M. J., Møhlenberg, F., Arenas, J. A., & Brinchmann, K. (2018). *Risk Modelling - Dispersion Potential and Propagation of Pacific Oyster*. *December*.

Blomqvist, M., Ab, H., & Ab, H. (2013). *Kartering av naturtyperna sublittorala sandbankar och rev i Västra Götaland och Östergötland*. 1–65.

Bolander, M., Andersen, J., E., Simonsen, J., A., Petersen, P., K., Baadegaard, S. (2019). Udbredelsen af Stillehavsøsters (Crassostrea gigas) omkring Sjælland og øerne [Bachelor's thesis]. Copenhagen University.

Boukadida, K., Mlouka, R., Clerandeau, C., Banni, M., & Cachot, J. (2021). Natural distribution of pure and hybrid *Mytilus sp.* along the south Mediterranean and North-east Atlantic coasts and sensitivity of D-larvae stages to temperature increases and metal pollution. *Science of the Total Environment*, *756*, 143675. https://doi.org/10.1016/j.scitotenv.2020.143675

Burioli, E. A. V., Prearo, M., Riina, M. V., Bona, M. C., Fioravanti, M. L., Arcangeli, G., & Houssin, M. (2016). Ostreid herpesvirus type 1 genomic diversity in wild populations of Pacific oyster *Crassostrea gigas* from Italian coasts. *Journal of Invertebrate Pathology*, *137*(May 2008), 71–83. https://doi.org/10.1016/j.jip.2016.05.004

Carrasco, N., Green, T., & Itoh, N. (2015). Marteilia spp. parasites in bivalves: A revision of recent studies. *Journal of Invertebrate Pathology*, *131*, 43–57. https://doi.org/10.1016/j.jip.2015.07.016

Casas, S. M., Reece, K. S., Li, Y., Moss, J. A., Villalba, A., & La Peyre, J. F. (2008). Continuous culture of Perkinsus mediterraneus, a parasite of the European flat oyster *Ostrea edulis*, and characterization of its morphology, propagation, and extracellular proteins in vitro. *Journal of Eukaryotic Microbiology*, *55*(1), 34–43. https://doi.org/10.1111/j.1550-7408.2008.00301.x

Coolen, J. W. P., Boon, A. R., Crooijmans, R., van Pelt, H., Kleissen, F., Gerla, D., Beermann, J., Birchenough, S. N. R., Becking, L. E., & Luttikhuizen, P. C. (2020). Marine stepping-stones: Connectivity of *Mytilus edulis* populations between offshore energy installations. *Molecular Ecology*, *29*(4), 686–703. https://doi.org/10.1111/mec.15364

Crawford, T. W., Commito, J. A., & Borowik, A. M. (2006). Fractal characterization of *Mytilus edulis* L. spatial structure in intertidal landscapes using GIS methods. *Landscape Ecology*, *21*(7), 1033–1044. https://doi.org/10.1007/s10980-006-0003-1

Eguchi, S., Harino, H., & Yamamoto, Y. (2010). Assessment of antifouling biocides contaminations in Maizuru Bay, Japan. *Archives of Environmental Contamination and Toxicology*, *58*(3), 684–693. https://doi.org/10.1007/s00244-009-9394-8

Faust, E., André, C., Meurling, S., Kochmann, J., Christiansen, H., Jensen, L. F., Charrier, G., Laugen, A. T., & Strand, Å. (2017). Origin and route of establishment of the invasive Pacific oyster *Crassostrea gigas* in Scandinavia. *Marine Ecology Progress Series*, *575*, 95–105. https://doi.org/10.3354/meps12219

Gallardi, D. (2014). Effects of Bivalve Aquaculture on the Environment and Their Possible Mitigation: A Review. *Fisheries and Aquaculture Journal*, *05*(03). https://doi.org/10.4172/2150-3508.1000105

Gamfeldt, L., Lefcheck, J. S., Byrnes, J. E. K., Cardinale, B. J., Duffy, J. E., & Griffin, J. N. (2015). Marine biodiversity and ecosystem functioning: What's known and what's next? *Oikos*, *124*(3), 252–265. https://doi.org/10.1111/oik.01549

Garcia, M., L., Mårdberg, M., Nilen, S., Schlyter, P., (2018). *Effects of salinity levels on the distribution and size of the Pacific oyster (Crassostrea gigas) along the west coast of Skåne, Sweden* [Student report]. Lund University.

Gazeau, F., Gattuso, J. P., Dawber, C., Pronker, A. E., Peene, F., Peene, J., Heip, C. H. R., & Middelburg, J. J. (2010). Effect of ocean acidification on the early life stages of the blue mussel *Mytilus edulis*. *Biogeosciences*, *7*(7), 2051–2060. https://doi.org/10.5194/bg-7-2051-2010

Ghaffari, H., Wang, W., Li, A., Zhang, G., & Li, L. (2019). Thermotolerance Divergence Revealed by the Physiological and Molecular Responses in Two Oyster Subspecies of *Crassostrea gigas* in China. *Frontiers in Physiology*, *10*(September), 1–15. https://doi.org/10.3389/fphys.2019.01137

Giakoumi, S., Katsanevakis, S., Albano, P. G., Azzurro, E., Cardoso, A. C., Cebrian, E., Deidun, A., Edelist, D., Francour, P., Jimenez, C., Mačić, V., Occhipinti-Ambrogi, A., Rilov, G., & Sghaier, Y. R. (2019). Management priorities for marine invasive species. *Science of the Total Environment*, *688*, 976–982. https://doi.org/10.1016/j.scitotenv.2019.06.282

Goedknegt, M. A., Nauta, R., Markovic, M., Buschbaum, C., Folmer, E. O., Luttikhuizen, P. C., van der Meer, J., Waser, A. M., Wegner, K. M., & Thieltges, D. W. (2019). How invasive oysters can affect parasite infection patterns in native mussels on a large spatial scale. *Oecologia*, *190*(1), 99–113. https://doi.org/10.1007/s00442-019-04408-x

Grabowski, J. H., Brumbaugh, R. D., Conrad, R. F., Keeler, A. G., Opaluch, J. J., Peterson, C. H., Piehler, M. F., Powers, S. P., & Smyth, A. R. (2012). Economic valuation of ecosystem services provided by oyster reefs. *BioScience*, *62*(10), 900–909. https://doi.org/10.1525/bio.2012.62.10.10

Haaverstad, B., H., (2015) *Overvåking av stillehavsøsters 2015*. (M-679). Retrieved from https://www.miljodirektoratet.no/globalassets/publikasjoner/m679/m679.pdf

Haaverstad, B., H., (2016) *Overvåking av stillehavsøsters 2016*. (M-667). Retrieved from https://www.miljodirektoratet.no/globalassets/publikasjoner/m667/m667.pdf

Hartwell, S. I., Dasher, D., & Lomax, T. (2019). Characterization of organic contaminants in fjords and bays on the Kenai Peninsula Alaska. *Environmental Monitoring and Assessment*, *191*(7). https://doi.org/10.1007/s10661-019-7530-0

Helmer, L., Farrell, P., Hendy, I., Harding, S., Robertson, M., & Preston, J. (2019). Active management is required to turn the tide for depleted *Ostrea edulis* stocks from the effects of overfishing, disease and invasive species. *PeerJ*, *2019*(2), 1–26. https://doi.org/10.7717/peerj.6431

Forsberg, H. Kier, J., Jakobsson, K., (2021). *The invasive Pacic Oyster (Crassostrea gigas) in Scanian coastal waters: Assessment of its distribution and dependance of local salinity levels* [Student report]. Lund University

Helmer, L., Hauton, C., Bean, T., Bass, D., Hendy, I., Harris-Scott, E., & Preston, J. (2020). Ephemeral detection of *Bonamia exitiosa* (Haplosporida) in adult and larval European flat oysters *Ostrea edulis* in the Solent, United Kingdom. *Journal of Invertebrate Pathology*, *174*(June), 107421. https://doi.org/10.1016/j.jip.2020.107421

Holbach, A., Maar, M., Timmermann, K., & Taylor, D. (2020). A spatial model for nutrient mitigation potential of blue mussel farms in the western Baltic Sea. *Science of the Total Environment*, *736*, 139624. https://doi.org/10.1016/j.scitotenv.2020.139624

Holm, M. W., Lindegarth, S., Bodvin, T., Norling, P., & Mortensen, S. (2014). *7Kh Lqydvlyh 3Dflàf R\Vwhu. 2*.

Isbell, F., Gonzalez, A., Loreau, M., Cowles, J., Díaz, S., Hector, A., MacE, G. M., Wardle, D. A., O'Connor, M. I., Duffy, J. E., Turnbull, L. A., Thompson, P. L., & Larigauderie, A. (2017). Linking the influence and dependence of people on biodiversity across scales. *Nature*, *546*(7656), 65–72. https://doi.org/10.1038/nature22899

Kazour, M., & Amara, R. (2020). Is blue mussel caging an efficient method for monitoring environmental microplastics pollution? *Science of the Total Environment*, *710*, 135649. https://doi.org/10.1016/j.scitotenv.2019.135649

Kelly, R. P., Closek, C. J., O'Donnell, J. L., Kralj, J. E., Shelton, A. O., & Samhouri, J. F. (2017). Genetic and manual survey methods yield different and complementary views of an ecosystem. *Frontiers in Marine Science*, *3*(JAN), 1–11. https://doi.org/10.3389/FMARS.2016.00283

Kerstin Stelzer, Heyer, K., Bourlat, S., & Ab, S. (2013). *MarCoast II - Marine and Coastal Environmental Information Services Ballast Water Option - Application of ecological Niche modelling and earth observation for the risk assessment and monitoring of the invasive species in the Baltic Sea*. *1*, 1–57.

King, N. G., Wilmes, S. B., Smyth, D., Tinker, J., Robins, P. E., Thorpe, J., Jones, L., & Malham, S. K. (2021). Climate change accelerates range expansion of the invasive non-native species, the Pacific oyster, *Crassostrea gigas*. *ICES Journal of Marine Science*, *78*(1), 70–81. https://doi.org/10.1093/icesjms/fsaa189

Kochmann, J., Buschbaum, C., Volkenborn, N., & Reise, K. (2008). Shift from native mussels to alien oysters: Differential effects of ecosystem engineers. *Journal of Experimental Marine Biology and Ecology*, *364*(1), 1–10. https://doi.org/10.1016/j.jembe.2008.05.015

Laing, I., Walker, P., & Areal, F. (2006). Return of the native - Is European oyster (*Ostrea edulis*) stock restoration in the UK feasible? *Aquatic Living Resources*, *19*(3), 283–287. https://doi.org/10.1051/alr:2006029

Laugen, A. T., Hollander, J., Obst, M., & Strand, Å. (2015). The Pacific oyster (Crassostrea gigas) invasion in Scandinavian coastal waters: Impact on local ecosystem services. *Biological Invasions in Changing Ecosystems: Vectors, Ecological Impacts, Management and Predictions*, 230–252. https://doi.org/10.1515/9783110438666-015

Lee, Y. J., Han, E., Wilberg, M. J., Lee, W. C., Choi, K. S., & Kang, C. K. (2018). Physiological processes and gross energy budget of the submerged longline-cultured pacific oyster *Crassostrea gigas* in a temperate bay of Korea. *PLoS ONE*, *13*(7), 1–24. https://doi.org/10.1371/journal.pone.0199752

Leidenberger, S., Obst, M., Kulawik, R., Stelzer, K., Heyer, K., Hardisty, A., & Bourlat, S. J. (2015). Evaluating the potential of ecological niche modelling as a component in marine non-indigenous species risk assessments. *Marine Pollution Bulletin*, *97*(1–2), 470–487. https://doi.org/10.1016/j.marpolbul.2015.04.033

Li, A., Li, L., Wang, W., & Zhang, G. (2020). Acetylome Analysis Reveals Population Differentiation of the Pacific Oyster *Crassostrea gigas* in Response to Heat Stress. *Marine Biotechnology*, *22*(2), 233–245. https://doi.org/10.1007/s10126-020-09947-6

López-Sanmartín, M., Batista, F. M., del Carmen Marín, M., Garrido, I., Quintero, D., Grade, A., Ruano, F., de la Herrán, R., & Navas, J. I. (2015). Detection of Marteilia refringens infecting the European flat oyster *Ostrea edulis* and the dwarf oyster Ostrea stentina in southern Portugal and Spain. *Journal of Invertebrate Pathology, 130*, 52–55. https://doi.org/10.1016/j.jip.2015.07.003

Lourdes Martínez García, Magnus Mårdberg, Sofie Nilèn and Pascal Schlyter (2018). *Effects of salinity levels on the distribution and size of the Pacific oyster (Crassostrea gigas) along the west coast of Skåne*, [Student report]. Lund University

Malmedal, T. Ersland, T., E., (2021). Oyster Registration - Web Application [Bachelor's thesis]. University of Agder.

Martinelli, J. C., Lopes, H. M., Hauser, L., Jimenez-Hidalgo, I., King, T. L., Padilla-Gamiño, J. L., Rawson, P., Spencer, L. H., Williams, J. D., & Wood, C. L. (2020). Confirmation of the shell-boring oyster parasite Polydora websteri (Polychaeta: Spionidae) in Washington State, USA. Scientific Reports, 10(1), 1–14. https://doi.org/10.1038/s41598-020-60805-w

McKindsey, C. W., Thetmeyer, H., Landry, T., & Silvert, W. (2006). Review of recent carrying capacity models for bivalve culture and recommendations for research and management. *Aquaculture*, *261*(2), 451–462. https://doi.org/10.1016/j.aquaculture.2006.06.044

Meng, J., Wang, T., Li, L., & Zhang, G. (2018). Inducible variation in anaerobic energy metabolism reflects hypoxia tolerance across the intertidal and subtidal distribution of the Pacific oyster (Crassostrea gigas). *Marine Environmental Research*, *138*(April), 135–143. https://doi.org/10.1016/j.marenvres.2018.04.002

Morga, B., Arzul, I., Chollet, B., & Renault, T. (2009). Infection with the protozoan parasite *Bonamia ostreae* modifies in vitro haemocyte activities of flat oyster *Ostrea edulis*. *Fish and Shellfish Immunology*, *26*(6), 836–842. https://doi.org/10.1016/j.fsi.2009.03.018

Morga, B., Renault, T., Faury, N., Lerond, S., Garcia, C., Chollet, B., Joly, J. P., Lapègue, S., Harrang, E., & Arzu, I. (2017). Contribution of in vivo experimental challenges to understanding flat oyster *Ostrea edulis* resistance to *Bonamia ostreae*. *Frontiers in Cellular and Infection Microbiology*, *7*(OCT), 1–13. https://doi.org/10.3389/fcimb.2017.00433

Mortensen, S. H., Aavik, K., Lyngstad, T. M., & Norheim, K. (2021). The surveillance and control programme for *Bonamiosis* and *Marteiliosis* in European flat oysters (*Ostrea edulis sp*.) and the blue mussel (*Mytilus edulis sp*.) in Norway 2020. Surveillance Programmes for Terrestrial and Aquatic Animals in Norway. https://www.hi.no/templates/reporteditor/report-pdf?id=45337&38570693

Mortensen, S., Strand, A., Bodvin, T., Alfjorden, A., Skar, C. K., Jelmert, A., Aspán, A., Sælemyr, L., Naustvoll, L. J., & Albretsen, J. (2016). Summer mortalities and detection of ostreid herpesvirus microvariant in Pacific oyster *Crassostrea gigas* in Sweden and Norway. *Diseases of Aquatic Organisms, 117*(3), 171–176. https://doi.org/10.3354/dao02944

Nahrgang, J., Brooks, S. J., Evenset, A., Camus, L., Jonsson, M., Smith, T. J., Lukina, J., Frantzen, M., Giarratano, E., & Renaud, P. E. (2013). Seasonal variation in biomarkers in blue mussel (*Mytilus edulis*), Icelandic scallop (Chlamys islandica), and Atlantic cod (Gadus morhua)-Implications for environmental monitoring in the Barents Sea. *Aquatic Toxicology*, *127*(9037), 21–35. https://doi.org/10.1016/j.aquatox.2012.01.009

Naustvoll LJ, Jelmert A, Heiberg S. (2019). *Stillehavsøsters- effekt av ryddeaksjoner*. Rapport fra Havforskningsinstituttet.

Nehls, G., Diederich, S., Thieltges, D. W., & Strasser, M. (2006). Wadden Sea mussel beds invaded by oysters and slipper limpets: Competition or climate control? *Helgoland Marine Research*, *60*(2), 135–143. https://doi.org/10.1007/s10152-006-0032-9

Nielsen P, Olsen J, Geitner K & Nielsen MM. (2020). Konsekvensvurdering af fiskeri af blåmuslinger, europæisk østers, stillehavsøsters og søstjerner i Løgstør Bredning 2020/2021 DTU Aqua-rapport nr. 374-2020. Institut for Akvatiske Ressourcer, Danmarks Tekniske Universitet. 60 pp. + bilag

Nielsen, P., Geitner, K., Jakobsen, J., Köppl, C.J., & Petersen, J.K. (2018). Fagligt grundlag for forvaltningsplan for udvikling af bæredygtige fiskerier af muslinger og østers i Vadehavet. DTU Aqua-rapport nr. 334-2018. Institut for Akvatiske Ressourcer, Danmarks Tekniske Universitet. 33 pp. + bilag.

Nielsen, P., Geitner, K., Olsen, J. & Nielsen, M.M. (2018). Konsekvensvurdering af fiskeri af flad østers, stillehavsøsters og søstjerner i Nissum Bredning 2018/2019. DTU Aqua-rapport nr. 333-2018. Institut for Akvatiske Ressourcer, Danmarks Tekniske Universitet. 52 pp. + bilag

Nielsen, P., Geitner, K., Olsen, J., Nielsen, M., M., (2018). *Notat vedrørende fiskeri af blåmus-linger, søstjerner, europæisk østers og stillehavsøsters i Løgstør Bredning 2018/2019*. Retrieved from https://www.aqua.dtu.dk/-/media/Institutter/Aqua/Publikationer/Notater/Notat-vedr-fiskeri-af-blaamuslinger-soestjerner-oesters-Loegstoer-Bredning-2018-2019.ashx?la=da&hash=B82991648F5508049E852587744E27CF49C73849

Nielsen, P., Geitner, K., Olsen, J., Nielsen, M., M., (2019). *Notat vedrørende fiskeri af blåmus-linger, søstjerner, europæisk østers og stillehavsøsters i Løgstør Bredning 2019/2020*. Retrieved from https://www.aqua.dtu.dk/-/media/Centre/DSC_Forskning/Raadgivning/Notat-fiskeri-blaamuslinger-soestjerner-europaeisk-oesters-stillehavsoesters-Loegstoer-Bredning-2019.ashx?la=da&hash=E030D589915B0CADAE06852F54E1B59940474AA4

Nielsen, P., Nielsen, M., M., Geitner, K., (2019). *Notat vedrørende fiskeri af europæisk østers og søstjerner i Nissum Bredning 2019/2020*. Retrieved from https://www.aqua.dtu.dk/-/media/Centre/DSC_Forskning/Raadgivning/Notat-fiskeri-europaeisk-oesters-soestjerner-i-Nissum-Bredning-2019-2020.ashx?la=da&hash=03D48D4A5C2A9030E3783084F1A7EE1F27F722AF

Nielsen, P., Nielsen, M., M., Geitner, K., (2020). *Notat vedrørende fiskeri af søstjerner og stillehavsøsters i Nissum Bredning 2020/2021*. Retrieved from https://www.aqua.dtu.dk/-/media/Centre/DSC_Forskning/Raadgivning/Notat-vedr-fiskeri-af-soestjerner-ogstillehavsoesters-i-Nissum-Bredning-2020-2021.ashx?la=da&hash=05E3E851FC998D76D9C23F747E778B365E45FD79

Nielsen, P., Nielsen, M.M., Geitner, K. & Petersen, J.K. (2018). Konsekvensvurdering af fiskeri af blåmuslinger og søstjerner i Løgstør Bredning 2017/2018. DTU Aqua-rapport nr. 330-2019. Institut for Akvatiske Ressourcer, Danmarks Tekniske Universitet. 58 pp. + bilag.

OSPAR (2009) Background document for Ostrea edulis and Ostrea edulis beds. In Haelters J and Francis Kerckhof F (eds), Biodiversity Series 428. Paris: OSPAR Commission, pp. 1–22. (2009). 2009.

Pack, K. E., Rius, M., & Mieszkowska, N. (2021). Long-term environmental tolerance of the non-indigenous Pacific oyster to expected contemporary climate change conditions. *Marine Environmental Research*, *164*, 105226. https://doi.org/10.1016/j.marenvres.2020.105226

Palareti, G., Legnani, C., Cosmi, B., Antonucci, E., Erba, N., Poli, D., Testa, S., & Tosetto, A. (2016). Comparison between different D-Dimer cutoff values to assess the individual risk of recurrent venous thromboembolism: Analysis of results obtained in the DULCIS study. *International Journal of Laboratory Hematology*, *38*(1), 42–49. https://doi.org/10.1111/ijlh.12426

Paul-Pont, I., Dhand, N. K., & Whittington, R. J. (2013). Spatial distribution of mortality in Pacific oysters Crassostrea gigas: Reflection on mechanisms of OsHV-1 transmission. *Diseases of Aquatic Organisms*, *105*(2), 127–138. https://doi.org/10.3354/dao02615

Pearce, J., & Ferrier, S. (2000). Evaluating the predictive performance of habitat models developed using logistic regression. *Ecological Modelling*, *133*(3), 225–245. https://doi.org/10.1016/S0304-3800(00)00322-7

Perry, F., & Jackson, A. (2017). Native oyster (*Ostrea edulis*). *MarLIN - Marine Life Information Network: Biology and Sensitivity Key Information Reviews, [on-Line]*, 1–28. https://dx.doi.org/10.17031/marlinsp.1146.2

Peterson, A. T. (2012). *Ellsworth J B 2000 Surviving Change A survey of educational change mdels Syracuse NY ERIC Clearinghouse on Information and Technology ISBN0-937597-50-3.pdf*. *78*(4), 419–433.

Pettersen, A. K., Turchini, G. M., Jahangard, S., Ingram, B. A., & Sherman, C. D. H. (2010). Effects of different dietary microalgae on survival, growth, settlement and fatty acid composition of blue mussel (*Mytilus galloprovincialis*) larvae. *Aquaculture*, *309*(1–4), 115–124. https://doi.org/10.1016/j.aquaculture.2010.09.024

Pogoda, B., Brown, J., Hancock, B., Preston, J., Pouvreau, S., Kamermans, P., Sanderson, W., & Nordheim, H. Von. (2019). The Native Oyster Restoration Alliance (NORA) and the Berlin Oyster Recommendation: Bringing back a key ecosystem engineer by developing and supporting best practice in Europe. *Aquatic Living Resources*, *32*. https://doi.org/10.1051/alr/2019012

Pogoda, B., Boudry, P., Bromley, C., Cameron, T. C., Colsoul, B., Donnan, D., Hancock, B., Hugh-Jones, T., Preston, J., Sanderson, W. G., Sas, H., Brown, J., Bonacic, K., von Nordheim, H., & zu Ermgassen, P. S. E. (2020). NORA moving forward: Developing an oyster restoration network in Europe to support the Berlin Oyster Recommendation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *30*(11), 2031–2037. https://doi.org/10.1002/aqc.3447

Reise, K., Buschbaum, C., Buttger, H., & Wegner, M. K. (2017). Invading oysters and native mussels: From hostile takeover to compatible bedfellows. *Ecosphere*, *8*(9). https://doi.org/10.1002/ecs2.1949

Reise, K., Buschbaum, C., Büttger, H., Rick, J., & Wegner, K. M. (2017). Invasion trajectory of Pacific oysters in the northern Wadden Sea. *Marine Biology*, *164*(4), 0. https://doi.org/10.1007/s00227-017-3104-2

Ridge, J. T., Gray, P. C., Windle, A. E., & Johnston, D. W. (2020). Deep learning for coastal resource conservation: automating detection of shellfish reefs. *Remote Sensing in Ecology and Conservation*, *6*(4), 431–440. https://doi.org/10.1002/rse2.134

Schikorski, D., Renault, T., Saulnier, D., Faury, N., Moreau, P., & Pépin, J. F. (2011). Experimental infection of Pacific oyster *Crassostrea gigas* spat by ostreid herpesvirus 1: Demonstration of oyster spat susceptibility. *Veterinary Research*, *42*(1), 1–13. https://doi.org/10.1186/1297-9716-42-27

Sezer, N., Kılıç, Ö., Metian, M., & Belivermiş, M. (2018). Effects of ocean acidification on 109Cd, 57Co, and 134Cs bioconcentration by the European oyster (*Ostrea edulis*): Biokinetics and tissue-to-subcellular partitioning. *Journal of Environmental Radioactivity*, *192*(June), 376–384. https://doi.org/10.1016/j.jenvrad.2018.07.011

Shelmerdine, R., & Leslie, B. (2009). Restocking of the native oyster, *Ostrea edulis*, in Shetland : habitat identification study. *Scottish Natural Heritage Commissioned Report*, *396*, 1–33.

Sillanpää, J. K., Ramesh, K., Melzner, F., Sundh, H., & Sundell, K. (2016). Calcium mobilisation following shell damage in the Pacific oyster, Crassostrea gigas. *Marine Genomics*, *27*, 75–83. https://doi.org/10.1016/j.margen.2016.03.001

Simberloff, D., Martin, J.-L., Genovesi, P., Maris, V., Wardle, D. A., Aronson, J., et al. (2012). Impacts of biological invasions: what's what and the way forward. Trends in Ecology & Evolution, 28(1), 58–66. http://doi.org/10.1016/j.tree.2012.07.013

Smyth, D. M., Horne, N. S., Ronayne, E., Millar, R. V., Joyce, P. W. S., Hayden-Hughes, M., & Kregting, L. (2020). Wild gregarious settlements of *Ostrea edulis* in a semi-enclosed sea lough: a case study for unassisted restoration. *Restoration Ecology*, *28*(3), 645–654. https://doi.org/10.1111/rec.13124

Stagličić, N., Šegvić-Bubić, T., Ezgeta-Balić, D., Bojanić Varezić, D., Grubišić, L., Žuvić, L., Lin, Y., & Briski, E. (2020). Distribution patterns of two co-existing oyster species in the northern Adriatic Sea: The native European flat oyster *Ostrea edulis* and the non-native Pacific oyster Magallana gigas. *Ecological Indicators*, *113*(September 2019), 106233. https://doi.org/10.1016/j.ecolind.2020.106233

Strand, Å., Blanda, E., Bodvin, T., Davids, J. K., Jensen, L. F., Holm-Hansen, T. H., Jelmert, A., Lindegarth, S., Mortensen, S., Moy, F. E., Nielsen, P., Norling, P., Nyberg, C., Christensen, H. T., Vismann, B., Holm, M. W., Hansen, B. W., & Dolmer, P. (2012). Impact of an icy winter on the Pacific oyster (*Crassostrea gigas* Thunberg, 1793) populations in Scandinavia. *Aquatic Invasions*, *7*(3), 433–440. https://doi.org/10.3391/ai.2012.7.3.014

Tangen, J., E., (2017). Oppdragsgiver: Fylkesmannen i Telemark ved seniorrådgiver Odd Frydenlund Steen.

Tangen, J., E., (2018). *Stillehavsøsters Overvåking og kartlegging i kommunene Kragerø, Bamble og Porsgrunn, Telemark 2018*. Retrieved from https://jomfrulandnasjonalpark.no/wp-content/uploads/2018/11/Rapport-stillehavs%C3%B8sters-Telemark-2018.pdf

Tangen, J., E., (2019). Oppdragsgiver: Fylkesmannen i Telemark ved seniorrådgiver Odd Frydenlund Steen.

Tangen, J., E., (2020). Oppdragsgiver: Fylkesmannen i Vestfold og Telemark v/rådgiver Hanne Thoen.

Thomas, Y., & Bacher, C. (2018). Assessing the sensitivity of bivalve populations to global warming using an individual-based modelling approach. *Global Change Biology*, *24*(10), 4581–4597. https://doi.org/10.1111/gcb.14402

Thomas, Y., Razafimahefa, N. R., Ménesguen, A., & Bacher, C. (2020). Multi-scale interaction processes modulate the population response of a benthic species to global warming. *Ecological Modelling*, *436*(March), 109295. https://doi.org/10.1016/j.ecolmodel.2020.109295

Thorngren, L., Bergström, P., Dunér Holthuis, T., & Lindegarth, M. (2019). Assessment of the population of *Ostrea edulis* in Sweden: A marginal population of significance? *Ecology and Evolution*, *9*(24), 13877–13888. https://doi.org/10.1002/ece3.5824

Tinelli, A., Santacroce, M. P., Passantino, G., Patruno, R., Desantis, S., Leone, R., Gorgoni, P., & Zizzo, N. (2020). Histological features of Rickettsia-like organisms in the European flat oyster (*Ostrea edulis* L.). *Environmental Science and Pollution Research*, *27*(1), 882–889. https://doi.org/10.1007/s11356-019-07007-8

Van der Schatte Olivier, A., Jones, L., Vay, L. Le, Christie, M., Wilson, J., & Malham, S. K. (2020). A global review of the ecosystem services provided by bivalve aquaculture. *Reviews in Aquaculture*, *12*(1), 3–25. https://doi.org/10.1111/raq.12301

Vera, M., Pardo, B. G., Cao, A., Vilas, R., Fernández, C., Blanco, A., Gutierrez, A. P., Bean, T. P., Houston, R. D., Villalba, A., & Martínez, P. (2019). Signatures of selection for bonamiosis resistance in European flat oyster (*Ostrea edulis*): New genomic tools for breeding programmes and management of natural resources. *Evolutionary Applications*, *12*(9), 1781–1796. https://doi.org/10.1111/eva.12832

Wang, Z., Lu, X., Liang, Y., & Zheng, Z. (2012). A Marteilia-like parasite in blue mussels *Mytilus edulis* in china. *Journal of Aquatic Animal Health*, *24*(3), 161–164. https://doi.org/10.1080/08997659.2012.675926

Waser, A. M., Lackschewitz, D., Knol, J., Reise, K., Wegner, K. M., & Thieltges, D. W. (2020). Spread of the invasive shell-boring annelid *Polydora websteri* (Polychaeta : Spionidae) into naturalised oyster reefs in the European Wadden Sea. *Marine Biodiversity*, *50*(5). https://doi.org/10.1007/s12526-020-01092-6

Waykar, B., & Deshmukh, G. (2012). Evaluation of bivalves as bioindicators of metal pollution in freshwater. *Bulletin of Environmental Contamination and Toxicology*, *88*(1), 48–53. https://doi.org/10.1007/s00128-011-0447-0

Windle, A. E., Poulin, S. K., Johnston, D. W., & Ridge, J. T. (2019). Rapid and accurate monitoring of intertidal Oyster Reef Habitat using unoccupied aircraft systems and structure from motion. *Remote Sensing*, *11*(20). https://doi.org/10.3390/rs11202394

Worm, B., Barbier, E. B., Beaumont, N., Duffy, J. E., Folke, C., Halpern, B. S., Jackson, J. B. C., Lotze, H. K., Micheli, F., Palumbi, S. R., Sala, E., Selkoe, K. A., Stachowicz, J. J., & Watson, R. (2006). Impacts of biodiversity loss on ocean ecosystem services. *Science*, *314*(5800), 787–790. https://doi.org/10.1126/science.1132294

Wrange, A. L., Valero, J., Harkestad, L. S., Strand, Ø., Lindegarth, S., Christensen, H. T., Dolmer, P., Kristensen, P. S., & Mortensen, S. (2010). Massive settlements of the Pacific oyster, Crassostrea gigas, in Scandinavia. *Biological Invasions*, *12*(5), 1145–1152. https://doi.org/10.1007/s10530-009-9535-z

Yang, C. Y., Sierp, M. T., Abbott, C. A., Li, Y., & Qin, J. G. (2016). Responses to thermal and salinity stress in wild and farmed Pacific oysters Crassostrea gigas. *Comparative Biochemistry and Physiology -Part A : Molecular and Integrative Physiology*, *201*, 22–29. https://doi.org/10.1016/j.cbpa.2016.06.024

Yund, P. O., Tilburg, C. E., & McCartney, M. A. (2015). Across-shelf distribution of blue mussel larvae in the northern Gulf of Maine: Consequences for population connectivity and a species range boundary. *Royal Society Open Science*, *2*(12). https://doi.org/10.1098/rsos.150513

Zwerschke, N., Eagling, L., Roberts, D., & O'Connor, N. (2020). Can an invasive species compensate for the loss of a declining native species? Functional similarity of native and introduced oysters. *Marine Environmental Research*, *153*(September), 104793. https://doi.org/10.1016/j.marenvres.2019.104793

Zwerschke, N., Hollyman, P. R., Wild, R., Strigner, R., Turner, J. R., & King, J. W. (2018). Limited impact of an invasive oyster on intertidal assemblage structure and biodiversity: the importance of environmental context and functional equivalency with native species. *Marine Biology*, *165*(5), 1–13. https://doi.org/10.1007/s00227-018-3338-7

Appendix 1

Table 1. Examples of currently used techniques for surveying coastal bivalves. The main field technique (MainTech) alongside any further explanation and usage of equipment (SubsetTech) are given in separate columns. If the studies estimated density (Dens) and individual sizes (Size) it is indicated by 1 (yes) or 0 (no). Substrate type (Subst) is given as: Not mentioned (0), Rock (1), Concrete (2), Boulders (3), Reefs (4), Berg (5), Mud (6), Seagrass (7), Reef (8), Pebble (9), Sand (10), Gravel (11). Minimum and maximum water depth (MinD, MaxD) is given in meters under sea level. In case no mention in samples water depth it is marked by (_).

Reference	Location(s)	Species	Purpose	MainTech	SubsetTech	Dens	Size	Subst	MinD	MaxD
Nehls et al 2006	Schleswig-Holstein, Germany	Blue mussel, Pacific oyster	Monitoring	Manual survey	UAS, Transect with square frame	1	1	6,10	_	_
Cascas et al 2008	the Balearic Island of Menorca, Spain	Flat oyster	Research on disease (*Perkinsus mediterraneus*)	Manual survey	Random collection	0	0	0	_	_
Kochmann et al 2008	Königshafen, Germany	Blue mussel, Pacific oyster	Interaction between two species	Manual survey	Random collection	0	0	6,10	_	_
Eguchi et al 2009	Maizuru Bay, Japan	Blue mussel	Assessment of Antifouling Biocides Contaminations	Manual survey	Random collection	0	1	0	_	_

Morga et al 2009	Quiberon Bay, France	Flat oyster	Research on disease (*Bonamia ostreae*)	Manual survey	Random collection	0	0	0	_	_
Shelmerdine & Leslie 2009	Scotland	Flat oyster	Habitat identification	Manual survey,Video recording	Transect line with frame, ROV	1	1	1,3,6,9 ,10,11	0	9
Wrange et al 2009	Norway, Sweden, Denmark	Pacific oyster	Monitoring	Fishing, Manual survey	Dredge, transect with square frame and aquascope	1	1	0	0	2
Gazeau et al 2010	Yerseke, Netherland	Blue mussel	Research on ocean acidification	Fishing	-	0	0	0	_	_
Schikorski et al 2011	France	Pacific oyster	Research on disease (ostreid herpesvirus)	Manual survey	Random collection	0	0	0	_	_
Strand et al 2012	Norway, Sweden, Denmark	Pacific oyster	Research on mortality	Manual survey	Transect line with square frame and aquascope	0	0	0	0	1.8
Wang et al 2012	China	Blue mussel	Research on disease (*Marteilia sp.)*	Manual survey	Random collection	0	1	0	_	_
Nahrgang et al 2013	Tromsø, Norway	Blue mussel	Research on biomarkers	Manual survey	Random collection	0	1	0	_	_
Paul-Pont et al 2013	Woolooware Bay, Australia	Pacific oyster	Research on mortality	Manual survey	Random collection	0	1	6	_	_
Haaverstad 2015	Vestfold and the Agder, Norway	Pacific oyster	Monitoring	Manual survey	Transects with square frame, snorkeling	1	0	1,5,6	0	2

López-Sanmartín et al 2015	Portugal, Spain	Flat oyster, Dwarf oyster	Research on disease (*Marteilia refringens*)	Manual survey	Random collection	0	0	0	–	–
Yund et al 2015	The Gulf of Maine, USA	Blue mussel,True mussel	Mapping	Fishing	Water pump	0	0	0	0	5
Burioli et al 2016	Italy	Pacific oyster	Research on disease (ostreid herpesvirus)	Manual survey	Random collection	0	1	0	0	0.5
Haaverstad 2016	Vestfold and the Agder, Norway	Pacific oyster	Monitoring	Manual survey	Transects with square frame, snorkeling	1	0	1,5,6	0	2
Mortensen et al 2016	Sweden, Norway	Pacific oyster	Research on mortality (ostreid herpesvirus)	Manual survey	Visual observation and sampling	0	0	0	–	–
Sillanpää et al 2016	Sylt, Germany	Pacific oyster	Research on Pacific oyster shell	Manual survey	Random collection	0	1	0	–	–
D'Auriac et al 2017	Norway, Sweden, Denmark	Pacific oyster	Impacts of invasive species	Manual survey	Random collection	0	1	0	–	–
Barille et al 2017	Bourgneuf Bay, France	Pacific oyster	Research on Pacific oyster shell	Manual survey	Random collection	0	0	1,6	–	–
Faust et al 2017	European waters	Pacific oyster	Research on establishment of invasive species	Manual survey	Random collection	0	1	0	–	–
Morga et al 2017	Southern Brittany, France	Flat oyster	Research on disease (*Bonamia ostreae*)	Manual survey	Random collection	0	0	0	–	–

Nielsen et al 2017	Løgstør Bredning, Denmark	Blue mussel, Pacific oyster	Impact assessment of fishing	Fishing	_	1	0	0	0	3
Reise et al 2017	Sylt, Island	Pacific oyster	Monitoring	Manual survey	Random collection	1	1	6	_	_
Tangen 2017	Telemark, Norway	Pacific oyster	Monitoring, Mapping	Manual survey	Transects and sampling squares	1	0	1,3,4	0	2.8
Lee et al 2018	Geoje Hansan Bay, South Korea	Pacific oyster	Research on physiological processes	Manual survey	Random collection	0	0	0	_	_
Lourdes et al 2018	Skåne, Sweden	Pacific oyster	Salinity and distribution relation	Photography	Go pro camera	0	0	1,2	0	0.5
Meng et al 2018	Bayuquan, China	Pacific oyster	Research on anaerobic energy metabolism	Manual survey	Random collection	0	1	0	10	13
Naustvoll et al 2019	Agder, Norway	Pacific oyster	Effect of removal programmes	Manual survey	Transect line	1	0	0	0	2
Nielsen et al 2018	Nissum Bredning, Denmark	Flat oyster, Pacific oyster	Impact assessment of fishing	Fishing	Scraper, snorkeling, brile	1	0	0	0	3
Nielsen et al 2018	Løgstør Bredning, Denmark	Blue mussel, Flat oyster, Pacific oyster	Impact assessment of fishing	Fishing	_	1	0	0	0	3
Sezer et al 2018	Çanakkale, Turkey	Flat oyster	Effects of ocean acidification	Fishing	_	0	1	0	_	_

Stagličić et al 2018	Western Istrian coast, Croatia	Flat oyster,Pacific oyster	Monitoring	Manual survey	Diving	1	0	1	0	6
Tangen 2018	Telemark, Norway	Pacific oyster	Monitoring, Mapping	Manual survey	Transects with square frame and aquascope	1	0	1,3,4	0	2.5
Yang et al 2016	Denial Bay, Australia	Pacific oyster	Research on Responses to thermal and salinity stress	Manual survey	Random collection	0	1	0	_	_
Zwerschke et al 2018	UK, Ireland, France	Flat oyster, Pacific oyster	Impacts of invasive species	Photography	Nikon D90 camera	1	0	1,6,11	_	_
Allison et al 2019	East coast of Essex, UK	Flat oyster	Monitoring	Fishing	Ladder dredge	1	1	6,10,11	0	4
Ghaffari et al 2019	Qingdao and Xiamen, China	Pacific oyster, Portuguese oyster	Research on physiological and molecular responses	Manual survey	Random collection	0	1	0	_	_
Goedknegt et al 2019	The Wadden Sea, Denmark, Germany	Blue mussel, Pacific oyster	Relation between Pacific oyster and parasite distribution	Manual survey	Random collection	0	1	0	_	_
Hartwell et al 2019	Alaska, USA	Blue mussel	Research on metal,metalloid concentrations in fjords	Manual survey	Random collection	0	0	0	_	_
Bolander et al 2019	Zealand, Denmark	Pacific oyster	Mapping	Manual survey	Transects line, Snorkeling	0	1	0	_	_

Kazour & Amara 2019	Camiers, France	Blue mussel	Studying potential of blue mussel in monitoring pollution	Manual survey	Random collection	0	1	0	_	_
Luke et al 2019	Langstone & Chichester Harbours, UK	Flat oyster	Research on stock size	Fishing	Dredge	1	1	0	_	_
Nielsen et al 2019	Nissum Bredning, Denmark	Flat oyster, Pacific oyster	Impact assessment of fishing	Fishing	Scraper, snorkeling, brile	1	0	0	0	3
Nielsen et al 2019	Løgstør Bredning, Denmark	Blue mussel, Flat oyster, Pacific oyster	Impact assessment of fishing	Fishing	_	1	0	0	0	3
Nielsen et al 2019	The Wadden Sea, Denmark	Blue mussel, Pacific oyster	monitoring	Photography, Manual survey	UAS, transect with square frame	0	0	0	0	1
Ridge et al 2019	North Carolina, USA	Eastern oyster	Mapping	Photography	UAS	0	0	7,8	_	_
Tangen 2019	Telemark, Norway	Pacific oyster	Monitoring, Mapping	Manual survey	Transects with square frame and aquascope	1	0	1,3,4	0	2.5
Thorngren et al 2019	Skagerrak, Sweden	Flat oyster	Monitoring	Video recording	Go pro camera	1	0	1,10	0	10
Tinelli et al 2019	The Apulian coastline, Italy	Flat oyster	Research on disease (Rickettsiales)	Manual survey	Random collection	0	0	0	_	_
Vera et al 2019	Ireland,Spain,France,Denmark,Scotland	Flat oyster	Research on disease (bonamiosis)	Manual survey	Random collection	0	0	0	_	_

Windle et al 2019	North Carolina, USA	Eastern oyster	Monitoring	Photography	UAS	1	0	7,8	_	_
Zwerschke et al 2019	Lough Foyle, Ireland	Flat oyster, Pacific oyster	Impacts of invasive species	Manual survey	Random collection and purchased from local growers	1	0	0	_	_
Ahlers et al 2020	The west coast of Scania, Sweden	Pacific oyster	Monitoring	Video recording	Go pro camera	1	0	1,2	0	0.5
Boukadida et al 2020	Tunisia, France, Portugal, UK	Blue mussel	Temperature and pollution relation with larval distribution	Manual survey	Random collection	0	0	0	_	_
Coolen et al 2020	North sea	Blue mussel	Research on population genetic differentiation	Manual survey	Diving	0	0	1,11	0	27
Helmer et al 2020	The solent, UK	Flat oyster	Research on disease (*Bonamia exitiosa*)	Fishing	Dredge	0	0	0	_	_
Li et al 2020	China	Pacific oyster	Response to heat stress	Manual survey	Random collection	0	0	0	_	_
Nielsen et al 2020	Nissum Bredning, Denmark	Flat oyster, Pacific oyster	Impact assessment of fishing	Fishing	Scraper, snorkeling, brile	1	0	0	0	3
Nielsen et al 2020	Løgstør Bredning, Denmark	Blue mussel, Flat oyster, Pacific oyster	Impact assessment of fishing	Fishing	_	1	0	0	0	3

Smyth et al 2020	Strangford Lough, Ireland	Flat oyster	Research on restoration	Photography	–	1	1	1,6,9,10	–	–
Tangen 2020	Vestfold and Telemark, Norway	Pacific oyster	Monitoring, Mapping	Manual survey	Transects with square frame and aquascope	1	0	1,3,4	0	2.5
Waser et al 2020	The Wadden Sea, Denmark, Germany	Pacific oyster	Parasite detection (*Polydora websteri*)	Manual survey	Random collection	0	0	0	–	–
Aamodt 2021	Karmøy, Norway	Pacific oyster	Mapping	Manual survey	Transect line	1	0	0	0	1
Mortensen et al 2021	Norway	Blue mussel, Flat oyster	Parasite detection (bonamiosis, marteiliosis)	Manual survey	Random collection, snorkeling, diving	0	0	0	–	–

Appendix 2

Table 2. Summary of modelling studies of coastal bivalves including location, species, the aim of the project, and modelling technique.

Reference [author(s) year]	Location(s)	Species	Purpose	Modelling technique
Laugen et al 2015	Scandinavia	Pacific oyster	Identifying suitable habitat, larval dispersal	Niche modelling, Oceanographic modelling
D'Auriac et al 2017	Scandinavia	Pacific oyster	Identifying distribution pattern	Oceanographic modelling
Birkeland et al 2018	Norway	Pacific oyster	Identifying potential distribution	Oceanographic modelling
Thomas & Bacher 2018	North-East Atlantic coast	Pacific oyster/Blue mussel/Mediterranean mussel	Identifying sensitivity to global warming	Individual modelling
Holbach et al 2020	The western Baltic Sea	Blue mussel	Nutrient mitigation by mussel farms	Oceanographic modelling
King et al 2020	European waters	Pacific oyster	Identifying expansion range by reproduction	Mechanistic modelling
Pack et al 2020	UK	Pacific oyster	Predicting future distribution	Oceanographic modelling
Thomas et al 2020	North-East Atlantic coast	Blue mussel	Modulate the response to global warming	Individual modelling
Bergstrom et al 2021	Sweden	Pacific oyster/Flat oyster	Identifying high-density areas	Distribution modelling

Appendix 3

Table 3. Result of mapping survey performed by ROV in July 2020. The table indicates the location name and coordinates of the study site, the source that led us to that site, the size (m2) of the area that was inspected, the bottom substrate, minimum and maximum water depth, and presence of bivalves. The column O.E. represents Ostrea edulis, M.E. represents Mytilus edulis and C.G. represents Crassostrea gigas. An 'X' marked in the bivalve columns indicates 'Absent' while a number estimates the number of individuals found in the area.

Location	Longitude/Latitude	Source	Size (m^2)	Substrate	Depth(min/max)	O.E.	M.E.	C.G
Breidvika	59.70518/5.39179	Citizen science	350	Sand	58/103	X	X	X
Sandvikvåg	59.93057/5.32791	SNOK	410	Sand/Rock	105/123	X	X	X
Skåravika	60.13938/5.15212	IMR	717	Sand	80/220	5+	X	X
Torangsvåg	60.12079/5.15988	SNOK	118	Rock	190/300	X	X	X
Steinvik	60.00055/5.118	IMR	122	Rock	210/500	X	X	X
Botnvika	60.24023/5.29115	Citizen science	480	Sand/Rock	56/195	X	X	3
Flatholmen	60.32102/4.98073	Citizen science	274	Sand	60/100	12+	X	X
Pollen-godvika	60.28935/5.09199	IMR	273	Sand/Rock	50/90	5+	3	X
Mjelkevika	60.26972/5.32387	Citizen science	485	Sand	70/200	10+	X	2
Lønningshavn	60.27565/5.2193	Citizen science	46	Mudd	65/90	X	X	2
Austvika	59.27566/5.54763	Citizen science	265	Sand/Mudd	70/130	15+	15+	3+
Møllevegen	59.33672/5.27922	Citizen science	238	Sand	55/115	15+	X	8+

Torvastadvegen	59.36659/5.24755	Citizen science	402	Sand/Mudd	75/250	150+	150+	X
Eigeøry	58.44096/5.88509	Citizen science	86	Sand/Rock	65/100	3+	X	X
Sveigeholmen	58.28626/6.65458	Citizen science	241	Sand	85/230	15+	10+	3+

Appendix 4

Protocol for mapping coastal bivalves in new areas:

1. Identify the areas that have a potential for coastal bivalve's presence through using resources such as marine research centers database, citizen science, and modelling studies.

2. Visit the site to check the environmental conditions and answer the following 3 questions:

A: Is the location accessible for performing the survey?

B: Is there any sign of dead or alive bivalves in the area? Note: Do a quick visual survey.

C: Which type of sampling techniques are suitable for this area? Note: Use the decision tree (Figure 1).

3. Each team must have a datasheet to take note of all the data that is collected during the survey including the methods that have been used for sampling.

4. Follow the following rules for each sampling technique:

A: Transect method by foot in areas shallower than 1 meter:

After searching in nearshore areas to find the starting point of bivalves, 3 line transects will be conducted. While 2 people are responsible for each transect, researchers use either 25 x 25 cm or 50 x 50 cm metal squares for sampling. The first person begins to search inside the square while wearing gloves to find any bivalves. The other member must write down the essential information such as location name, time, date, substrate, water depth, bivalves dimension (length, width, height). Transects continue until it is too deep to reach the bottom with bare hands. Each data sheet must clearly show how many of each species has been found during the transect. Note: Both live and dead bivalves must be counted however, there is no need to measure any dimension of the dead bivalves.

B: Transect method by snorkeling and diving in areas deeper than 1 meter:

Conduct a line transect to perform the survey by snorkeling/diving while the other team member must have a clear view for safety reasons. The snorkeler/diver must check the presence and absence of each species in the transect line. Since it is not usually possible to measure any dimension or check the vital status of the bivalves the snorkeler/diver should only estimate the density of each species by categorizing them into small, medium, high levels. There should be hand gestures for communication between team members to inform the presence and absence of the bivalves during the survey. The person who is responsible to take note of the survey result should take note of the location name, time, date, substrate, presence, and absence of each species in the datasheet.

C: Sampling by aerial and underwater drone:

Conduct a systematic pattern for survey while one person is responsible for the operation of the drone and the other must take notes about the location name, time, date, substrate, and any other extra information presented from the drone operator. The drone operator must record a video and take pictures during the entire process and announce the presence and absence of the species to the other team member. All the recorded files must be transferred to the computer hard drive after the survey for further analysis. In the video analysis process, all the results should be checked and the counting of the bivalves must be added to the existing data. All the recorded files should be documented in a secure place in case of any need for re-examination. Note: If possible, the researcher should take note of the vital status of the bivalves in the video to analyze the process.

7. At the end of the mapping survey all team members must recheck the datasheet to be sure that all sections of the data sheet are filled in.

8. The outcome of the mapping survey must contain the following information: The name and longitude/latitude of the location, time and date of the survey, team members name, substrate, water depth range (min/max) in the area, presence/absence of bivalves, count of the live/dead bivalves (if possible), length and width and height of live bivalves (if possible).

9. After the survey one person must be responsible to gather all the data sheets and entering all the data and prepare the final report of the survey.

Appendix 5

Protocol for monitoring coastal bivalves:

1. Study the previous data about the location to have a better understanding of the site.

2. Unify all the previous data and identify any potential lack of data in the previous study (water depth range, the vital status of the bivalves, substrate, etc.)

3. Visit the location for performing the survey. Note: use the previous sampling techniques only if there is no better method suitable in the area.

4. Follow the mapping protocol for performing the survey.

5. After preparing the final report of the survey, all data must be added to existing data from the previous attempt to have a clear and unified document about the location categorized by each survey attempt.

6. Analyse the data to compare the current density of the species with the previous surveys in the same location.

7. Analyse the data to estimate mortality in the area (if the dead bivalves were counted during the current and previous surveys).

8. The outcome of the monitoring project must contain the following information:

A: Trend of the density of each type of bivalves that were a presence in the area during current and previous surveys.

B: Trend of the mortality rate of the presence of bivalves (if it was possible to measure vital status)

C: A complete version of each survey that contains all of the outcomes of the mapping survey in each attempt that can be used separately.

9. All monitoring projects must be able to fulfill the aim of the study (revealing the impact of clearing programmes of Pacific oysters, invasion trend in the area, etc.)