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Classification of invasion boundaries of *Magallana gigas* on the Swedish west coast and involvement of stakeholders in the dynamic management plan

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Popular scientific summary

The management of invasive species is notoriously difficult, especially as some species can have both negative and positive effects on the environment and on society. The invasive Pacific oyster (*Magallana gigas*) is one of those species and is since 2006 established on the Swedish west coast. Generally, management measures depend on the severity of the invasion, hence on the oysters' invasion stage. When this varies on a limited geographical scale, as for the Pacific oyster along the Swedish west coast, there is a need for a dynamic management that is adaptive to changing conditions over space and time. However, often such tools are missing. Therefore, this study aimed at providing a classification of the oysters' invasion boundaries along the Swedish west coast, hence a basis for the design of a dynamic management model. Further, as dynamic management depends on the acceptance and contribution of stakeholders, a survey to investigate municipality representatives' knowledge level and perceptions of the oysters was conducted. Based on the results, a model designed to enable classification of invasion stages was revised and applied to the Pacific oysters in Sweden. The model showed decreasing invasion stages along the west coast, from established populations in the northern municipalities to absence of oysters in the south. However, this presents only a first screening of the coastline and further contributions from the end users, for example from municipalities, is needed to refine the classification. Overall, municipality stakeholders showed a low knowledge level of the Pacific oyster, and further, a low willingness to participate in management actions, likely due to missing resources such as funding. These challenges need to be addressed to allow an efficient and successful management of the oysters. Based on the results of the survey, fact sheets and project reports could increase stakeholders' knowledge levels, and providing municipality stakeholders with the chance to participate in knowledge platforms might lead to co-creation of knowledge and better involvement. This work provides a basis for development of a dynamic management of the Pacific oyster in Sweden through classification of invasion stages along the coast and identification of stakeholders' knowledge, attitudes, and needs.

Abstract

The Pacific oyster (*Magallana gigas*) is one of the most invasive species globally and can have negative and positive effects on the ecosystem. Since 2006, the Pacific oyster is established in Sweden. Previous research raised the need for a dynamic management, as the oysters' invasion stages vary along the coastline. This study provides a classification of the invasion boundaries along the west coast as a base for the dynamic management of the species. For this, a previously designed model was revised in an iterative process and then used to determine the oysters' invasion stages. Moreover, to facilitate further stakeholder involvement into the management process, a survey was conducted to investigate municipality stakeholders' knowledge level and attitudes towards the Pacific oyster. The results from the model showed decreasing invasion stages of the oysters along the coast, from established populations in the north to absence of oysters in the south. Results presented are a first classification of the coastline and further contributions, provided for example by municipalities, is needed to refine the classification. In general, stakeholders showed a low level of knowledge of the oysters and a low willingness to participate in management, likely due to a lack of resources. Findings also suggest that providing easy-to-assimilate knowledge compilations such as fact sheets, and establishment of knowledge platforms for stakeholders might lead to a co-creation of knowledge and facilitate involvement.

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1 Introduction

Invasive alien species (IAS) pose one of the major threats to biodiversity nowadays and, in combination with climate change, are expected to have increasingly adverse effects not only on ecosystems but also on the services they provide (Crowl et al., 2008). Moreover, invasive species management has become a socio-ecological problem with effects on human health and the economy (Bax et al., 2003). Thus, there is an urgent need to sustainably manage AIS and to protect not only our biodiversity but our ecosystems in general as well as the services they provide for human wellbeing (Mainka & Howard, 2010). Invasion in the marine environment is caused by anthropogenic activities, either unintentionally, e.g., through shipping and the transport of ballast water, or intentionally, e.g., through aquaculture (Geburzi & McCarthy, 2018).

Once a marine invasive species has been introduced to an environment and has passed the "ecological filter" of new biotic and abiotic conditions, it goes through different invasion phases before becoming a fully established species (Reise et al., 2006; Blackburn et al., 2011; Geburzi & McCarthy, 2018). Based on the degree of establishment, four invasion stages are often differentiated; Before invasion, Lag time, Expansion, and Persistence (Figure 1, Geburzi and McCarthy, 2018). Depending on the stage of invasion different management actions apply. Whereas the prevention of invasions is arguably the most effective measure (Pyšek & Richardson, 2010). However, if a species has been introduced, early detection of the arrival may render immediate eradication as successful. With increasing abundance and establishment of the invasive species however, eradication becomes difficult, hence containment measures to prevent further dispersal are necessary. If an invader has reached the last stage and is persistent in an environment, meaning the species is fully established, efforts should be taken to mitigate negative effects and protect native species. In general, invasion management in the marine environment is considered far more challenging than on land (Geburzi & McCarthy, 2018).

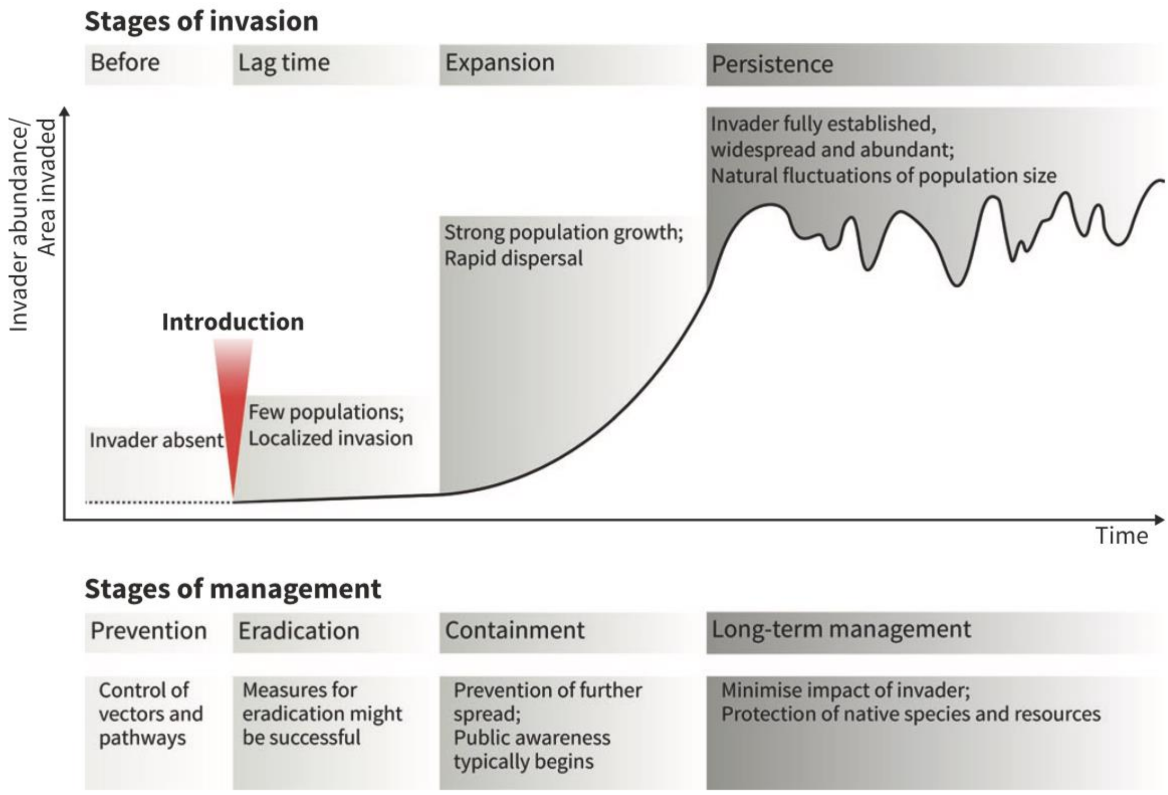

Figure 1: Invasion curve of marine invasive species by Geburzi and McCarthy (2018).

This raises the need for different management for varying invasion stages, i.e., a dynamic management approach, that is adaptative to changing conditions in time and space (Maxwell et al., 2015). Especially on a local scale, such dynamic management models have been proven to be effective as it allows to adjust the management based on the population dynamics and invasion stages of IAS (Buchadas et al., 2017). An example of a local dynamic management model of an invasive species is the Arctic red king crab (*Paralithodes camtschaticu*) in Norway, which was introduced into the Barents Sea from Russia in the 1960s and 70s. As total eradication would be both costly and was not feasible, the Norwegian government developed a dynamic management approach where eradication measures (open-access fishery) were combined with commercial exploitation (regulated commercial fishery). Hence, since 2008, high fishing pressure was successful in limiting further expansion of the crabs, while the establishment of a viable crab fishery was able to provide an income for coastal communities (Sundet & Hoel, 2016).

One of the most invasive species globally is the Pacific oyster, *Magallana gigas* (Thunberg 1973) which has its origins in the Japanese Sea (Laugen et al., 2015). *Magallana gigas* (hereafter: Pacific oyster, oyster) is one of the main aquaculture species worldwide (Wrange et al., 2010) and was introduced for farming purposes in Europe in the 1960s (Laugen et al., 2015). Generally, it was assumed that low water temperatures would prevent reproduction, and hence natural dispersal of the oyster, however, a series of warm summers and mild winters allowed a successful reproduction of the oysters in the wild (Wrange et al., 2010). Hence, 30 years after the first introductions of the species in Europe, feral populations have settled in Germany and the Netherlands (Laugen et al., 2015).

As an intertidal species, the Pacific oyster shows high tolerance to changing abiotic conditions and can withstand extreme temperatures from below 0 °C (Diederich et al., 2005) to ~ 30 °C (Le Gall & Raillard, 1988). As an ecosystem engineer, the species is able to modify its environment (Jones et al., 1994), e.g., by forming reefs and, thereby, provide an habitat for other species due to its physical structure, alter water flow and trap sediment (Ruesink et al., 2005). The oysters can have both negative and positive effects on ecosystems, i.e., habitat alterations and competition over space with native species (Laugen et al., 2015), and increase of biodiversity (Norling et al., 2015) and provisioning (Mortensen et al., 2019), respectively.

The Pacific oyster was introduced in Scandinavia in the 1970s and nowadays feral populations of the oysters are found from Denmark, to the west coasts of Sweden and Norway (Wrange et al., 2010). In Sweden, the Pacific oyster was farmed between 1973 and 1976 in northern Bohuslän (Tjärnö) (Eklund et al., 1977). However, it was not until 2006, that the oysters were first sighted in large numbers along the Swedish west coast (Laugen et al., 2015). In recent years the Pacific oyster has expanded its populations and distribution in Scandinavia (Wrange et al., 2010; Laugen et al., 2015). And neither extreme winter conditions (Strand et al., 2011; Strand et al., 2012) nor summer mortalities (Mortensen et al., 2016) have been able to eradicate the oyster populations. Along the Swedish coastline, the invasion stages of the oysters differ greatly, with high densities in the north and low densities in the south (Wrange et al., 2010; Laugen et al., 2015). In the Baltic, currently no Pacific oysters are present (Laugen et al., 2015).

The existence of different invasion stages along the coastline opens for the possibility of a dynamic management approach of the species in Sweden. To achieve this, the boundaries between different invasion stages must be determined first.

In previous projects, a model to determine the invasion stages of the oysters was developed (Le Gall, 2022, Figure 2). By using field data in combination with physical-chemical parameters (temperature and salinity), seven different invasion stages can be being distinguished in the model, based on key life or population stages of the oysters (Figure 2).

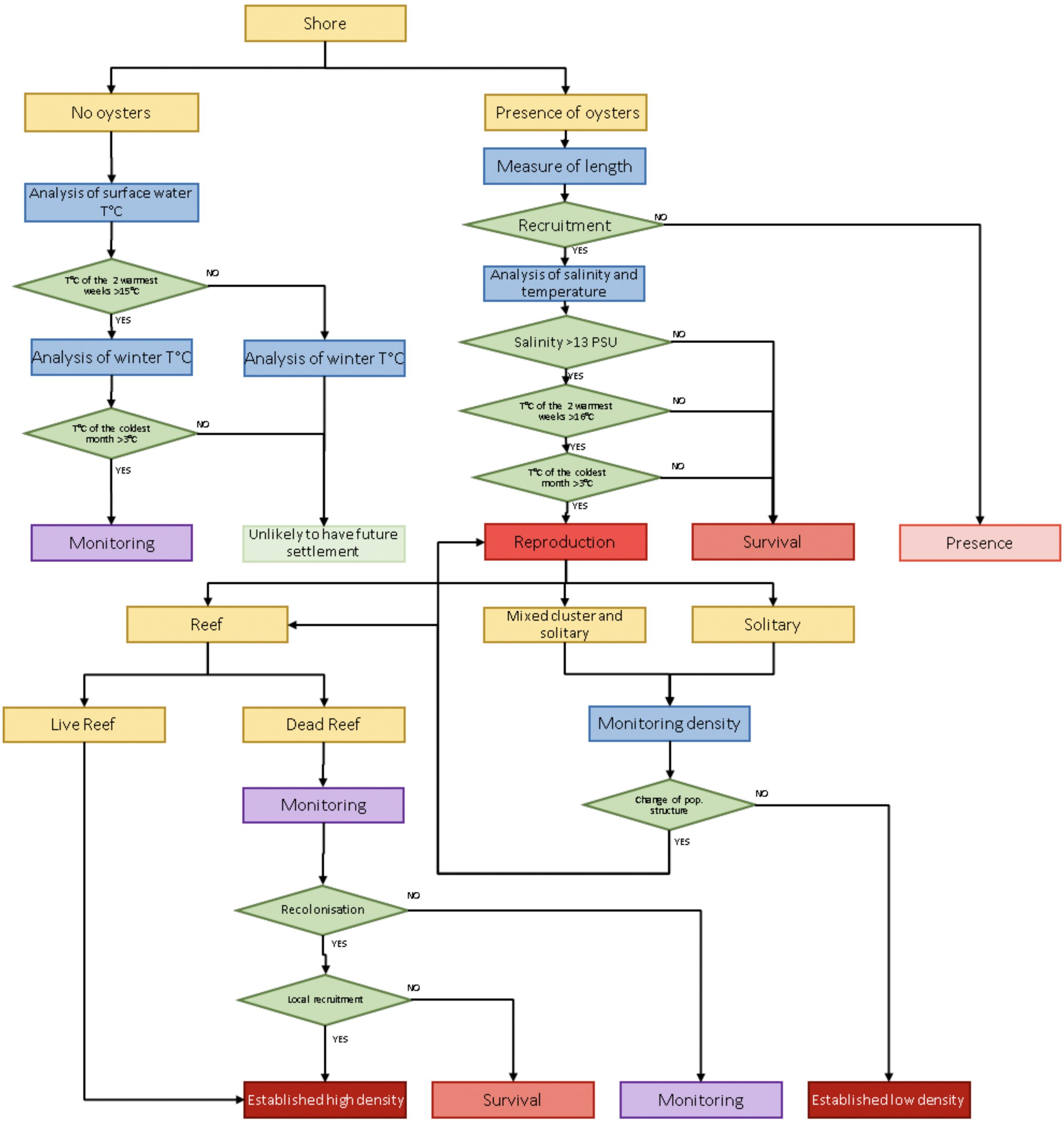

Figure 2: Classification model to determine invasion stages of the Pacific oyster according to Le Gall (2022). The model can be followed at a given site and allows to distinguish between seven invasion stages; Absence/Unlikely to have future settlement, Absence/Monitoring, Presence, Survival, Reproduction, Established low density, and Established high density.

Le Gall (2022) describes five criteria to distinguish between the different stages of invasion; Recruitment, Reproduction, Juvenile survival, Population structure, and Changes of population structure over time. Recruitment describes a populations' ability to recruit new juveniles, either through larvae drift (foreign recruitment) or through local reproduction. In the model, the recruitment test analyses foreign recruitment, while reproduction analyses the ability of a population to reproduce locally, thus, for a population to be self-sufficient in the recruitment of new larvae (Le Gall, 2022). Reproduction is determined through the analysis of local abiotic conditions, as it mainly depends on temperature and salinity during the reproductive period (Ruiz et al., 1992). Further, temperature during the winter determines the survival of the oyster recruits during the first year (Child & Laing, 1998; Le Gall, 2022).

The first two invasion stages refer to sites where oysters are not present. Analysing the local abiotic conditions for reproduction and juvenile survival allow to identify whether a site gets classified as *Unlikely to have future settlement* or *Monitoring*. If the conditions for local reproduction are fulfilled, future invasion is considered possible and monitoring of the area is necessary to allow an early detection and activation of management actions (Le Gall, 2022).

At sites with oysters present, tests for reproduction and juvenile survival allow to distinguish between *Presence*, *Survival* and *Reproduction*. *Presence* populations are merely surviving, which means they don't have any new larvae coming to the population. However, if foreign recruitment is taking place, but local conditions for reproduction and/or juvenile survival are not fulfilled, the population is not self-sufficient as it depends on larvae drift from other locations and gets classified as *Survival*. Finally, if both recruitment and the local conditions for reproduction are given, then a population gets defined as *Reproduction*. Populations in this invasion stage are reproducing locally, hence, are self-sufficient in sustaining the population and can contribute to an expansion of the invasion (Le Gall, 2022).

After this point, all populations except for reef formations are defined as *Reproduction*, however, depending on the identified population structure and changes in the population structure over time further classification can be done. In general, three population structures are distinguished depending on the oysters' density; solitary, cluster and reef formation. If oysters are present in the lower density categories, solitary or mixed cluster and solitary, it needs to be determined by monitoring whether a population is filling its ecological niche. If no changes in the population structure over time are observed, then a population gets classified as *Established low density*. However, if the population structure is changing over time, then the situation gets re-assed accordingly. If the population structure at a given site is the worst-case scenario, a (live) reef, then the decision is straight forward to *Established high density*. However, if the reef is dead, e.g., due to ice-formation during winter, but the test for recruitment is positive, then the population needs to be monitored to determine if recolonisation is taking place. In case of recolonisation, the population structure and changes of the population structure over time need to be monitored. Without recolonisation, the site gets classified as *Monitoring* as colonisation has once already happened (Le Gall, 2022).

The described model by Le Gall (2022) was tested at six different sites on the west coast of Sweden and proved to be effective in discriminating between different invasion stages. However, in order to develop a dynamic management plan for the Pacific oyster in Sweden, the coastline needs to be classified according to the model and invasion boundaries of the oysters defined. For this, data is lacking, thus the mapping of the oysters needs to be extended. By testing the model in the field, the model can not only be adjusted in an iterative way, it will also provide proof of concept for the applicability of the model to stakeholders.

Due to the range of varying impacts of the oysters, different stakeholders are expected to show different needs and objectives when it comes to the management of the oysters (Novoa et al., 2018). Understanding the knowledge level and awareness of stakeholders and their perception of invasive species as well as their commitment to engage in management, can therefore be essential for managers to reduce potential conflicts of interest and increase the likelihood of successful management actions. Especially in terms of prevention and early eradication measures (Shackleton et al., 2019b). Consequently, in invasive species management, stakeholder involvement, and hence participation and collaboration between different stakeholders, is recognized as increasingly important (Shackleton et al., 2019a; Shackleton et al., 2019b). The next step in the process, in addition to motivate and engage stakeholders to participate in the collection of data, which is essential for refinement of the model, is to connect the model to suitable management options. Especially, since the Pacific oyster is not on the national list of invasive species, there is no legal obligation, e.g., for administrative counties or municipalities, to manage the oysters. Thus, to sustainably manage the oysters, it is crucial to investigate and integrate stakeholders' knowledge of and attitudes towards the oysters into the design of a dynamic management plan. In Sweden, most of the management has so far been discussed on national (i.e., Swedish Agency for Marine and Water Management) or county level, while little engagement has been encouraged on municipality level. Municipalities are, however, important actors in terms of data collection for refinement of the classification of invasion stages along the coastline. Moreover, as observed in Norway, they can also play a key role in the implementation of management action of the Pacific oyster, i.e., organising clearing actions[1]. Hence the knowledge level, attitudes and interests of municipalities should be explored.

Aim and hypotheses

To address these knowledge gaps, the aim of this thesis is to further test and expand the model developed by Le Gall (2022), to provide not only a classification of the west coast according to the oysters' invasion stages but also a revised model that can be used by the stakeholders. Moreover, as dynamic management of invasive species requires a co-creation process, where the expertise, and objectives from different stakeholders, i.e., authorities, scientists, industry, and the public, are integrated into the design of the dynamic management plan, this thesis aims at investigating primarily municipality stakeholders' knowledge level and attitudes towards the Pacific oyster.

The following hypothesis were formulated:

H1: The existing model (Le Gall, 2022, Figure 1) provides a discrimination of invasion stages of the Pacific oysters along the Swedish west coast.

H2: Stakeholders' knowledge level differs between municipalities with many and few or no oysters present, hence between municipalities with different invasion stages of the oysters.

H3: Stakeholders' attitudes towards the Pacific oyster differ depending on stakeholders' knowledge level of the oysters.

2 Methods

[1] https://www.no17.no/2023/02/06/stillehavosters/

To achieve the objectives of this thesis two methods were combined; 1) existing biological data was complemented, where necessary, by field work to classify the Swedish west coast according to the invasion stages of the Pacific oyster on a municipality level, and 2) municipality stakeholders were contacted to investigate stakeholders' knowledge level of and attitudes towards the oysters.

2.1 Biological data for classification of invasion stages

2.1.1 Analysis of existing data

To classify the coastline according to the invasion stages of the Pacific oysters, biological data about the oyster populations relevant for the model (i.e., locations of sites, densities of oysters, population structure and length measurements of oysters) were explored from existing survey data from different surveys conducted between the years of 2017 and 2022. After compiling a list of the municipalities along the Swedish west coast, from Vellinge in the south to Strömstad in the north, the previously surveyed sites were sorted by municipalities. Munkedal and Burlöv were excluded from the classification of the west coast as both municipalities cover only a minor stretch of the coast. For each of the remaining 24 municipalities, three to five oyster sites were selected from the existing survey data, based on a worst-case scenario, thus, sites with the highest oyster densities within the municipality. Further, site selection was based on the accessibility by car and water depth (0 – 1 m) on site. In some cases, the highest density sites within a municipality were not accessible and, therefore, other sites had to be selected. In that situation, it was later confirmed whether the municipalities reached the highest invasion stage in the classification, and if that was not the case, the higher density sites that could not be reached were noted for further studies after this project (Appendix 7.1). Sorting of the survey sites per municipalities and determination of the sites' accessibility for the field work was done in QGIS Version 3.26.3 (QGIS Development Team, 2021).

This thesis work is part of the DynamO project (Dynamic management of the invasive Pacific oyster) a research project of the Swedish Environmental Research Institute (IVL)[2], investigating the sustainable management of the invasive Pacific oyster in Sweden as a case study. Two surveys conducted in the scope of the DynamO project in 2021 and 2022 (2021 oyster overview survey for clearing experiments; 2022 SDM (spatial distribution modelling)

[2] https://www.ivl.se/english/ivl/project/dynamo/about-the-project.html

Square Survey), respectively, provided the most detailed information, including site coordinates, oyster densities, length measurements, and population structures, and complete data for direct application to the invasion model from nine municipalities was extracted. In April 2023, additional data for three sites in Tanum was provided by Grebbestad high school (Appendix 7.2). Moreover, from a compilation of different surveys conducted between 2017 and 2020 (Ringhals Survey 2017; 2018 ME (*Mytilus edulis*) Stock assessment; 2020 Area Video Survey; Strömstad-Helsingborg Survey 2019; Martinez Garcia et al., 2018; Ahlers et al., 2020) data, although not complete for evaluation in the model, from all remaining municipalities except Laholm were extracted.

As the density of oysters varies along the coastline, with very low to no densities in the south, some of the selected sites were sites which were previously surveyed but with no oysters recorded. If it was not possible to select any, or enough (≥3), sites for a municipality from the existing survey data, sightings of the Pacific oyster recorded in *Artportalen*[3] was added to the dataset. Records from *Artportalen* were extracted for 10 sites in seven municipalities. In total, 82 sites were selected from the existing survey data (including *Artportalen*), of these 21 sites in nine municipalities included enough biological data for model evaluation of the municipality, while 49 sites in the remaining 16 municipalities lacked some biological data. Additionally, one site in Stenungsund municipality included only a few length measurements, hence, not enough biological data for classification of the municipality. Consequently, 17 municipalities lacked data for model classification.

In addition to analysis of existing field survey data and performed field surveys, municipality representatives were contacted in the questionnaire to check if additional data about the oyster populations was available at municipality level, if any field work regarding the oyster monitoring was planned, and if any additional biological data would be available during the timespan of this study. However, this did not result in any new data, only the county administrative board of Skåne had participated in oyster surveys but this was done in collaboration with the DynamO project.

2.1.2 Data collection – field work

Field work was carried out to complement the existing survey data and to test and verify the applicability of the data collection protocol (Appendix 7.2). The protocol is summarised briefly

[3] https://www.artportalen.se/ViewSighting/SearchSighting

here; After arriving at a given site, the coast was visually scanned for oysters. If no oysters were present, only the date and site coordinates were noted. If oysters were present, additional records of bottom substrate, population structure, and length measurements of 50 oysters per site were taken. The oysters were measured from the umbo (the hinge of the oyster shell) to the farthest side using a calliper. At low density sites all the oysters that were found were measured until 50 length measurements were reached. If less than 50 oysters were found, all the oysters were measured. At high density sites, a sampling square (0.25 m^2) was placed in the densest oyster spot, then all the oysters in the square were measured. If the oysters in the square did not reach 50, then the square was placed again in another spot and the measuring continued. Following the worst-case scenario approach, the densest type of population structure was noted for each site (reef > cluster > solitary). Reef formations was the densest type, oysters covering 90 – 100% of the substrate and were growing on top of each other. If the coverage was less dense (<90%) but oysters were still growing in clumps, the population structure would be described as a cluster. The least dense structure were solitary growing oysters (Figure 3).

Figure 3: Population structures of the Pacific oyster, solitary (left), cluster (middle) and reef (right, photo by Ane T. Laugen).

Due to the limited time available for the field work, the municipalities in the south, where fewer biological data was available, and the oysters were either not present or only present in low densities, were surveyed more exhaustively. E.g., in the municipalities in Skåne, except for in Båstad, all the sites noted in previous surveys were surveyed. Moreover, during the field work one additional site was added for Kävlinge, Lomma and Laholm municipalities, respectively, to reach three sites per municipality. The sites were chosen based on substrate or structures the oysters could grow on, i.e., jetties. As Laholm only covers a short stretch on the coastline and no previous survey data existed, only two sites were selected in the municipality. From Båstad northwards, and with increasing oyster densities, only the highest density sites from the list of previously selected sites were visited. It was noticed during the field work that the highest density sites for Orust and Stenungsund could not be reached, thus, one additional site in proximity to those sites was surveyed instead, respectively. In Sotenäs, the highest density sites were not accessible by car and the selected survey sites had comparatively low oyster densities. Therefore, records in *Artportalen* were checked for high oyster densities and based on the information one additional site was surveyed (Appendix 7.1). Although enough data for model evaluation was available from Strömstad, one additional site was visited together with the supervisor for practicing the field work procedures. In total, 39 sites were visited and surveyed for oysters during the work with this thesis (Figure 4).

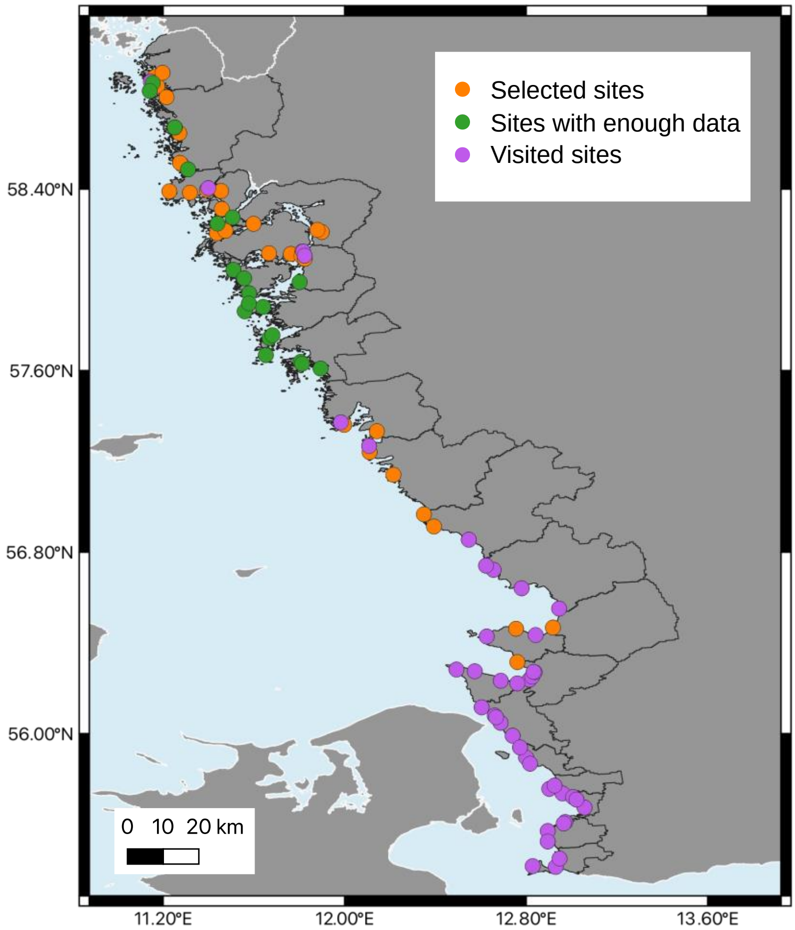

Figure 4: Map of sites lacking biological data for model classification (orange) identified from previous surveys, sites lacking biological data and visited during fieldwork (purple) and sites with enough biological data for model classification (green). Projection WGS84, Claire Roesch.

2.2 Data collection - Abiotic data (sea surface temperature and salinity)

Since it was not possible to use on site measurements of temperature and salinity for the selected sites, abiotic data from existing databases were explored, including SMHI[4]/Sharkweb[5], BioOracle[6] and Copernicus Marine Services[7]. Due to the data coverage and temporal and geographical resolution for the selected sites, Copernicus Marine Services was selected as data provider.

The downloaded Copernicus data, Baltic Sea Biogeochemistry Analysis and Forecast (E.U. Copernicus Marine Service Information, 2019), was explored and analysed in R (R Core Team, 2023; RStudio Team, 2023). Daily averages for sea surface salinity (*so*) and sea surface temperature (*the*) variable were extracted for 2021/2022 using the `brick()` command from the `ncdf4 package` (Pierce, 2023). In a next step, the data was converted to the coordinate reference system WGS84 with `projectRaster()` command from the `raster package` (Hijmans, 2023). To extract data for the selected sites for classification (see section 2.3), the coordinates were moved to the nearest raster point containing a value. First, the coordinates had to be converted into a point file with `locs2sp()`, before being moved to the nearest raster point with `points2nearestcell()` (both included in the `rSDM package;` Rodriguez-Sanchez (2023)). Finally, daily temperature and salinity averages for 2021/2022 could be extracted for the selected sites using `extract()` command from the `raster package` (Hijmans, 2023).

As needed for the model classification, for winter 2022, the temperature records of December 2021, January, February, and March 2022, and for summer 2022, temperature as well as salinity records of July and August 2022, were analysed. The period for winter was chosen based on the coldest months during winter 2021/2022. The summer period (July and August) was based on the reproductive period of the oysters (Strand et al., 2022) and the warmest months during summer.

The quality of the Copernicus data was evaluated by comparing the extracted winter and summer temperature data for a site in Tjärnö, with long-term averages of winter and summer sea surface temperatures measured at the Tjärnö Marine Laboratory (Bertils brygga and lab

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[4] https://www.smhi.se/q/Stockholm/2673730
[5] https://sharkweb.smhi.se/hamta-data/
[6] https://www.bio-oracle.org
[7] https://marine.copernicus.eu

water)[8]. The long-term summer and winter averages were calculated for a twenty-year period, 1995-2015. The period 2016-2022 was excluded from the analysis due to a transition at the lab to an automated system which, through visual inspection, was observed to produce data with less variance and warmer winter temperatures (most likely as a consequence of the water being unintentionally heated in the pipes before reaching the recording unit). The 1995-2015 was visually compared to 2021/2022 in boxplots to verify that the Copernicus data represented a normal year (Figure 5).

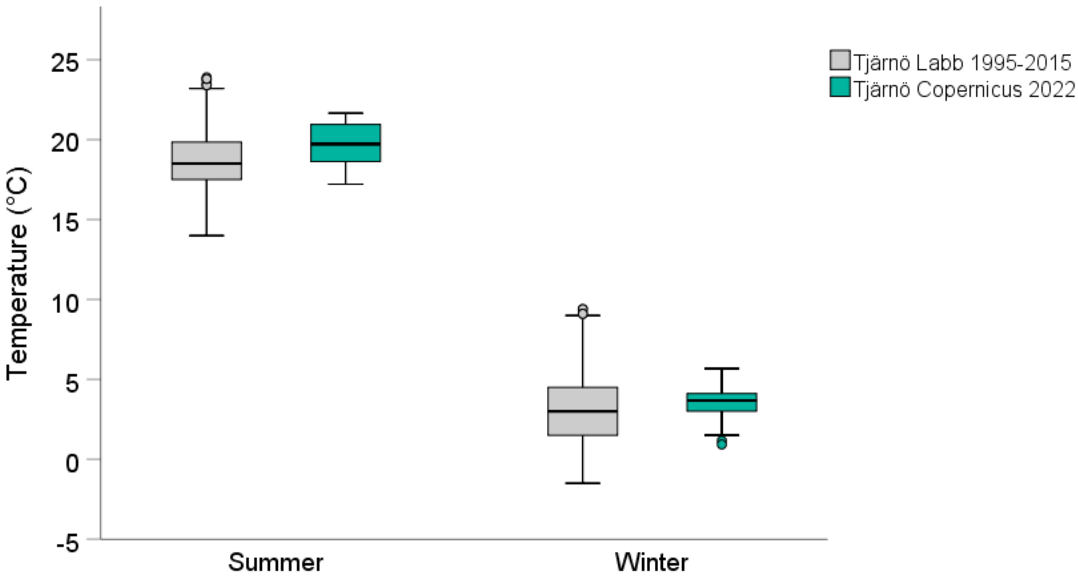

Figure 5: Temperature ranges for summer and winter for data from Tjärnö Marine Laboratory (1995-2015) and data extracted for Tjärnö from Copernicus Marine Services (2022). The y-axis represents the temperature in °C. The line inside the boxes represents the mean, the box illustrates the 25th and 75th percentiles, the whiskers show max and mix data, and outliers are illustrated as circles.

2.3 Classification of invasion stage for each municipality

The model classification of invasion stages was based on 60 sites of the previously selected and added sites during field work, of these, 39 sites were visited during the field work (see section 2.1.2), while 21 sites contained enough biological data from existing surveys (see section 2.1.1, Figure 4). To determine the invasion stage for each site, biological and abiotic data was combined. The site classification was based on the model by Le Gall (2022), however,

[8] https://www.weather.mi.gu.se/tjarno/data.shtml

the model was adjusted due to decisions made during data extraction (see section 2.2) and experiences made during the classification work.

For determination of reproduction (local recruitment), length-frequency distributions of the oysters were performed in Excel. Since the aim was to classify municipalities according to the worst-case invasion stages of the oysters and due to the limited time available for field work, it was decided to analyse oyster length measurements on a municipality level. Therefore, all available length measurements within a municipality were combined and length-frequency distributions were created to determine recruitment. Histograms were done for each municipality where length measurements were available. As described by the model, individuals ≤25 mm were considered less than a year old (Le Gall, 2022), and consequently represented recruitment in the model (Appendix 7.3).

After classifying each site according to the invasion stage, the respective municipalities were classified according to the worst-case invasion stage found in the municipality. As monitoring was necessary to determine a final classification for low density sites with solitary and/or cluster populations, in this study the categories identified in the data were; absence, survival (previously "Presence"), sink (previously "Survival"), source (previously "Reproduction") and established reef (previously "Established high density"). Geographical visualization of the results was performed in QGIS Version 3.26.3 (QGIS Development Team, 2021).

2.4 Stakeholder attitudes and knowledge

To investigate stakeholders' attitudes and knowledge about the Pacific oysters an online survey was designed and sent out to municipality representatives (primarily municipality ecologists) at all municipalities in the target area, as well as to representatives of the county administrative boards of Skåne, Halland and Västra Götaland. Representatives of the municipalities were sourced from existing contact lists provided by the county administrative boards of Västra Götaland and Skåne, and was revised by contacting the municipalities during reminders about the survey. The survey was constructed in a way that no sensitive data (i.e., age or gender) was collected, thus, no ethical permit was needed. Since the survey was in English, participants were given the option to answer to open questions in Swedish, and to contact the project coordinator for an interview in Swedish instead of responding to the survey, if they so wished. Swedish answers were then translated to English for the analysis of the survey.

The survey included both open and closed questions and was structured in four sections. In the first section, the general knowledge about the Pacific oyster was investigated, followed by questions about stakeholders' local knowledge, meaning in their municipality or area they were active in. In the last two parts, questions were posed about stakeholders' attitudes towards the oyster as well as their management objectives. As the management objectives of stakeholders were investigated in another thesis work, they will not be further discussed in this study (Appendix 7.4).

Analysis of the survey included a regression analysis of the stakeholders' knowledge level in relation to latitude and oyster densities and was performed in R (linear model: knowledge level ~ latitude). For this, the knowledge level from very low to very high was quantified from 1 to 5 (1 very low, 2 low, 3 medium, 4 high, and 5 very high knowledge). For each municipality, the mean latitude was chosen as a representative variable. The data was visually checked for normality before performing the regression analysis. To answer the posed hypotheses, survey answers of knowledge level and attitudes were quantified in relation to invasion stages and knowledge level, respectively.

3 Results

3.1 Applicability and verification of the model by Le Gall (2022)

The model designed by Le Gall (2022) was modified based on this projects' work. The revised model is presented in Figure 6, the changes made are summarized here.

Based on current biological data available and based on questions arising during site analysis, the proxies for evaluation of reproductive potential and juvenile survival in the model were updated. In the original model, the average temperature and salinity of the two warmest weeks during summer was used to identify conditions that allow for reproduction. Recent data, however, show that histological signs of spawning can be observed in oysters in the end of July and early August in normal years, and in June and a second time end of August to early September in extremely warm years (Strand et al., 2022). Comparable results are described by Diederich et al. (2005), who reported spawning of the oysters in the Wadden Sea for end of July and August. This indicates that the reproductive season of the oysters may be longer than two weeks. Moreover, July and August are, based on long-term temperature data by Tjärnö Marine Laboratory[9], on average the two warmest months during summer, and temperatures during this period frequently exceed the temperature limit for spawning of the oysters (16 °C, Ruiz et al. 1992). Hence, a modification of the time interval for temperature and salinity from two weeks to the period of July and August was used as a new criterion in the model.

Further, the salinity threshold for reproduction, which was originally set to >13 PSU, was revised to >13 PSU for Varberg and municipalities north of Varberg, and >8 PSU for municipalities south of Varberg based on a preliminary report by Kinnby et al. (2023), who found that oyster populations from the southern part of the west coast (Hallands Väderö) were able to reproduce in lower salinities than oyster populations from the northern part of the coast (Bohuslän). Moreover, the geographical limit for the higher salinity threshold was set to Varberg, as there were no high density populations found south of Varberg in previous surveys[10]. Finally, if temperatures are too low during the winter, the chances for juveniles to survive are very low. Le Gall (2022) used the average temperature during the coldest month in

[9] https://www.weather.mi.gu.se/tjarno/data.shtml
[10] https://hannapartoft.shinyapps.io/shiny_oysters/?_ga=2.237831168.1686877105.1646251396-325310896.1643018757

winter to evaluate the potential for juvenile survival. In an experiment by Child and Laing (1998), however, high mortalities of oyster juveniles were recorded after 7 weeks at 3 °C (>95% mortalities). Therefore, the winter period was extended to the seven coldest coherent weeks and the threshold was set to ≥3 °C. The thresholds were adjusted to not underestimate the influence of salinity and temperature on the reproduction and overestimate the influence of severe winters on juvenile survival.

In addition to modifying the abiotic parameters for the first part of the decision tree, the second part of the model was adjusted to better represent field conditions. The major changes were that the terminology was modified to better describe the characteristics of the different invasion stages, and that the flows between different stages were clarified. With the revised model, surveyed sites can be classified in eight different invasion stages; Absence/*Unlikely to have future settlement,* Absence/*Future settlement possible* (previously "No oysters/Monitoring")*, Survival* (previously "Presence")*, Sink* (previously "Survival")*, Source* (previously "Reproduction")*, Established solitary/low density, Established cluster/medium density* (previously one category)*,* and *Established reef/high density* (previously "Established high density") (Figure 7).

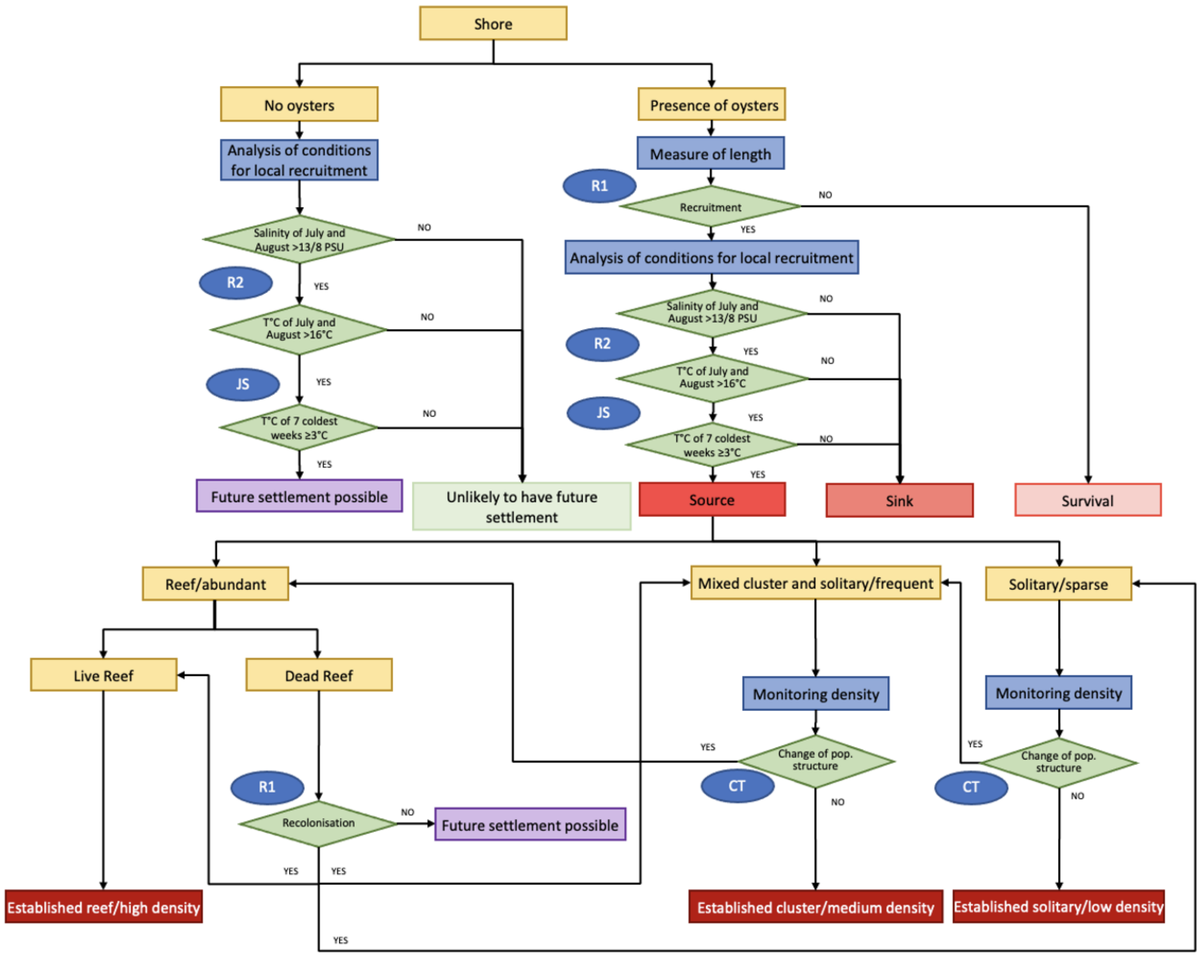

Figure 6: Revised model to determine the invasion stage of the Pacific oyster according to Le Gall (2022). R1: Recruitment (foreign recruitment) JS: Juvenile Survival R2: Reproduction (local recruitment) CT: Change of population structure over Time.

3.2 Classification of the Swedish west coast according to the invasion stages of the Pacific oyster

The revised model (see above) was used to determine the invasion stages at the 60 sites for which data was acquired (Table 1 – 3). Municipality tests for recruitment were positive for 12 municipalities, the majority of which were located in the northern part of the coast (10 in Västra Götaland, Table 1; 1 in Halland, Table 2; 1 in Skåne, Table 3). Average salinity during July and August 2022 was >8 PSU at all sites from Vellinge to Falkenberg, and >13 PSU at all sites from Varberg to Strömstad. Winter temperatures were in general high enough to sustain winter survival of juveniles, except for some sites in Uddevalla, Orust, Stenungsund, Göteborg, and Halmstad (Table 1 and 2). Summer temperatures during the reproductive period were high enough for reproduction at all sites (>16 °C). At the sites with oysters present, all three population structures (solitary, cluster and reef formation) were identified (Table 1 – 3).

At most of the surveyed sites oysters were growing either on rocks or other hard substrates, i.e., jetties or harbour walls. Oysters growing on rocks were often covered in algae, especially in the southern parts of the coastline (Figure 7).

Figure 7: Examples of surveyed sites, left solitary growing oysters on rocks (site: Skälderviken in Ängelholm); right oyster growing on rocks and muddy substrate in mix cluster and solitary population structures (site: Näs in Stenungsund).

Table 1: Model classification of sites and municipalities in Västra Götaland. Length data: number of available length measurements within a municipality; Min. size (mm): smallest measured individual within a municipality; Recruitment: Recruitment test performed on a municipality level. Municipality classification: worst-case site classification found within a municipality.

Municipality	Site	Length data	Min size (mm)	Recruit -ment	Average Salinity (PSU) July + August 2022	Average Temperature (°C) July + August 2022	Average Temperature (°C) 7 coldest weeks	Population structure	Site classification	Municipality classification
Strömstad	Svalhagen	1927	4	yes	25.5	18.8	4.3	Reef	**Established reef/high density**	**Established reef/high density**
	Kockholmen				25.5	18.6	4.3	Reef/Cluster	**Established reef/high density**	
	Tjärnö				25.2	19.7	3.1	Cluster	**Source**	
Tanum	Grebbestad1	422	12	yes	25.5	18.3	4.3	Cluster	**Source**	**Established reef/high density**
	Grebbestad2				25.5	18.5	3.9	Reef	**Established reef/high density**	
	Grebbestad3				25.5	18.5	3.9	Reef	**Established reef/high density**	
	Skredsvik				24.6	18.5	4.3	Cluster	**Source**	
Sotenäs	Skeppsudden	100	16	yes	24.0	19.5	3.2	Cluster	**Source**	**Source**
Lysekil	Smalsundet	323	6	yes	23.4	18.4	4.1	Reef	**Established reef/high density**	**Established reef/high density**
Uddevalla	Getevik	918	2	yes	20.7	19.1	2.6	Reef	**Sink**	**Sink**
Orust	Broccoli garden	50	11	yes	20.0	19.5	2.0	Cluster	**Sink**	**Sink**
Stenungsund	Näs	63	5	yes	20.0	19.5	2.2	Cluster	**Sink**	**Sink**
	NG513				19.8	19.2	2.8	Cluster	**Sink**	
Tjörn	NG33	149	6	yes	22.4	18.8	3.3	Cluster	**Source**	**Source**
	NG90				21.3	18.8	3.7	Cluster	**Source**	
	NG72				22.0	19.0	3.6	Cluster	**Source**	
Kungälv	NG79	46	27	no	22.1	18.8	4.1	Cluster	**Survival**	**Survival**
	NG160				20.4	18.9	3.5	Cluster	**Survival**	
	NG88				21.4	18.8	3.9	Cluster	**Survival**	
Öckerö	NG223	103	18	yes	20.7	18.9	3.8	Cluster	**Source**	**Source**
	SG179				18.8	19.0	3.7	Cluster	**Source**	
	NG248				20.7	18.9	3.8	Cluster	**Source**	
Göteborg	SG585	194	14	yes	19.1	19.3	3.2	Cluster	**Source**	**Source**
	SG503				12.5	19.1	3.1	Cluster	**Sink**	

	SG510				10.4	19.0	2.7	Cluster	**Sink**	

Table 2: Model classification of sites and municipalities in Halland. Length data: number of available length measurements within a municipality; Min. size (mm): smallest measured individual within a municipality; Recruitment: Recruitment test performed on a municipality level. Municipality classification: worst-case site classification found within a municipality.

Municipality	**Site**	**Length data**	**Min size (mm)**	**Recruit-ment**	**Average Salinity (PSU) July + August 2022**	**Average Temperature (°C) July + August 2022**	**Average Temperature (°C) 7 coldest weeks**	**Population structure**	**Site classification**	**Municipality classification**
Kungsbacka	Onsala Halvon	101	26	no	20.3	19.0	3.8	Cluster	**Survival**	**Survival**
Varberg	Ringhals	62	25	yes	19.2	19.3	3.8	Solitary	**Source**	**Source**
Falkenberg	Grimsholmen	100	30	no	16.6	19.3	3.0	Cluster	**Survival**	**Survival**
Halmstad	Bengtsgård	51	36	no	16.2	19.3	3.0	Solitary	**Survival**	**Survival**
	Grötviks harbour				15.3	19.5	2.9	Solitary	**Survival**	
Laholm	Lagaoset	-		no	13.8	19.3	3.0	No oysters	**Future settlement possible**	**Future settlement possible**

Table 3: Model classification of sites and municipalities in Skåne. Length data: number of available length measurements within a municipality; Min. size (mm): smallest measured individual within a municipality; Recruitment: Recruitment test performed on a municipality level. Municipality classification: worst-case site classification found within a municipality.

Municipality	**Site**	**Length data**	**Min size (mm)**	**Recruit-ment**	**Average Salinity (PSU) July + August 2022**	**Average Temperature (°C) July + August 2022**	**Average Temperature (°C) 7 coldest weeks**	**Population structure**	**Site classification**	**Municipality classification**
Båstad	Båstad	100	19	yes	13.6	19.4	3.3	Cluster	**Source**	**Source**
	Torekov				14.3	19.0	3.4	Solitary	**Source**	
Ängelholm	Ronnea2	100	35	no	13.1	19.2	3.4	Cluster	**Survival**	**Survival**
	64865852				12.7	19.2	3.5	No oysters	**Future settlement possible**	
	98757030				13.1	19.2	3.5	No oysters	**Future settlement possible**	
Höganäs	Norra Häljaröd	103	39	no	12.9	19.2	3.8	Cluster	**Survival**	**Survival**
	Arild2				13.3	18.9	3.6	Solitary	**Survival**	
	Revets Badplats				13.1	19.1	3.5	Solitary	**Survival**	
	Molle				13.9	18.7	3.6	Solitary	**Survival**	

Helsingborg	Helsingborg	50	28	no	12.4	18.8	3.7	Solitary	**Survival**	**Survival**
	Domsten				13.0	18.6	3.6	Cluster	**Survival**	
	Sofiero				12.7	18.7	3.7	No oysters	**Future settlement possible**	
	Raa				11.9	18.7	3.8	No oysters	**Future settlement possible**	
Landskrona	Borstahusen	56	32	no	11.4	18.7	3.7	Solitary	**Survival**	**Survival**
	Alabodarna1				11.7	18.7	3.8	Solitary	**Survival**	
	Landskrona				11.2	18.9	3.5	No oysters	**Future settlement possible**	
Kävlinge	Barsebackshamn			no	10.3	18.7	3.7	No oysters	**Future settlement possible**	**Future settlement possible**
	98681469				9.9	18.9	3.6	No oysters	**Future settlement possible**	
	Barsebäckstrand				10.0	18.8	3.5	No oysters	**Future settlement possible**	
Lomma	Lomma Smabatshamn			no	9.4	19.5	3.7	No oysters	**Future settlement possible**	**Future settlement possible**
	Bjarred Hamn				9.5	19.4	3.6	No oysters	**Future settlement possible**	
	Långa bryggan				9.5	19.4	3.6	No oysters	**Future settlement possible**	
Malmö	Malmo			no	9.4	19.0	3.8	No oysters	**Future settlement possible**	**Future settlement possible**
	Utsiktspunkt Oresund				10.1	18.7	3.8	No oysters	**Future settlement possible**	
	Ribersborg Kallbadhus				9.4	19.0	3.8	No oysters	**Future settlement possible**	
	Klagshamn Strand				10.0	18.7	3.7	No oysters	**Future settlement possible**	
Vellinge	Skanor Hamn			no	8.9	18.6	3.7	No oysters	**Future settlement possible**	**Future settlement possible**
	Hallviken Falsterbokanalen N				9.8	19.0	3.3	No oysters	**Future settlement possible**	
	Lilla Hammar				9.8	18.9	3.3	No oysters	**Future settlement possible**	

The municipality classification according to the worst-case scenario showed a clear trend in the oysters' distribution along Sweden's west coast, ranging from high densities in the northern municipalities to absence of oysters in the south (Figure 8). The southernmost municipality where oysters were found in the scope of this study was Landskrona. The municipality was classified as *Survival* as the Pacific oyster was present but the test for recruitment negative (52 length measurements, min. size 31 mm; Table 3). South of Landskrona no oysters were found, yet as the analysis of the local abiotic conditions was positive for reproduction and juvenile survival, Vellinge, Malmö, Lomma, and Kävlinge were classified as Absence/*Future Settlement Possible*. North of Landskrona, oysters were found in all municipalities except for Laholm. Overall, there were no municipalities classified as *Unlikely to Have Future Settlement* (Figure 8).

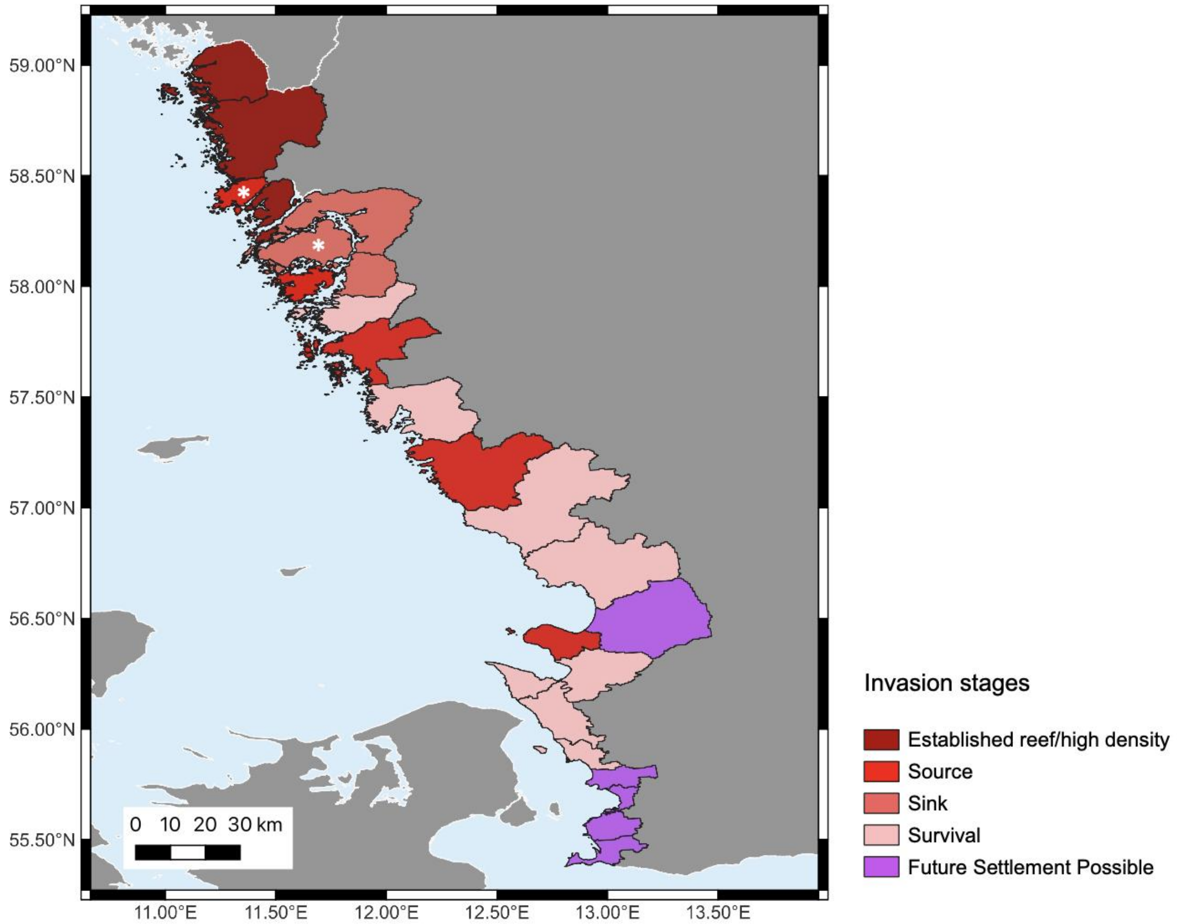

Figure 8: Overview of invasion stages of the Pacific oyster on the Swedish west coast as determined by the revised model. Municipalities were the highest density sites were not accessible are marked (*). Projection WGS84, authors Linn Martini and Claire Roesch.

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Reef formations were only found within the northernmost municipalities in Västra Götaland, Strömstad, Tanum, and Lysekil. Those municipalities were classified with the worst-case invasion stage, *Established reef/high density*. Sotenäs, Tjörn, Göteborg and Öckerö were classified as *Source* as the tests for recruitment and local reproduction were positive, however, monitoring of the population structure was needed to identify the final classification; *Established solitary* or *cluster*. Uddevalla, Orust and Stenungsund were classified as *Sink*. The Pacific oyster was present in those municipalities and tests for reproduction were positive, however, as the seven coldest coherent weeks in winter were below 3 °C (Uddevalla 2.6 °C, Orust 2.0 °C, and Stenungsund 2.8 °C) the test for juvenile survival was negative. The Pacific oyster was present in Kungälv, however, the smallest identified individual was 27 mm, hence, test for recruitment was negative, the municipality was classified as *Survival*. In Sotenäs and Orust, the highest density sites could not be reached in the scope of this study (Table 1, Figure 9).

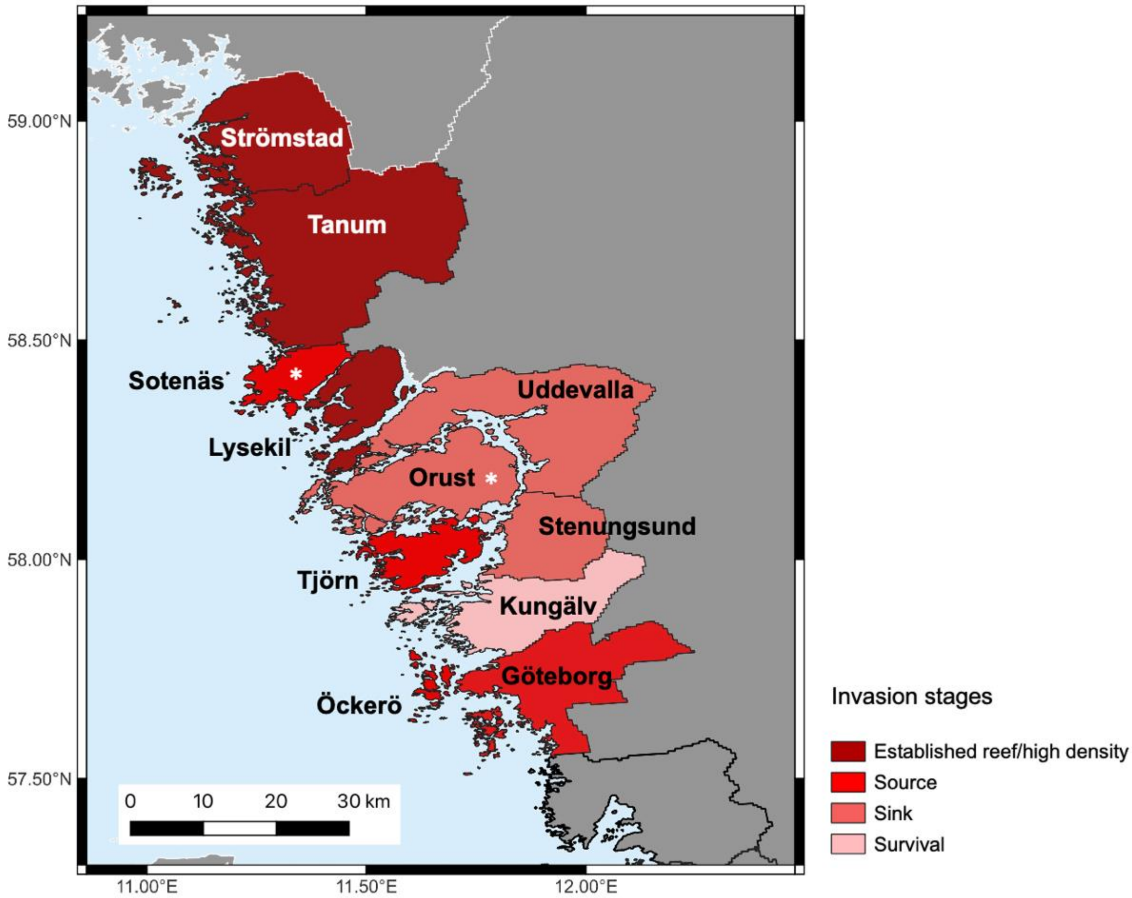

Figure 9: Classification of Västra Götland by invasion stages of the Pacific oyster. Municipalities were the highest density sites were not accessible are marked (*). Projection WGS84, authors Linn Martini and Claire Roesch.

In Halland the worst-case invasion stage classified was *Source* (Varberg). Again, monitoring of the population structure was necessary to determine further classification; *Established cluster/medium density* or *Established solitary/low density*. Kungsbacka, Falkenberg and Halmstad were classified as *Survival*, as there was no local recruitment observed in those municipalities. Laholm was classified as Absence/*Future settlement possible* as oysters were not present in this municipality, but the analysis of local abiotic conditions was positive for reproduction (Table 2, Figure 10).

Figure 10: Model classification of Halland by invasion stages of the Pacific oyster. Projection WGS84, authors Linn Martini and Claire Roesch.

In Skåne, a clear trend of decreasing level of invasion was identified along the coastline, as the classification of invasion stages ranged from *Source* in Båstad, to *Survival* in Ängelholm, Höganäs, Helsingborg and Landskrona, to Absence/*Future Settlement Possible* in Kävlinge, Lomma, Malmö and Vellinge. In Båstad recruits were found (min. size 19 mm) and the analysis of local abiotic conditions were in favour for reproduction. In the four municipalities classified as *Survival,* oysters were present, however, tests for recruitment were negative. During the field work, no oysters were found at the selected sites in the four southernmost municipalities, Kävlinge, Lomma, Malmö and Vellinge (Table 3, Figure 11).

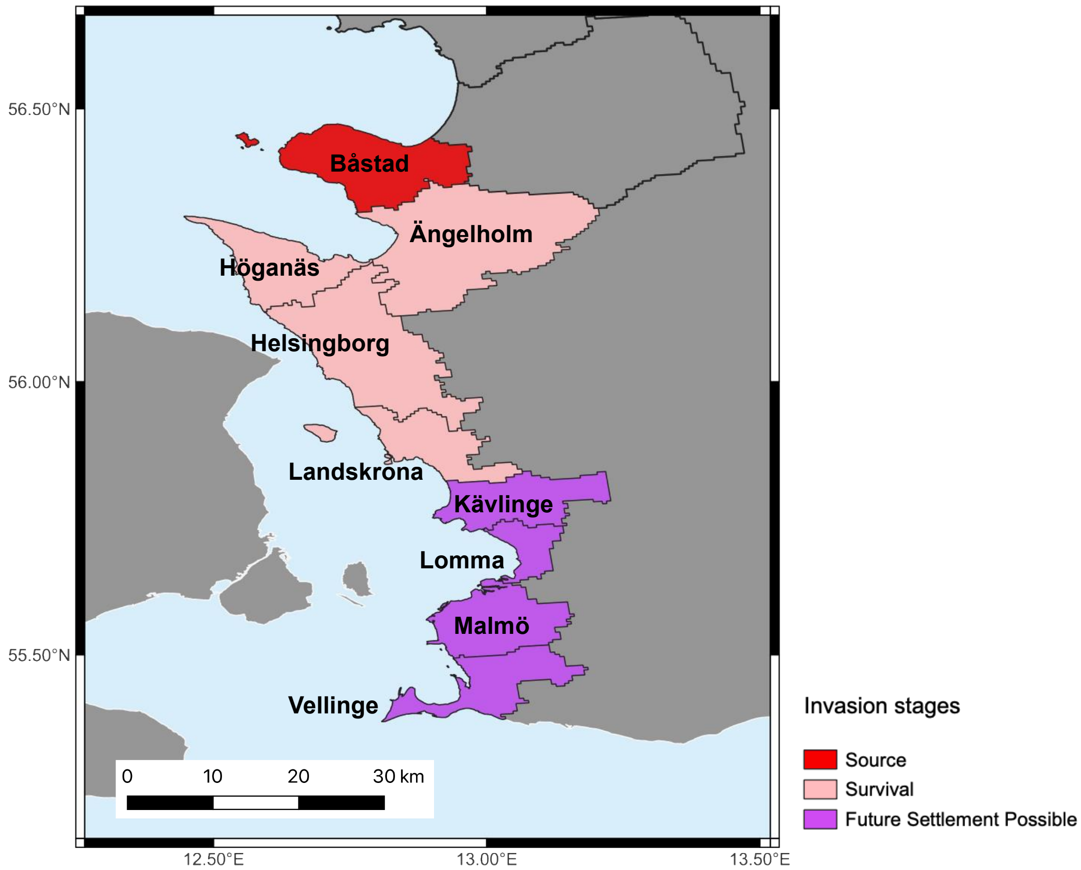

Figure 11: Model classification of Skåne by invasion stages of the Pacific oyster. Projection WGS84, authors Linn Martini and Claire Roesch.

3.3 Stakeholders' knowledge level of and attitudes towards the Pacific oyster

The survey was completed by 18 out of 24 municipalities, and all three respective county administrative board representatives (Västra Götaland, Halland, and Skåne). Representatives from the municipalities included, e.g., ecologists, conservationist, environmental analyst, and marine biologists. The representatives of Västra Götaland and Skåne were coordinating the counties' work with aquatic invasive species, while the representative of Halland was working as a marine biologist for the county. Out of all the participants only the three county representatives and one municipality representative had heard of the DynamO project, however, all participants except for one municipality representative had heard of the Pacific oyster before taking part in the survey.

The average knowledge level about the Pacific oyster differed between the municipalities, however, linear regression analysis did not show a significant relationship between knowledge level and latitude (R^2 = 0.1006, P = 0.1078). In general, most of the municipality representatives rated their knowledge levels about the inquired categories (invasion history, distribution along the west coast, negative effects, positive effects, and management) between low and medium, the knowledge level was never perceived as very high. The representatives of the county administrative boards showed a higher average knowledge level than the respective municipality representatives (Figure 12).

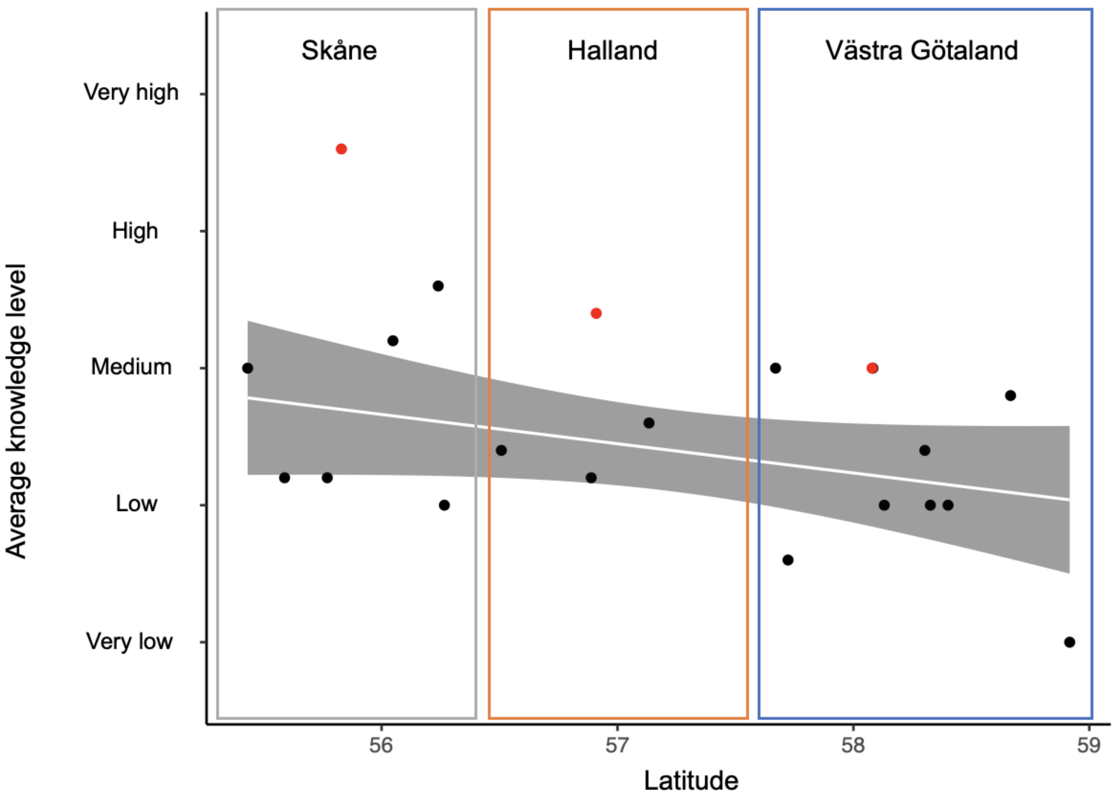

Figure 12: Average knowledge level of municipality representatives (black) and county administrative board representatives (red points) in relation to the latitude (Linear model, R^2 = 0.1006, P = 0.1078). The average knowledge level (y-Axis) ranges from very low to very high. The latitude (x-axis) is categorized in county administrative boards Skåne (grey), Halland (orange) and Västra Götaland (blue).

Comparative results were seen in the analysis of average knowledge level in relation to the identified invasion stages, as there was a decreasing trend in oyster densities identified along the coast from north to south (see section 3.2). Moreover, one participant stated a very low knowledge level in a municipality classified with the most severe case, *Established reef/high* *density*, while in a municipality classified as *Survival* (a less severe invasion stage), one representative stated a high knowledge level (Figure 13).

Knowledge about the abundance or occurrence of the Pacific oyster was not correlated to the degree of invasion either. 13 out of the 18 municipalities stated to have knowledge about the occurrence or abundance of the Pacific oyster in their area. However, the five municipalities without any knowledge were classified ranging from absence of the oysters (*Future settlement possible*) to the most severe case of invasion (*Established reef/high density*). Further, knowledge of abundance or occurrence was not related to any surveys conducted by the municipalities.

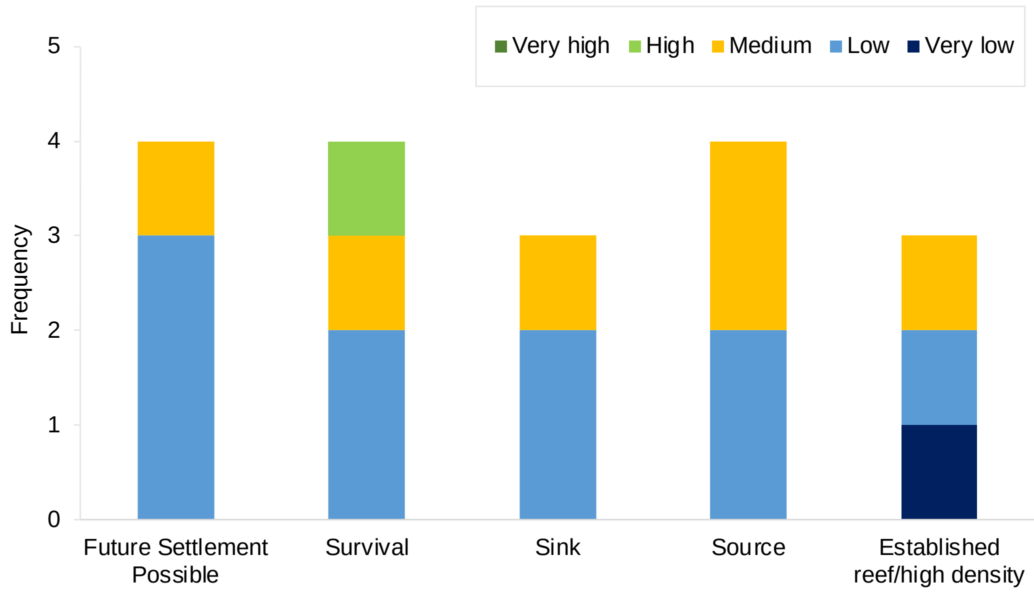

Figure 13: Stakeholders' average knowledge level of the Pacific oyster in relation to the invasion stages identified on a municipality level. Frequency of answers by municipality representatives on the y-axis, classified invasion stages on the x-Axis.

Moreover, when asked about their attitudes towards the Pacific oyster, the survey participants showed either a negative (around 40% of participants) or mixed (around 50% of participants) attitude, however, the perception was never positive (Figure 14). Negative attitudes towards the oysters were supported by key words of the categories “invasive” and “competitive”. Participants with a mixed attitude stated key words that can be grouped in “invasive species”, “threat to biodiversity”, “sharp/dangerous”, “food resource”, and “abundant”. Additionally, municipality representatives showed less knowledge about the positive effects of the Pacific oyster than about the negative effects.

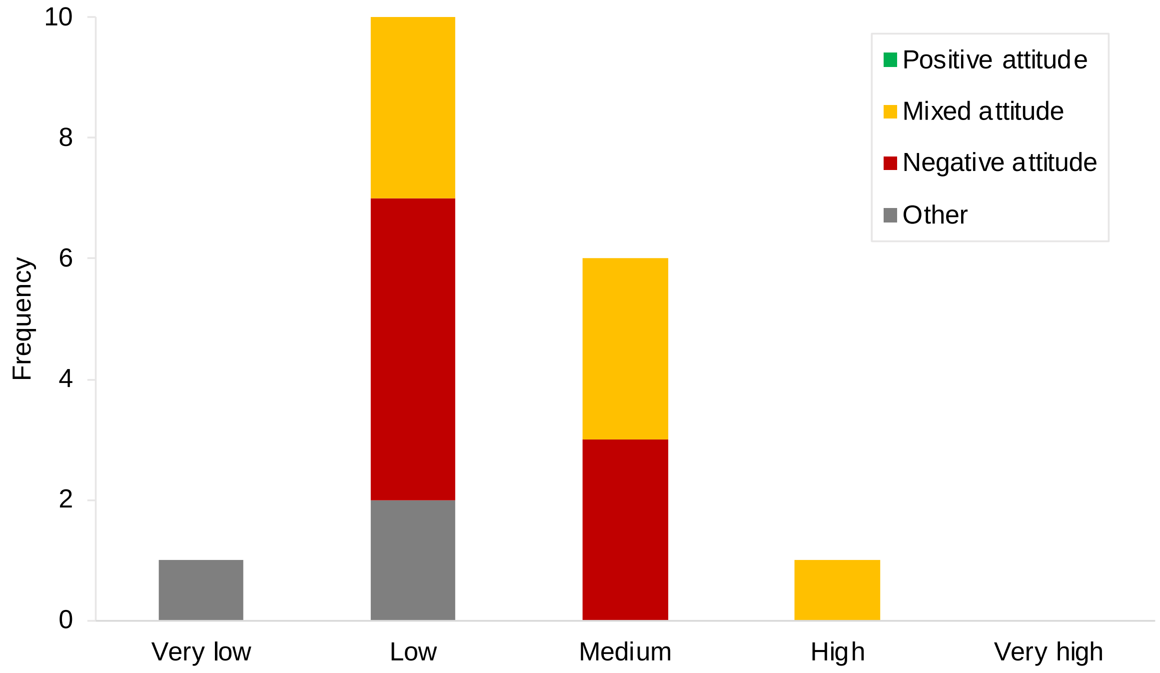

Figure 14: Stakeholders' attitudes towards the Pacific oyster in relation to the average knowledge level. Frequency of municipality representatives' answers on the y-axis and average knowledge level on the x-Axis.

Only three municipality representatives rated their knowledge level about the Pacific oyster as sufficient, these municipalities covered all invasion stages from Absence/*Future settlement possible* to *Source*. The remaining municipality representatives perceived their knowledge either as not sufficient (8) or they were unsure about it (6). Overall, most of the survey participants (>90% incl. municipality and county representatives) would like to gain more knowledge about the oysters. Preferred formats to receive information were fact sheets (12 responses), short films or videos (10 responses), followed by project reports or newsletter from projects (9 responses). One participant highlighted that the format did not matter but to receive "local information" was most important. Further, it was suggested to have information sessions online or on site about the Pacific oyster (Figure 15).

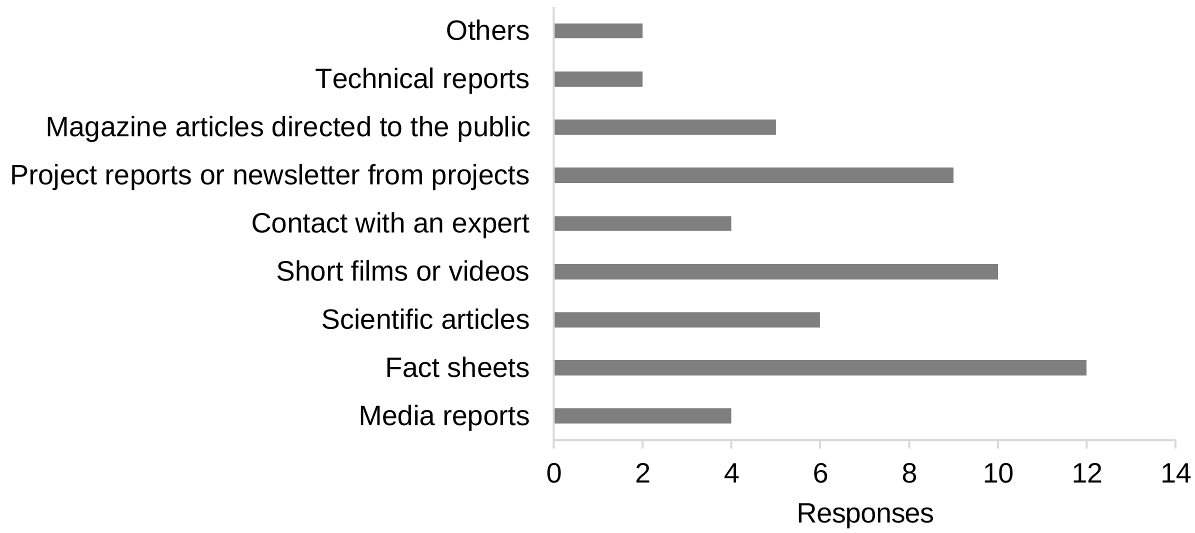

Figure 15: Survey answers of municipalities and county administrative board representatives on how to receive information about the Pacific oyster.

Around 60% of the municipality representatives believed there is a need for management actions of the Pacific oyster in general in Sweden, while 40% thought there is also a need for management in their specific area. When being asked where the responsibility for management actions of the Pacific oysters should lie, the majority of municipalities (15) stated "on a national level", meaning with national agencies, i.e., Swedish Agency for Marine and Water Management or the Environmental Protection Agency (Naturvårdsverket) (Figure 15). However, several participants highlighted that the responsibility for the oysters' management should not only lie with one actor but instead be a collaboration on multiple levels. Generally, it was mentioned that the coordination and main responsibility for management actions should be based on a higher level, but responsibilities should also be given to municipalities, private landowners, and the fishing or boating industry, explained by the polluter pays principle (2 responses) (Figure 16).

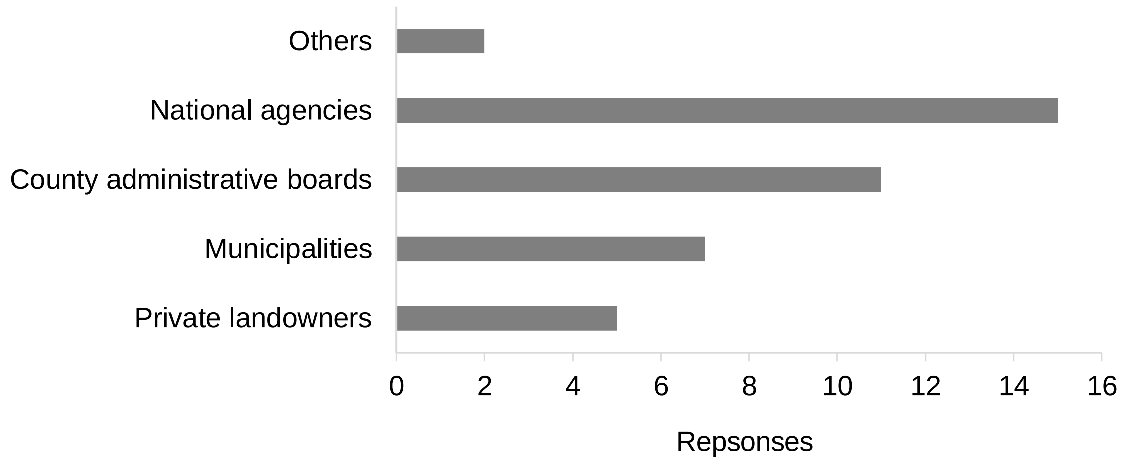

Figure 16: Survey answers of municipality representatives on responsibility for management actions of the Pacific oyster.

Overall, only one representative stated directly that their municipality would like to be involved in the management of the Pacific oyster, specifically by taking part in decision-making and participating in knowledge platforms. Four municipalities would not like to be involved in the oysters' management at all. In general, most municipality representatives were unsure whether their organization would like to be involved in the management of the Pacific oyster. The preferred form of involvement for both municipalities and county administrative boards was by participating in knowledge platforms (9 responses). None of the municipalities and only one of the county administrative board representatives stated they would like to be involved in the execution of management actions. Further, it was raised by one municipality representative that being involved in the management of the Pacific oyster would also be dependent on the availability of personnel and the political will (Figure 17).

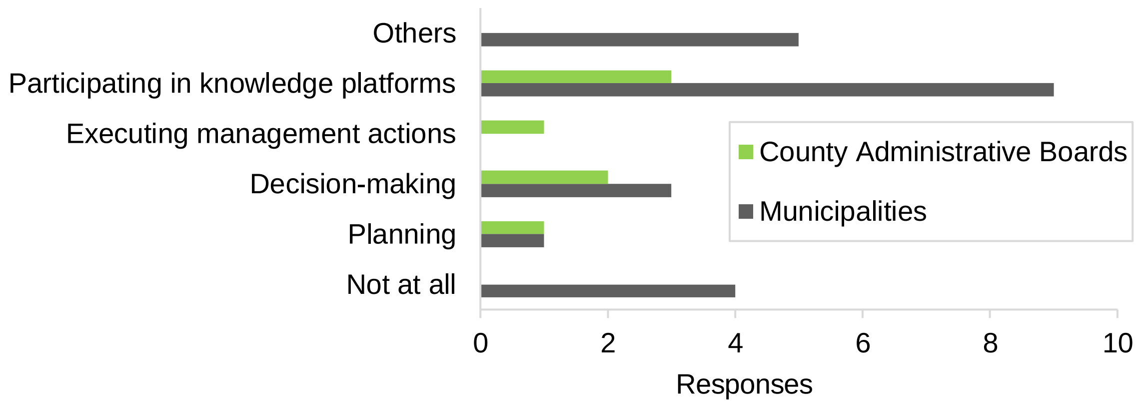

Figure 17: Survey answers of municipalities and county administrative board representatives on their preferred form of participation in the management of the Pacific oysters.

Most of the respondents (13 municipalities and 2 county administrative boards) stated that their municipality or county have no financial resources for management actions, while the remaining participants did not have any knowledge about their funding. Further, the majority of participants (11 municipalities and all three county administrative boards) stated they would need support in managing the Pacific oyster, e.g., with knowledge, monitoring, surveying, management suggestions, management actions, networks, inspiration, or funding.

Several participants showed an interest in using the oysters as a resource, e.g., for food or as a fertilizer. All three representatives from the county administrative boards and 5 out of 18 municipality representatives were in favor for a legislation change concerning the fishing rights of the Pacific oyster[11]. It was described by participants that the oysters are an invasive species of high potential risk, thus, its eradication should not be dependent on landowners' approval. The rest of the participants were not sure whether there should be a change in legislation as they would require more information before making a decision.

[11] Based on the Swedish Fisheries Act, the Pacific oyster is a resource that belongs to the landowners and can't be harvest or eradicated without their approval.

4 Discussion

In this study, the applicability of a model for evaluation of invasion stages of Pacific oysters in Sweden was confirmed and it was found that the Pacific oyster had reached different invasion stages along the Swedish coastline, supporting the need for a dynamic management approach. Knowledge levels about the species were, however, in general low among municipality and county stakeholders, hence limiting the potential for efficient management. Moreover, while municipality stakeholders showed an high interest in learning more about the species and its effects, the general interest in performing management actions was low. Further, stakeholders' showed either a mixed or negative attitude towards the oysters. Thus, challenges in terms of involvement of stakeholders were identified.

4.1 Applicability and implementation of the invasion model

To provide a sufficient discrimination of invasion stages of the Pacific oyster along Sweden's west coast, the model was revised in two main ways; Firstly, the thresholds for salinity during the reproductive period and temperature for the winter months were adjusted to better represent the current knowledge levels. Secondly, a revision of the invasion stages and the second part of the model allowed a clearer understanding of the oysters' invasion stages linked to the evaluation criteria. The revised model provided a first classification of the invasion stages of the oysters along the Swedish west coast. However, a final classification will require a number of iterations. It is likely that the abiotic criteria in the model must be revised as new (biological) data about the Pacific oyster's invasion and key life stages in Scandinavia become available. There are still knowledge gaps, e.g., about the oysters' reproductive period and of growth rates depending on salinity, that can affect the thresholds set in the model. As exemplified through the work with this project, the oysters spawning period will vary between years (Strand et al., 2022), and the model was therefore revised to include a longer spawning period (July and August). Moreover, Kinnby et al. (2023) found that the Pacific oyster is adapting to lower salinities, as populations from Halland Väderö could reproduce in much lower salinities than populations from the northern parts of the coastline. The Pacific oyster has yet not been recorded in the Baltic, however, this might change with continued adaptation of the oysters to low salinity conditions (Kinnby et al., 2023).

Further, very little is known about the oysters' growth rates in low salinity areas. Size limits used to determine recruitment with the model were based on growth patterns in the northern parts of the coast (Strand et al., 2022) and compared to measurements of recruits (1 year old oysters) recorded in Texel, Netherlands (Cardoso et al., 2007). Hence, established size limits for recruitment may not apply to the southern part of Sweden with lower salinities. Existing data, however, indicates that the oysters' grow rates are slower in low salinities (Brown & Hartwick, 1988), hence juveniles are smaller, and the limit for recruitment may need to be set lower in low salinity areas. Due to these knowledge gaps, the threshold for recruitment (individuals measuring up to 25 mm) was not revised in this work, however, with more data available, a more representative threshold based on the local situation could be established. Alternatively, instead of analysing length distributions in populations, spat collectors could be deployed in the sea to record settlement of seed (Strand et al., 2022).

Moreover, in addition to the aspects included in the current model (winter conditions, and temperature and salinity during the reproductive season), other aspects may impact the establishment and invasion success of the oysters, e.g. food availability and predation (Ruiz et al., 1992; Cardoso et al., 2007). Further, habitat availability may also affect the abundance of the Pacific oyster as the larvae needs a hard substrate to settle on (Laugen et al., 2015). Thus, some limitations to the model are given. However, if the model becomes too complex and detailed, it will become less user friendly and may require too much effort related to data collection, hence will not be used and important knowledge will go missing. Ultimately, there is a trade-off between the usability of the model (quick and simple) and its accuracy. However, based on the experiences in the field and from the thesis work, the model represents a decent compromise between these perspectives.

4.2 Oyster distribution and invasion stages

In this study, the southernmost municipality where oysters were found was Landskrona. However, in a previous survey, oysters were recorded even further south, in Malmö. In an underwater video survey, conducted by Martínez Garcia et al. (2018), Pacific oysters were recorded at two sites in Kävlinge and Malmö municipalities. As both sites, Barsebäckshamn and Malmö, were in harbours and too deep to be surveyed in the scope of this project, the sites were only visually surveyed from land, hence, it is possible that oysters were still present in these locations. On the other hand, the oysters may have disappeared over the last 5 years due to other factors, i.e., wave exposure or human interference (Bergström et al., 2021). Thus, based on the results of this work, exhaustive surveying of the sites might provide important information on the invasion front of the oysters. This situation highlights that the classification provided by this work represents a first screening of the coastline and should be updated in an iterative way with new data from municipalities. This is of particular importance in the invasion front, as based on the dynamic management approach, if the sites in this area would be updated from Absence to *Survival*, different management measures would become relevant. Further, early detection, especially at those low density sites, have a high chance of limiting further spread of the oysters.

Overall, no sites were classified as Absence/*Unlikely to have future settlement*, as the local abiotic conditions always fulfilled the requirements for reproduction at sites where oysters were not recorded. This could, however, change if municipalities located further into the Baltic were included, due to low salinities ≤8 PSU (SMHI, 2010; Riisgård et al., 2013). Moreover, in the scope of this work it was not possible to classify medium and low density sites as *Estbalished cluster* or *solitary*, as further monitoring of the population structure and changes over time was needed. Consequently, monitoring is an important tool to establish the invasion stage boundaries in those municipalities which are exposed to changing conditions. Ultimately, this is needed to allow for implementation of a dynamic management structure. However, for this it needs to be further discussed for how long a site should be monitored before classifying a low and medium density site.

Moreover, as mentioned before, less previous survey data was available from municipalities in the south, especially for Halland (<10 previously surveyed sites per municipality). Thus, to confirm that the worst-case scenarios were classified during this work, additionally surveying of municipalities where less previous data was available is suggested. Additionally, both Munkedal and Burlöv cover only a minor stretch of the coast and were, therefore, excluded from the model classification in this work. However, it is suggested to include these municipalities in future surveys to define invasion boundaries of the Pacific oyster. Alternatively, to be able to include those municipalities in the dynamic management plan without complementary field work, they could, as a first step, be classified based on the classifications of neighbouring municipalities.

All municipalities classified with the worst-case invasion stage, *Established reef/high density*, were located in Västra Götaland. Based on invasion frameworks (Geburzi & McCarthy, 2018), in these municipalities mitigation efforts to limit the effect on the ecosystems should be taken. Further, alternative uses of the resource, i.e., commercial harvesting, could be explored (Mortensen et al., 2019). However, it can be argued that most effort should be put into the southern parts of the coast, where densities are either low or oysters still absent. Thus, management has the highest possibility of an impact, either by preventing the introduction of the oysters or through early detection in combination with eradication (Pyšek & Richardson, 2010; Hansen et al., 2023).

4.3 Stakeholder engagement and knowledge

As apparent for the preceding discussion, stakeholder involvement is necessary to not only monitor but also to manage the oyster populations. As the DynamO project currently does not address municipality stakeholders, analysing their knowledge level and attitudes provides a basis for communication strategies and future involvement in the dynamic management plan. This might play a key role as the Pacific oyster is not listed on the Unions list for Invasive Alien Species, hence it is not regulated by the EU (Regulation (EU) 1143/2014) or the Swedish Invasive Alien Species regulation, and there is no general requirement to perform any management actions against the species.

Overall, municipality representatives showed a high interest in learning more about the Pacific oyster, especially in their area. No significant correlation between municipality representatives' knowledge level and oyster densities could be identified. Although, stakeholders in the southern municipalities, with lower levels of invasion, generally perceived themselves to have a higher knowledge level than municipalities in the northern parts of the coast where the most severe invasion stage *Established reef/high density* was recorded. However, described as the illusion of knowledge, the perceived knowledge level of participants can differ from their actual knowledge level (Park, 2001). As it was not investigated in this study what the actual knowledge level of the stakeholders was, it is possible that the municipalities in the north were more aware of their knowledge gaps than municipalities in the south, thus, rated their knowledge level lower. Moreover, different knowledge levels could also be related to the educational or professional background of the participant (i.e., marine biologist or environmental analyst), personal interests, or the municipalities previous involvement in marine monitoring or marine invasive species management, which was not directly inquired with the survey.

So called “conflict species”, are species that have both negative and positive effects on their environment and related socio-ecological systems (Novoa et al., 2018). Hence, usually there is a conflict between different stakeholders concerning the use and management of the species (Dickie et al., 2014; Novoa et al., 2018). As an ecosystem engineer and as described before, the Pacific oyster can have both negative and positive effects on its environment (Laugen et al., 2015). Moreover, as the oysters have a high commercial value (Mortensen et al., 2019), it can be considered as a “conflict” species. As the general perception of municipality representatives towards the oysters was either negative or mixed, but never positive, it seems to be important to share information especially about the positive effects of the oysters. In the situation of the Norway King Crab, the commercial value of the species was able to facilitate a change in stakeholders’ perception of the invasive species (Sundet & Hoel, 2016). Thus, increasing knowledge about the Pacific oysters’ economic value may facilitate attitude change in stakeholders, and therefore, increase the success of management actions aiming at using the oysters as a commercial resource for harvesting or tourism (Mortensen et al., 2019). Since a successful management of such “conflict” species is dependent on the acceptance of measures by stakeholders (Novoa et al., 2018) and as the individual knowledge can shape the perception of stakeholders, increasing the knowledge might increase the awareness thus the understanding of a need for management actions (Shackleton et al., 2019b). The survey gave valuable information on how stakeholders would like to learn more about the oyster, whereas most participants would prefer fact sheets and project reports as a source of information.

Based on the legal framework in Sweden, the main responsibility for administrative and coordinative work concerning the prevention, reduction and eradication of aquatic IAS lies with the Swedish Agency for Marine and Water Management (SwAM). Further, SwAM is responsible for coordinating this work with other agencies, i.e., amongst others, county administrative boards (SwAM, 2021). This mirrors the statement of most municipality representatives who expressed that the main responsibility and coordination should lie on a higher level, i.e. SwAM. Moreover, some representatives stated they would also like to see a shared responsibility of the oysters’ management on multiple levels, including municipalities and private landowners. However, most representatives were unsure whether their municipality would actually like to be involved in the management. This low willingness to participate is likely related to the lack of funding or missing legal responsibilities to manage the Pacific oyster. Supporting this assumption, it was addressed by one survey participant (county administrative board representative), if the Pacific oyster would be on the list of EU species and there would be a method reasonable in time and money all stakeholders (including municipalities and private landowners) should be involved in management actions. As the model and protocol provided by this work presents such a method, it might play a crucial role for the involvement of municipalities in the management.

An example illustrating how complex situations can be dealt with through stakeholder involvement, was the formation of Kosterhavet National Park. In that process, stakeholder engagement and involvement, hence a co-management process with local actors, was key for the success of the establishment of the park (Morf et al., 2011). Another example from Kosterhavet National Park, a pilot project of a collaboration between national park management and tourism stakeholders, highlighted the importance of building trust among stakeholders in order to overcome challenges, i.e., different perspectives or interests (Wogel, 2018). Moreover, it is discussed in the literature that in marine management early stakeholder involvement plays an important role, as it can lead to understanding, learning and interactions between stakeholders that would usually not meet (Gopnik et al., 2012). Hence, the integration of additional stakeholders, i.e., municipality representatives, in the process of developing a dynamic management plan for the oysters is likely a crucial step for its long-term success. To facilitate this process, the survey also provided important information on how to involve municipality stakeholders e.g. through participation in knowledge platforms and through an expressed interest in taking part in decision-making, e.g., on site selection or management actions.

Moreover, stakeholder involvement and the co-production of knowledge can increase the legitimacy, hence the trust in management measures (Moon et al., 2015). Only 40% of the municipality representatives believed that management actions were necessary in their area, however, based on invasive species framework, management measures can, and should be, applied to all stages of invasion (Geburzi & McCarthy, 2018). Especially, in areas with no or low oyster densities (southern parts of the coastline), co-production of knowledge might be of particular importance, as prevention and early eradication have the highest possibility of management success and can prevent further spread of the oysters. Similar to the situation of the king crab in Norway (Sundet & Hoel, 2016), in parts of the coast where the oysters have already established, although in different densities, the main management objectives should be to limit further expansion of the oysters and mitigate negative effects.

As the Pacific oyster is a comparable species to the red king crab, hence has a commercial potential, exploitation of the resource might be a measure for containment and mitigation of negative effects. However, according to the current interpretation of the Swedish Fisheries Act (Fiskelag (1993:787)), where no distinction is being made between the invasive Pacific oyster and the native European flat oyster (*Ostrea edulis*), the Pacific oysters belong to the landowners out to 200 m from shore. This means eradication and commercial harvest activities can not be performed without the landowners' permission. However, some landowners have established commercial activities, e.g., tourism (oyster safaris) or harvest (Mortensen et al., 2019). As analyzed from the survey, only a small part of the participants was in favor for a legislation change while most participants were unsure due to a lack of knowledge. Overall, there is a need for clarification of the legal framework to allow use of the resource to its full potential (Mortensen et al., 2019).

4.4 The path ahead …

The presented model for the classification of invasion stages needs further support from the end users to produce the most relevant results. Municipalities could easily contribute with, e.g., recruitment data (length measurements), population structure data, and monitoring of sites to determine a change of population structure over time, hence the boundary between source and *Established low/medium density* (solitary/cluster) stages.

However, given the limited activities at the municipality level regarding the mapping of oyster populations to date, overall low knowledge levels and willingness to participate in or perform management actions, these challenges need to be addressed first. As stakeholders showed a high interest in learning more about the Pacific oyster, fact sheets and project reports, especially about the respective local invasion situation should be made available. Further, municipality stakeholders seemed to be interested in participating in knowledge platforms, which could be a first step in involving stakeholders in the process. Finally, lack of financial resources might be one of the causes for the low interest in participating in management actions. Hence, the revised model should be presented to municipalities as it provides a simple method, where surveys of the Pacific oyster can be included in other marine surveys performed by the municipalities.

5 Conclusion

In this project, the applicability of the previously designed invasion stage model by Le Gall (2022) was tested and evaluated. The model was revised based on experiences made in the scope of this thesis work and mainly thresholds for salinity and temperature were updated, based on new available biological knowledge. Hence the model was adjusted in an iterative process and this thesis work provides a proof of concept for its applicability.

Moreover, the model was used to define invasion boundaries of the Pacific oysters' invasion stages along the Swedish west coast to serve as a base for a dynamic management model. Along the coastline, a clear trend in decreasing degree of invasion stages was noticed from north to south, from *Established high density/reef* to Absence/*Future settlement possible*, respectively. This supports the need of a dynamic management model for the Pacific oyster. In the scope of this project the southernmost invasion range of the oysters was in Landskrona, in the municipalities further south no oysters were recorded. However, in previous surveys oysters have been reported as far south as Malmö. Hence, this classification is a first screening of the coastline, which now needs to be updated by the contribution of knowledge by municipality stakeholders. Relevant data that could be provided by municipalities includes length data, population structure data and data on changes in the population structure. The latter would allow to finalise the classification of *Reproduction* sites in *Established low/medium density* sites, which is important for a dynamic management.

However, several challenges were identified for an efficient management of the oysters. Overall, municipality stakeholders showed a low level of knowledge of the oysters and their perception was either negative or mixed. Further, there was a low willingness to perform any management actions amongst municipalities, which is likely due to a lack of resources (i.e., funding). Valuable information was provided by the survey to address these challenges. Firstly, providing fact sheet and project reports could increase stakeholders' knowledge level about the oyster and lead to changes in attitudes; secondly, giving municipalities the chance to participate in knowledge platforms might be an important first step of municipality stakeholder involvement into the dynamic management model; thirdly, the revised model provides a simple and fast way of integrating surveys of the Pacific oyster in other marine surveys conducted by the municipalities.

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7 Appendix

7.1 List of selected sites

Table 4: List of selected sites with latitude and longitude sorted by municipalities (counties highlighted in blue Västra Götaland, orange Halland and grey Skåne). Information if sites are from existing surveys, *Artportalen* (red) or added sites (yellow) during the field work, identified knowledge gap (green all relevant data available, blue no oysters present), visited sites and selected sites (x) used for the classification of invasion stages. Comment: short explanation for the selection of sites for model classification, and/or population structure (reef or cluster) and/or number of available survey sites, and/or if a higher density site was identified in the municipality but could not be reached.

Municipality	Site	Lat	Lon	Survey source	Knowledge gap	Visited	Selected	Comment
Strömstad	Svalhagen	58.8683	11.1548	2022 SDM Square Survey		No	x	At least one of the selected sites had reef formations; >80 previously surveyed sites
	1383	58.8950	11.1642	2021 oyster overview survey for clearing experiments	Length measurements	No		
	1457	58.8547	11.1749	2021 oyster overview survey for clearing experiments	Length measurements	No		
	1373	58.9132	11.1975	2021 oyster overview survey for clearing experiments	Length measurements	No		
	Kockholmen	58.8331	11.1414	2022 SDM Square Survey		No	x	
	Tjärnö	58.8743	11.1461	Added site	Presence, length measurements, population structure	Yes	x	
Tanum	Skredsvik	58.4873	11.3100	2022 SDM Square Survey		No	x	At least one of the selected sites had reef formations; >100 previously surveyed sites
	Grebbestad1	58.6720	11.2508	Grebbestad High school 2023		No	x	
	Grebbestad2	58.6721	11.2523	Grebbestad High school 2023		No	x	
	Grebbestad3	58.6723	11.2517	Grebbestad High school 2023		No	x	
Sotenäs	F077	58.3908	11.2277	2020 Area Video Survey	Population structure, length measurements	No		Visited highest accessible density site of 64 previously survey sites in municipality; Population structure cluster

Municipality	Site	Lat	Lon	Survey source	Knowledge gap	Visited	Selected	Comment
	F116	58.3972	11.3933	2020 Area Video Survey	Population structure, length measurements	No		Higher density site identified that could not be reached: Site 57 (58.3472, 11.2175) - 2020 Square Survey
	F106	58.3846	11.3185	2020 Area Video Survey	Population structure, length measurements	No		
	Skepsudden	58.4047	11.3993	Added site	Presence, length measurements, population structure	Yes	x	
Lysekil	Smalsundet	58.2484	11.4399	2022 SDM Square Survey		No	x	Reef formation at selected site; 40 previously surveyed sites in municipality
	F131	58.3922	11.4556	2020 Area Video Survey	Population structure, length measurements	No		
	56	58.3128	11.4588	2020 Square Survey	Population structure, length measurements	No		
	M210	58.2061	11.4372	2018 ME Stock assessment	Population structure, length measurements	No		
	M191	58.2165	11.4749	2018 ME Stock assessment	Population structure, length measurements	No		
Uddevalla	Myt72	58.2113	11.8995	2019 Orust Squares Model evaluation	Population structure, length measurements	No		Reef formation at selected site; 77 previously surveyed sites in the municipality
	Myt79	58.2207	11.8807	2019 Orust Squares Model evaluation	Population structure, length measurements	No		
	M133	58.2475	11.5989	2018 ME Stock assessment	Population structure, length measurements	No		
	Getevik	58.2754	11.5061	2022 SDM Square Survey		No	x	
Orust	Myt34	58.1147	11.7631	2019 Orust Squares Model evaluation	Population structure, length measurements	No		Visited highest accessible density site of 90 previously survey sites in municipality; Population structure cluster

Municipality	Site	Lat	Lon	Survey source	Knowledge gap	Visited	Selected	Comment
	Myt30	58.1177	11.6667	2019 Orust Squares Model evaluation	Population structure, length measurements	No		Higher density site identified that could not be reached: Myt29 (58.0733, 11.5742) - 2019 Orust Squares Model evaluation
	Myt55	58.1251	11.8129	2019 Orust Squares Model evaluation	Population structure, length measurements	No		
	Broccoli	58.1254	11.8175	Added site	Presence, length measurements, population structure	Yes	x	
Stenungsund	NG513	57.9906	11.8018	2022 SDM Square Survey		No	x	Visited highest accessible density site of 17 previously surveyed sites in municipality; Population structure cluster Added site in close proximity to highest density site which was not accessible during field work
	Myt52	58.1055	11.8100	2019 Orust Squares Model evaluation	Population structure, length measurements	No		
	M190	58.0933	11.8242	2019 Orust Squares Model evaluation	Population structure, length measurements	No		
	Näs	58.1069	11.8238	Added site	Presence, length measurements, population structure	Yes	x	
Tjörn	NG33	58.0446	11.5104	2022 SDM Square Survey		No	x	Selected highest density sites of 29 previously surveyed sites in municipality; Population structure cluster
	NG90	57.9414	11.5793	2022 SDM Square Survey		No	x	
	NG72	58.0072	11.5573	2022 SDM Square Survey		No	x	
Kungälv	NG79	57.8618	11.5599	2022 SDM Square Survey		No	x	Selected highest density sites of 17 surveyed sites in municipality; Population structure cluster
	NG160	57.8810	11.6409	2022 SDM Square Survey		No	x	
	NG88	57.8965	11.5784	2022 SDM Square Survey		No	x	
Öckerö	NG223	57.7444	11.6689	2022 SDM Square Survey		No	x	Selected highest density sites of 15 previously surveyed sites in municipality; Population structure cluster
	SG179	57.6687	11.6530	2022 SDM Square Survey		No	x	

Municipality	Site	Lat	Lon	Survey source	Knowledge gap	Visited	Selected	Comment
	NG248	57.7563	11.6820	2022 SDM Square Survey		No	x	
Göteborg	SG585	57.6096	11.8942	2022 SDM Square Survey		No	x	Selected highest density sites of 21 previously surveyed sites in municipality; Population structure cluster
	SG503	57.6387	11.8062	2022 SDM Square Survey		No	x	
	SG510	57.6308	11.8126	2022 SDM Square Survey		No	x	
Kungsbacka	Onsala Halvon	57.3720	11.9838	Stromstad - Helsingborg Survey 2019	Population structure, length measurements	Yes	x	Visited highest density site of 1 previously surveyed sites in municipality; Population structure cluster
	64586748	57.3612	11.9983	Artportalen	Presence, length measurements, population structure	No		
	93236309	57.3331	12.1424	Artportalen	Presence, length measurements, population structure	No		
Varberg	Ringhals	57.2680	12.1081	Ringhals Survey 2017	Population structure, length measurements	Yes	x	Visited highest density site of 7 previously surveyed sites in municipality; Population structure cluster
	Bua Hamn	57.2409	12.1104	Ringhals Survey 2017	Population structure, length measurements	No		
	Torvik	57.1413	12.2153	Ringhals Survey 2017	Population structure, length measurements	No		
Falkenberg	Stranninge	56.9670	12.3497	Ringhals Survey 2017	Population structure, length measurements	No		Visited highest density site of 4 previously survey sites in municipality; Population structure cluster
	Torsvik	56.9133	12.3941	Ringhals Survey 2017	Population structure, length measurements	No		
	Grimsholmen	56.8551	12.5476	Ringhals Survey 2017	Population structure, length measurements	Yes	x	

Municipality	Site	Lat	Lon	Survey source	Knowledge gap	Visited	Selected	Comment
Halmstad	Haverdal	56.7223	12.6566	Ringhals Survey 2017	Population structure, length measurements	Yes		Visited highest density site of 2 previously surveyed sites in municipality; Population structure cluster
	12	56.6410	12.7804	Ringhals Survey 2017	Population structure, length measurements	Yes	x	
	Bengtsgård	56.7406	12.6236	Artportalen	Presence, length measurements, population structure	Yes	x	
Laholm	98285475	56.4676	12.9186	Artportalen	Presence, length measurements, population structure	No		0 previously surveyed sites; no sightings in Artportalen; Only two sites in the municipality due to short stretch of coastline
	Lagaoset	56.5513	12.9457	Added site	Presence, length measurements, population structure	Yes	x	
Båstad	Båstad	56.4348	12.8423	Martinez Garcia et al. 2018	Population structure, length measurements	Yes	x	Visited highest density site of 13 previously surveyed sites in municipality
	Kattvik	56.4626	12.7559	Ahlers et al. 2020	Population structure, length measurements	No		
	Torekov	56.4283	12.6265	Ahlers et al. 2020	Population structure, length measurements	Yes	x	
	Vejbystrand 1	56.3156	12.7617	Ringhals Survey 2017	Population structure, length measurements	No		
Ängelholm	64865852	56.2382	12.8149	Artportalen	Population structure, length measurements	Yes	x	Visited highest density of 1 previously surveyed site in municipality, no oysters have been recorded; Sites added from Artportalen
	98757030	56.2517	12.8268	Artportalen	Population structure, length measurements	Yes	x	
	97743642	56.2710	12.8376	Artportalen	Population structure, length measurements	Yes		

Municipality	Site	Lat	Lon	Survey source	Knowledge gap	Visited	Selected	Comment
	Ronnea	56.2723	12.8335	Ringhals Survey 2017	No oysters present	Yes	x	
Höganäs	Arlid 2	56.2751	12.5739	Ahlers et al. 2020	Population structure, length measurements	Yes	x	Selected highest density sites of 18 previously surveyed sites in in municipality
	Revets Badplats (fd Goslovshan)	56.2333	12.6885	Ringhals Survey 2017	Population structure, length measurements	Yes	x	
	Molle	56.2827	12.4933	Ringhals Survey 2017	Population structure, length measurements	Yes	x	
	Norra Häljaröd	56.2216	12.7613	Artportalen	Presence, length measurements, population structure	Yes	x	
Helsingborg	Helsingborg	56.0480	12.6877	Martinez Garcia et al. 2018	Population structure, length measurements	Yes	x	Visited highest density sites of 12 previously surveyed sites in municipality
	Raa	55.9910	12.7409	Martinez Garcia et al. 2018	Population structure, length measurements	Yes	x	
	Domsten	56.1162	12.6042	Martinez Garcia et al. 2018	Population structure, length measurements	Yes	x	
	Gravarliden/Sofiero	56.0799	12.6617	Artportalen	Presence, length measurements, population structure	Yes	x	
Landskrona	Borstahusen	55.8948	12.8003	Martinez Garcia et al. 2018	Population structure, length measurements	Yes	x	Visited highest density sites of 8 previously surveyed sites in municipality (1 no oysters recorded previously)
	Alabodarna 1	55.9396	12.7734	Ahlers et al. 2020	Population structure, length measurements	Yes	x	
	Landskrona	55.8678	12.8176	Ahlers et al. 2020	No oysters present	Yes	x	
Kävlinge	Barsebackshamn	55.7568	12.9023	Martinez Garcia et al. 2018	Population structure, length measurements	Yes	x	Visited highest density sites of 3 previously surveyed sites in municipality (2 no oysters recorded previously)

Municipality	Site	Lat	Lon	Survey source	Knowledge gap	Visited	Selected	Comment
	98681469	55.7366	12.9606	Artportalen	Presence, length measurements, population structure	Yes	x	
	Barsebäckstrand	55.7712	12.9254	Added site	Presence, length measurements, population structure	Yes	x	
Lomma	Lomma Smabatshamn	55.6746	13.0579	Ringhals Survey 2017	No oysters present	Yes	x	Visited highest density sites of 4 previously surveyed sites in municipality (all sites no oysters recorded previously)
	Bjarred Hamn	55.7206	13.0069	Ringhals Survey 2017	No oysters present	Yes	x	
	Långa bryggan	55.7098	13.0222	Added site	Presence, length measurements, population structure	Yes	x	
Malmö	Malmo	55.6104	12.9728	Martinez Garcia et al. 2018	Population structure, length measurements	Yes	x	Visited highest density sites of 5 previously surveyed sites in municipality (3 no oysters recorded previously)
	Utsiktspunkt Oresund	55.5710	12.8957	Ringhals Survey 2017	No oysters present	Yes	x	
	Ribersborg Kallbadhus	55.6044	12.9662	Ringhals Survey 2017	No oysters present	Yes	x	
	Klagshamn Strand	55.5249	12.8954	Ringhals Survey 2017	No oysters present	Yes	x	
Vellinge	Skanor Hamn	55.4162	12.8293	Ringhals Survey 2017	No oysters present	Yes	x	Visited all 3 previously surveyed sites in municipality (no oysters recorded)
	Hallviken Falsterbokanalen N	55.4126	12.9307	Ringhals Survey 2017	No oysters present	Yes	x	
	Lilla Hammar	55.4495	12.9476	Ringhals Survey 2017	No oysters present	Yes	x	

7.2 Survey protocol

Equipment:

- Mobile phone (to get coordinates)
- Waders
- Long gloves
- White boxes
- Caliper
- Folding rule
- Sampling square
- Clipboard, protocol, and pen

Implementation:

Look for the densest oyster bed you can find at the site (we are interested in "worst case" scenario).

Notes:

- Date
- Coordinates (WGS84, decimal degrees)
- Are there Pacific oysters on the site? (Yes/No)
- If no, you don't have to note anything more.
- If yes:

Are the oysters alive? (Yes/No, yes may also mean a mixture of live and dead oysters). Even if all are dead the following should be done:

- Identify the densest area of oysters/oyster shells (live and/or dead), note if the oysters/oyster shells in this area are in:
  1) Reef formation (= 90-100% coverage and growing on each other)
  2) Clusters (<90% coverage but growing on top of each other in clumps, this includes large oysters with only small live oysters)
  3) Solitary

  The densest type should be noted (i.e., reef > cluster > solitary), there will be several different types on some sites, but it is the densest type that determines how the site is assessed.
- Classify the bottom substrate as essentially: Mudflat/soft bottom, sand, gravel/shell hash, rocky bottom, boulders/stone slab.
- f live oysters are present, look for small oysters and place a sampling square (0.5 x 0.5m) where the small oysters are, if no small oysters are visible, place the square haphazardly where there are oysters and measure the length (in mm, from umbo to longest shell length) of 100 live oysters in the square. Make sure to check large oysters for attached small oysters. Write down the lengths in consecutive rows with commas in between, e.g., 102, 87, 88, 34, etc. Place the measured oysters in a box. The aim is to have a random sampling of the length so that not only large oysters are measured. Put all measured oysters back in each square when you have finished. The measurements should be representative of the locality. If 100 individuals are not reached in a square, place a new square randomly on the locality and continue measuring. Note the number of each sampling square.
- Other observations. Please describe the area in general (e.g., depth distribution of oysters, presence of macroalgae, whether there is eelgrass adjacent to the oysters and whether you see clear signs of recruitment (i.e., oysters smaller than 20 mm).

7.3 Municipality histograms

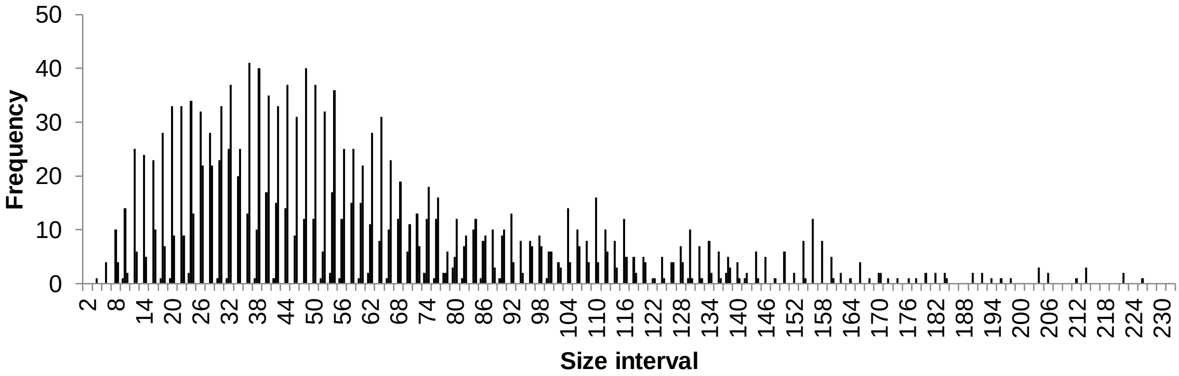

Figure 18: Strömstad municipality histogram. Total: 1927 length measurements, min. size: 4 mm, recruitment: positive.

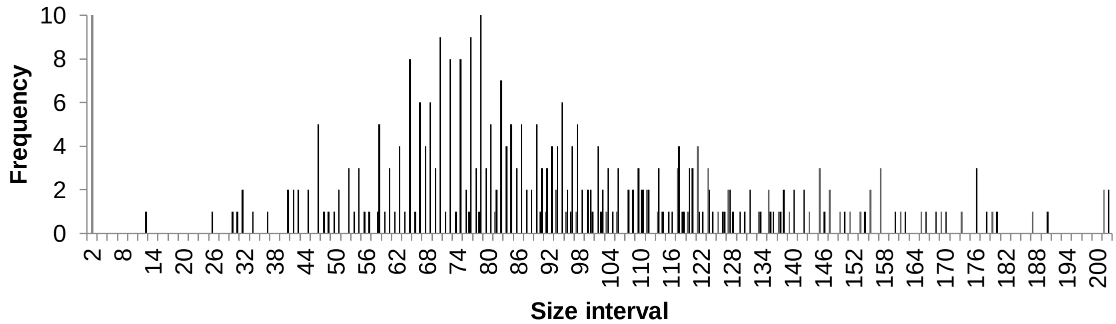

Figure 19: Tanum municipality histogram. Total: 422 length measurements, min. size: 12 mm, recruitment: positive.

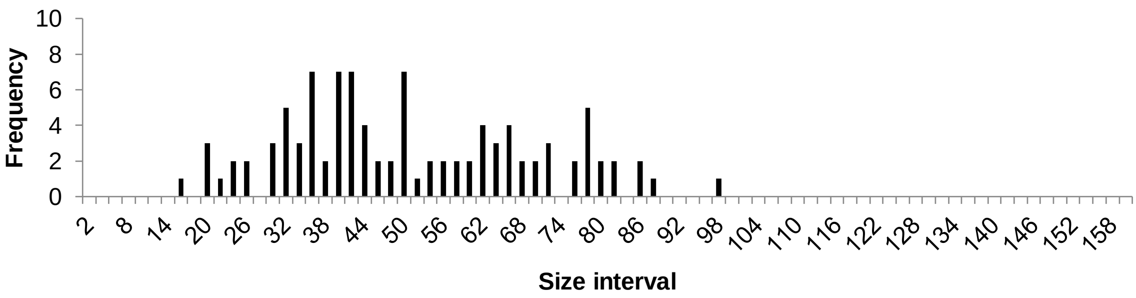

Figure 20: Sotenäs municipality histogram. Total: 100 length measurements, min. size: 16 mm, recruitment: positive.

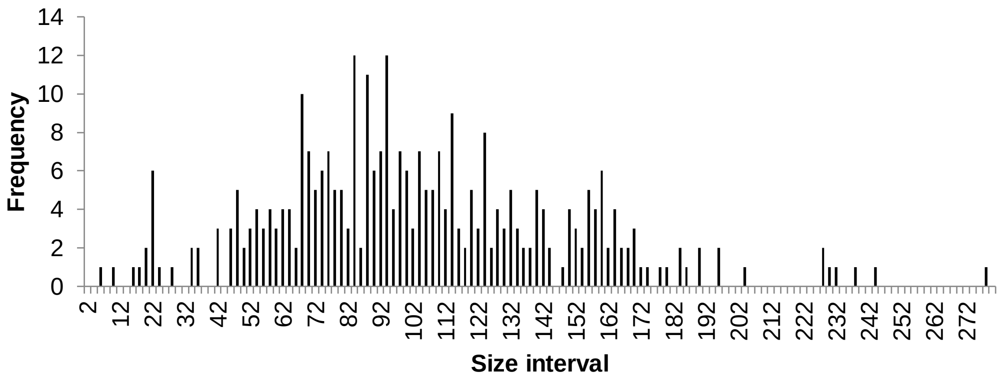

Figure 21: Lysekil municipality histogram. Total: 323 length measurements, min. size: 6 mm, recruitment: positive.

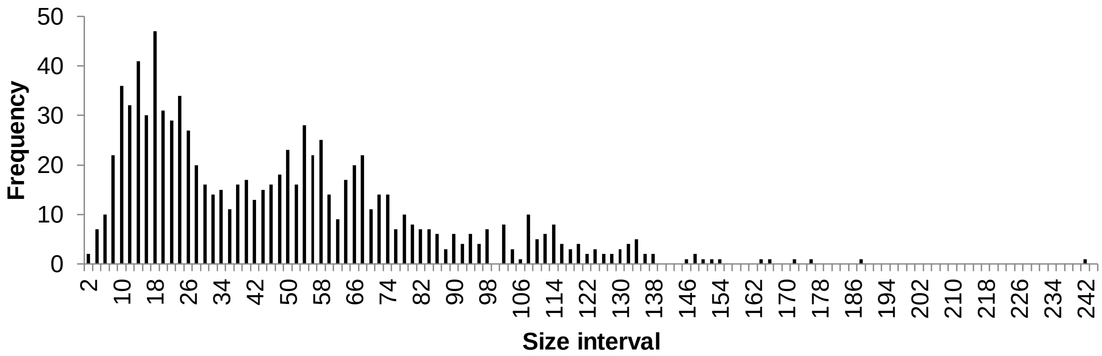

Figure 22: Uddevalla municipality histogram. Total: 918 length measurements, min. size: 2 mm, recruitment: positive.

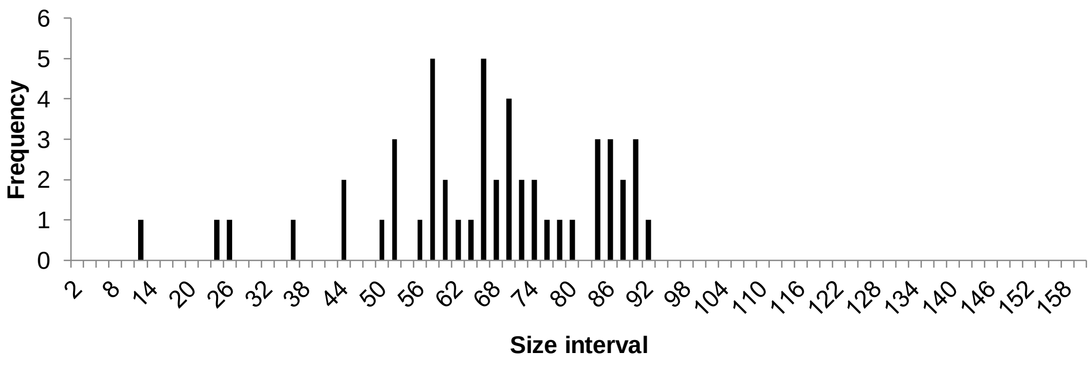

Figure 23: Orust municipality histogram. Total: 50 length measurements, min. size: 11 mm, recruitment: positive.

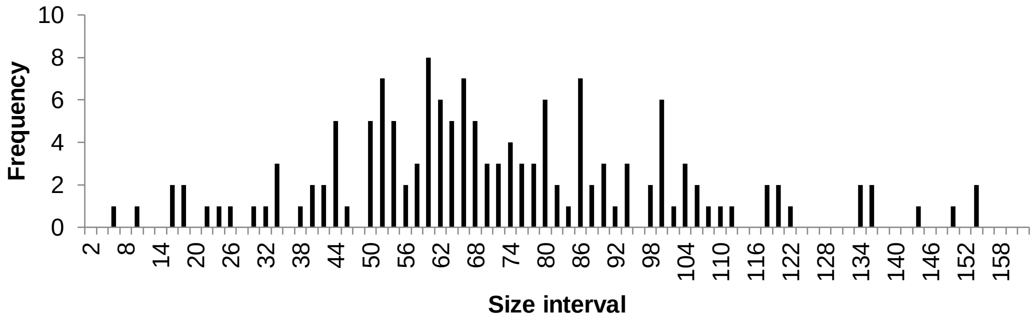

Figure 24: Tjörn municipality histogram. Total: 149 length measurements, min. size: 6 mm, recruitment: positive.

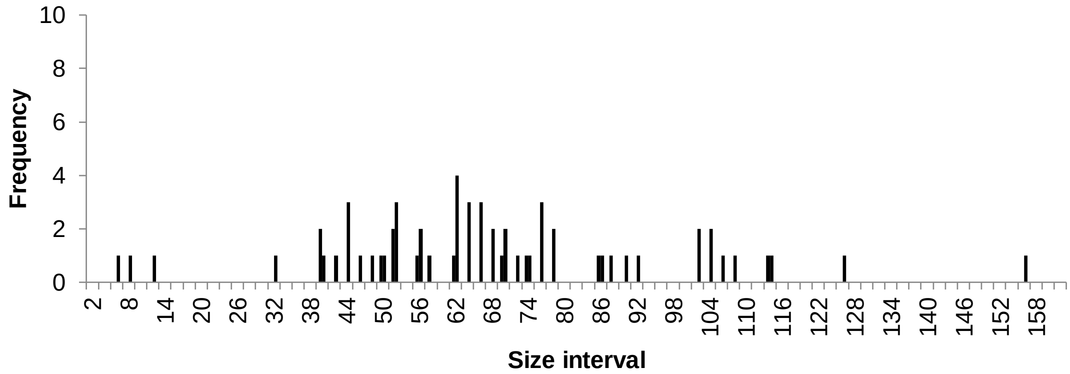

Figure 25: Stenungsund municipality histogram. Total: 63 length measurements, min. size: 5 mm, recruitment: positive.

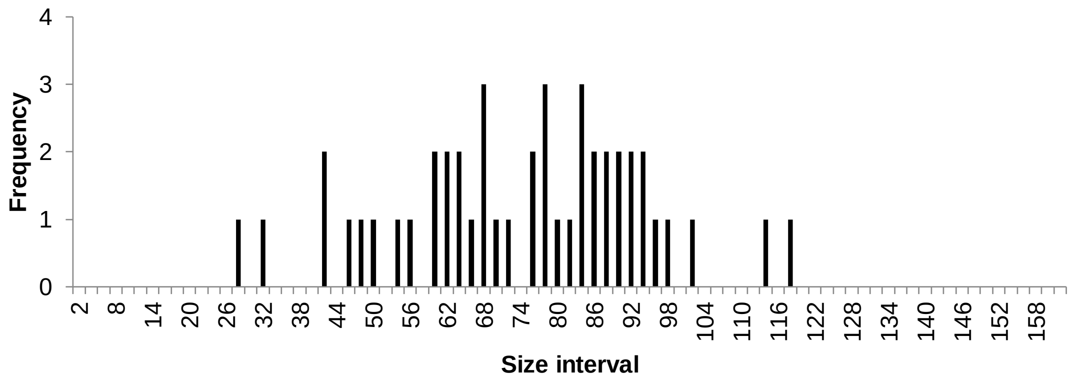

Figure 26: Kungälv municipality histogram. Total: 46 length measurements, min. size: 27 mm, recruitment: negative.

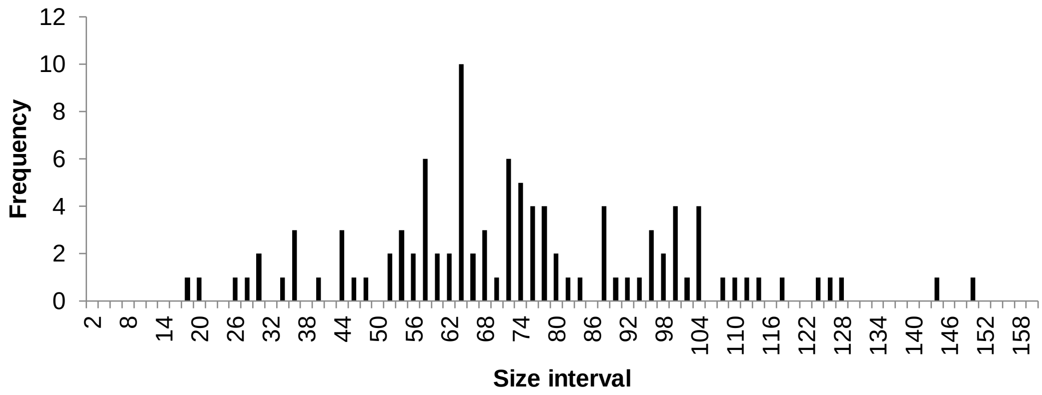

Figure 27: Öckerö municipality histogram. Total: 103 length measurements, min. size: 18 mm, recruitment: positive.

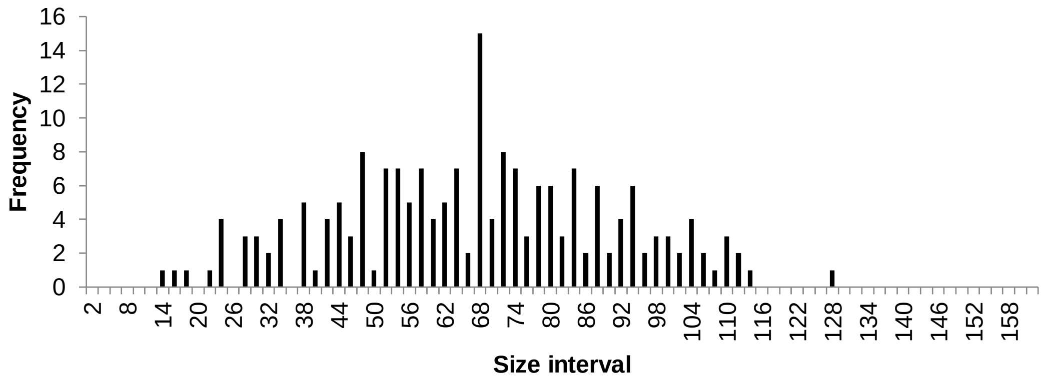

Figure 28: Göteborg municipality histogram. Total: 194 length measurements, min. size: 14 mm, recruitment: positive.

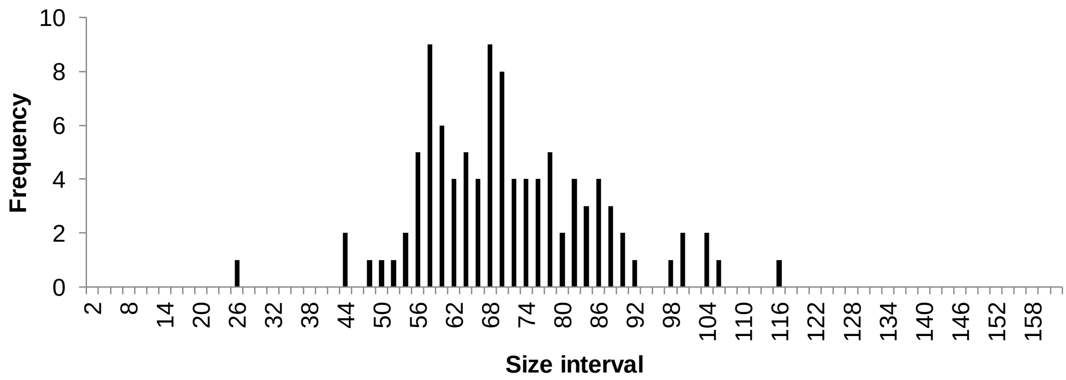

Figure 29: Kungsbacka municipality histogram. Total: 101 length measurements, min. size: 26 mm, recruitment: negative.

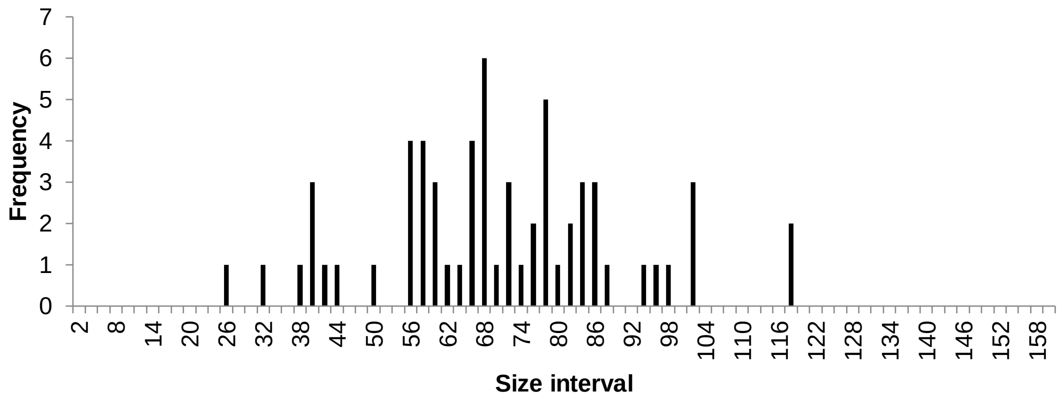

Figure 30: Varberg municipality histogram. Total: 62 length measurements, min. size: 25 mm, recruitment: positive.

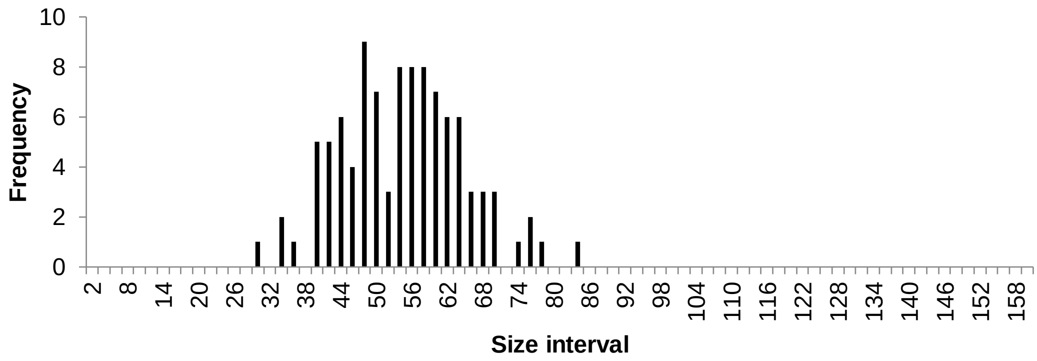

Figure 31: Falkenberg municipality histogram. Total: 100 length measurements, min. size: 30 mm, recruitment: negative.

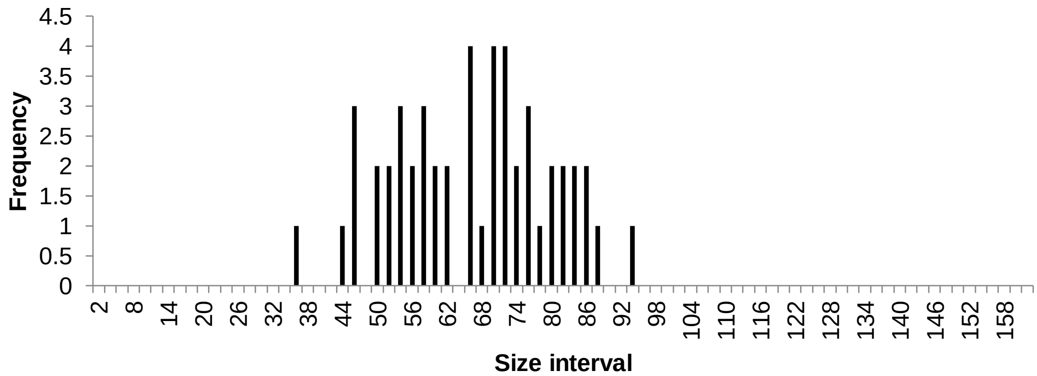

Figure 32: Halmstad municipality histogram. Total: 51 length measurements, min. size: 36 mm, recruitment: negative.

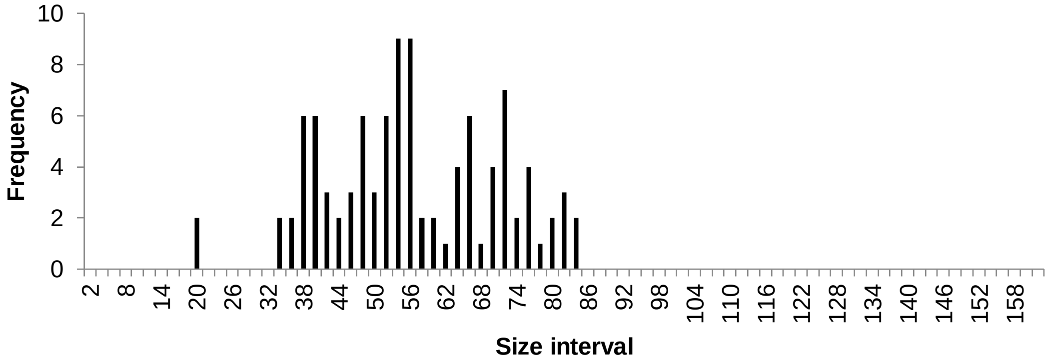

Figure 33: Båstad municipality histogram. Total: 100 length measurements, min. size: 19 mm, recruitment: positive.

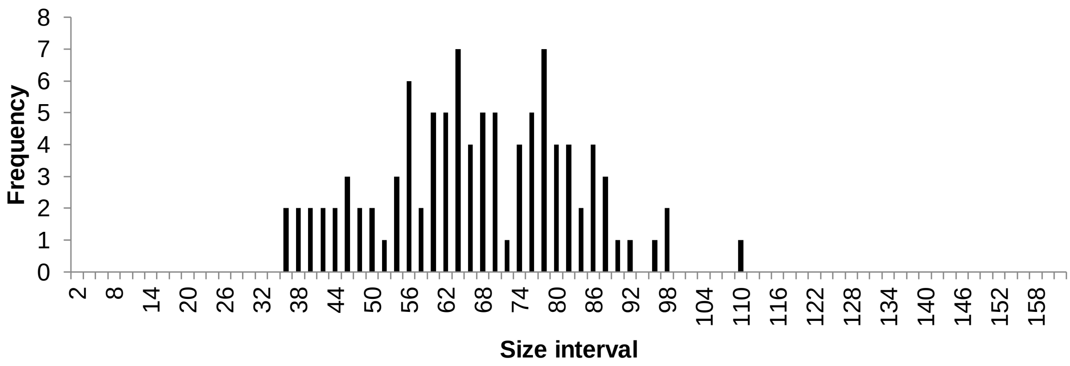

Figure 34: Ängelholm municipality histogram. Total: 100 length measurements, min. size: 35 mm, recruitment: negative.

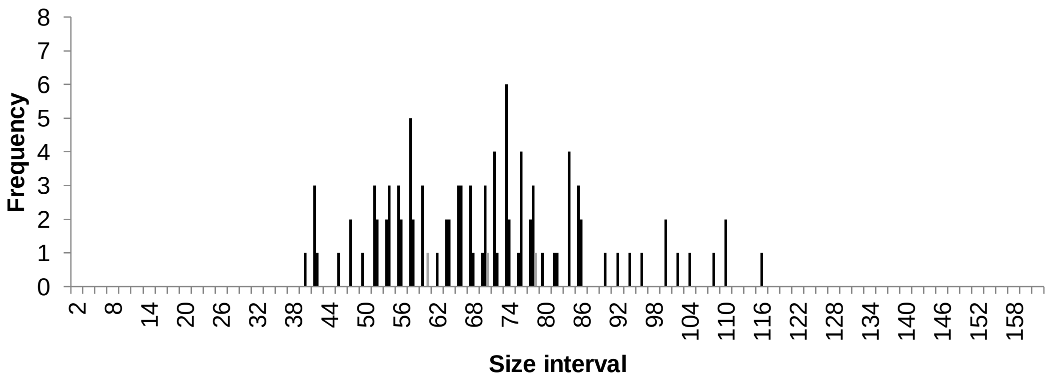

Figure 35: Höganäs municipality histogram. Total: 103 length measurements, min. size: 39 mm, recruitment: negative.

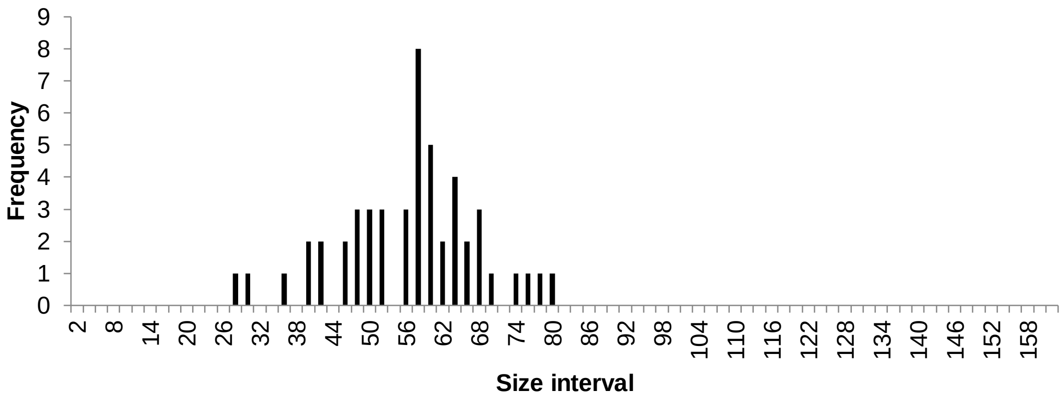

Figure 36: Helsingborg municipality histogram. Total: 50 length measurements, min. size: 28 mm, recruitment: negative.

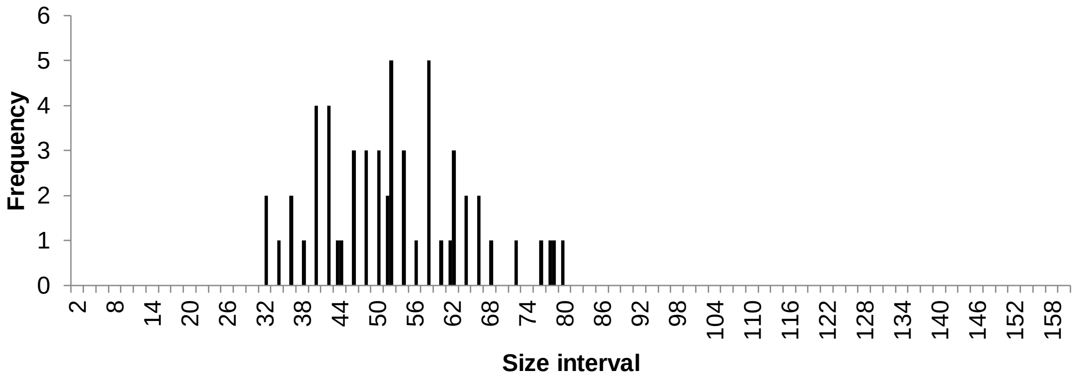

Figure 37: Landskrona municipality histogram. Total: 56 length measurements, min. size: 32 mm, recruitment: negative.

7.4 Online stakeholder survey

Stakeholder survey about knowledge of and attitudes towards the Pacific oyster – DynamO project (IVL)

Dear Participant,

This survey consists of four main sections and should take no longer than **15-20 minutes** to complete. Firstly, you will answer questions about your general knowledge of the invasive Pacific oyster. In the second section, you will be asked questions about your "local" knowledge of the Pacific oyster, for example in your municipality or in the geographical area you are active. In the final two sections, your attitudes and objectives concerning the oysters' management in Sweden in general and in your municipality or geographical area will be investigated, respectively.

We would appreciate your participation even if you haven't heard of the Pacific oyster before this survey or if you have no specific knowledge about the Pacific oyster in your area.

Thank you for your interest!

Data collected will be anonymized and only linked to the municipality, organization, or authority that you represent, not to you as an individual. Anonymized data from the study will be shared within the research group of the DynamO project, and may be presented in aggregated from to other parties. The results from this survey will be integrated and published in my Master thesis, and may be integrated in other publications in the scope of the DynamO project.

In compliance with the European Union's General Data Protection Regulation (GDPR), EU Data Protection Regulation 2016/679, you have the right to:

- **Withdraw your consent**
- **Request access to your personal information**
- **Have your personal information corrected, deleted or the processing thereof restricted**

If you wish to invoke any of these rights, you can contact me, Claire Roesch (gusroecl@student.gu.se), at any time.

By selecting "I agree" below, I confirm to have read the information above and to give my consent to participate in this survey.

- o **I agree**
- o **I do not agree**

1. Identification of the participant

1.1. What organization, municipality, authority, or other do you represent?

1.2. What is your role in this organization, municipality, authority, or other?

1.3. Have you heard about the DynamO project before this survey?

- o Yes
- o No

2. General information about the Pacific oyster

2.1. Have you heard about the invasive Pacific oyster before this survey?

- o Yes
- o No

2.2. Please read through the statements below and rate your knowledge level. (If you are doing the survey on the phone, note that not all answering options, ranging from very low to very high knowledge level, are visible on the screen. In that case, please scroll through the options to choose the right one.)

Knowledge level about…	Very low	Low	Medium	High	Very high
... the invasion history of the Pacific oyster in Sweden					
... the distribution of the Pacific oyster along the Swedish coastline					
... the negative effects of the Pacific oyster on ecosystems					
... the positive effects of the Pacific oyster on ecosystems					
... the management of the Pacific oyster					

2.3. Do you think your knowledge level about the Pacific oyster is sufficient?

- o Yes
- o No
- o I don't know

2.4. Would you like to gain more knowledge about the Pacific oyster?

- o Yes
- o No

2.5. If yes, in what format would you like to receive more information? (more than one answer can be selected)

- o I don't want more information
- o Contact with an expert
- o Media reports
- o Fact sheets
- o Magazine articles directed to the public
- o Technical reports

- Project reports/newsletters from projects
- Scientific articles
- Short films/videos
- Other:____

2.6. What is your attitude towards the Pacific oyster? Please select a statement or describe your attitude in your own words.
- I have a negative perspective of and attitude towards the Pacific oyster
- I have a mixed perspective of and attitude towards the Pacific oyster
- I have a positive perspective of and attitude towards the Pacific oyster
- I don't care about the Pacific oyster
- Other:____

2.7. Please state any key words that come to mind when you think of the Pacific oyster.

2.8. According to the current interpretation of the Swedish Fisheries Act the Pacific oysters belong to the landowners. This means eradication and commercial harvest activities can't be performed without the landowners' permission. On the other hand, some landowners have established commercial activities, for example tourism or harvest, and depend on the ownership of the oysters. Do you think the current situation is good or should there be a change in the legislation?

- It is good as it is
- The legislation should be changed
- I don't know
- Other:____

Please comment on your response:

3. <u>Stakeholders' local knowledge of the Pacific oyster</u>

3.1. Do you have any knowledge about the occurrence or abundance of the Pacific oyster in your area?
  - Yes
  - No

3.2. Has your organization done any surveys or contracted anyone to do surveys (for example vattenvårdsförbund or consultancy agencies) of the Pacific oyster in your area?
- Yes
- No
- I don't know

If no, please proceed to 3.3.
If yes, please answer the following questions

3.2.1. Please provide general information about the survey(s) conducted (like who conducted the survey, where, when, what methods were used, what was the purpose of the survey, etc.)

3.2.2. What variable(s) did you record? (more than one answer can be selected)
- Presence/absence of the oysters
- Live/dead oysters
- Density
- Length measurements
- Depth
- Bottom substrate
- Temperature
- Salinity
- Other:____

3.2.3. Are you willing to discuss and/or share your survey data with the DynamO project?
- Yes
- No

3.3. Is your organization planning to conduct any surveys in the future?
- Yes
- No
- I don't know

If yes, when or where are you planning to do the survey?

4. Management of the Pacific oyster

As the Pacific oyster is not regulated by the EU or the Swedish Invasive Alien Species (IAS) regulation there is no general requirement to perform any management actions. Given this condition and provided that there are no barriers in terms of the ownership of the oysters, please answer the following questions.

4.1. Do you think it is possible to do anything about the Pacific oyster in general in Sweden?
- Yes
- No
- I don't know

4.2. Do you think there is a general need for management actions of the Pacific oyster in Sweden?
- Yes
- No
- I don't know

4.3. If you think there is a need for management actions, what management objective(s) do you think would be relevant in an area with **no Pacific oysters present**? Please use the space below to state your management objective(s) or indicate if you think there is no need for management.

4.4. What management objective(s) do you think would be relevant in an area with **low density of Pacific oysters**? Please use the space below to state your management objective(s) or indicate if you think there is no need for management.

4.5. What management objective(s) do you think would be relevant in an area with **high density of Pacific oysters**? Please use the space below to state your management objective(s) or indicate if you think there is no need for management.

4.6. Given that you want to manage the Pacific oysters, what management technique(s) would you suggest in an area **no Pacific oysters present**? Please use the space below to state your management technique(s) or indicate if you think there is no need for management.

4.7. What management technique(s) would you suggest in an area with **low density of Pacific oysters**? Please use the space below to state your management technique(s) or indicate if you think there is no need for management.

4.8. What management technique(s) would you suggest in an area with **high density of Pacific oysters**? Please use the space below to state your management technique(s) or indicate if you think there is no need for management.

5. Local management of the Pacific oyster

5.1. Do you think there is a need for management actions of the Pacific oyster in your specific area?
- Yes
- No
- I don't know

If yes, please explain why:

5.2. What of the following management measures, if any, do you think could be relevant in your area? (more than one answer can be selected)

- No management actions needed

- Mapping (Kartläggning) of oyster populations
- Monitoring (Övervakning)
- Eradicating the oysters in your area completely
- Eradicating oysters at specific sites only
- Promoting commercial harvest
- Promoting recreational harvest
- Promoting consumption of oysters
- Disseminating information about the oysters to the public
- Promoting/organizing beach clean-ups, citizen science projects, collaboration with NGOs
- Performing beach clean-ups
- Participating in research activities
- Other:____

5.3. Has your organization arranged any management actions regarding the Pacific oyster?

- Yes
- No
- I don't know

If yes, please state your management action(s):

5.4. Does your organization have financial resources for management actions?

- Yes
- No
- I don't know

5.5. With whom do you think the responsibility for management actions should lie? (more than one answer can be selected)

- Private landowners
- Municipalities
- County administrative boards
- National agencies (i.e. SwAM (Hav) or Environmental Protection Agency (Naturvårdsverket))
- Other:____

Please explain your choice:

5.6. Does your organization want to be involved in the management of the Pacific oyster?

- Yes
- No
- I don't know

5.7. If yes, how would your organization like to be involved in the management of the Pacific oyster? (more than one answer can be selected)

- Not at all
- Planning
- Decision-making (for example selection of sites, methods, or management actions)
- Executing management actions
- Participating in knowledge platforms (reference group, research projects)
- Other:____

5.8. Would your organization need support in terms of the management? (for example knowledge, monitoring, surveying, management suggestions, management actions, networks, inspiration, funding, others)

- Yes
- No
- I don't know

If yes, please state with what you would like to have support with:

6. Conclusion

If you wish to state anything, leave a comment, or share any information, please use the space below.

7. Consent

7.1. I would like to share survey data or records of the Pacific oyster.
- Yes
- No

7.2. I would be willing to participate in an interview as a follow up on this survey.
- Yes
- No

7.3. I would like to receive information and updates about the DynamO project?
- Yes
- No

Please state your contact information to discuss survey data or records of the Pacific oyster, to be contacted for an interview, and/or to receive information and updates of the DynamO project.

Name:
Email:
Phone number:

Thank you very much for taking the time to participate in this survey!