UNIVERSITY OF GOTHENBURG

DEPARTMENT OF MARINE SCIENCES

TO CLEAR OR NOT TO CLEAR?

Ecosystem service and cost-efficiency implications for Pacific oyster (*Magallana gigas*) management in Sweden

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Popular scientific summary

The Pacific oyster is an established invasive species in Sweden that needs to be managed. This project looked first into the question if people and nature benefit from Pacific oysters or experience negative effects. It was investigated if there are differences in impacts depending on the substrate and number of oysters. It turned out that Pacific oysters had more impacts on soft substrate (mud, clay, sand) than on hard substrate (rock), and that these impacts were both positive and negative. Impacts were also stronger where oysters formed clusters (big clumps of oysters) and reefs. Surveys to the public and businesses showed that a large part of respondents had a negative attitude towards Pacific oysters which was mainly caused by the risk of cutting your feet on shells while wading and swimming. However, Pacific oysters were also appreciated as a food source and a species of commercial interest. One strategy of managing Pacific oysters are oyster clearings. Performed clearing activities were compared and it was analysed how to clear as many oysters as possible and from as big an area as possible. Mechanical methods such as dredging and excavating showed the best results on sites with a lot of Pacific oysters. At the same time, the methods didn't cost more than handpicking the oysters per weight or area cleared, but there were some limitations to the cost analysis so the estimations should be considered with caution. The number of oysters on a site also influenced how well and cheaply the site could be cleared with increasing costs for clearing a specific area, but decreasing costs for clearing a specific amount of oysters, with increasing oyster density. To summarize, the results show that Pacific oyster management should focus particularly on sites where the presence of oysters interferes with human activities, e.g. beaches, or causes unacceptable negative ecological effects. Oyster management should also make use of the fact that both the public and businesses are interested in oysters as a food source and source of income, which can be used to cover parts of the clearing costs.

Abstract

The Pacific oyster is an invasive species in Sweden with established populations along the Swedish West Coast. To support informed Pacific oyster management and provide a basis for decisions on whether, and how, to perform clearing of oysters, this project investigated both the impacts of Pacific oysters on ecosystem services in a systematic review, complemented by stakeholder surveys, and evaluated previously performed clearings in a (cost)-efficiency analysis. Focus was set on the factors substrate, oyster-mediated habitat complexity (solitary oysters, clusters or reefs) and clearing method (manual and mechanical). Pacific oysters were found to have positive and negative impacts on all (supporting, regulating, provisioning and cultural) ecosystem service groups. The impact degree depended on habitat complexity and substrate, with higher impacts (both positive and negative) on soft substrate and for reef formations. The surveys on perceived Pacific oyster impacts by both the public and businesses identified negative impacts on recreation (cut risk) as the main cause of concern but also indicated a positive exploitation potential in terms of recreational picking, cultural and economic uses. The cost-efficiency analysis showed that both clearing- and cost efficiency of clearing activities were impacted by oyster density rather than by substrate. For oyster weight-dependent efficiency indicators, increasing density had a positive effect, allowing more kg of oysters to be picked per working hour and at a lower cost. Area-dependent efficiency indicators were affected negatively by increasing density, decreasing the area that could be cleared per working hour and at a higher cost. Because of data limitations, limited analysis could be performed for method comparisons. The combined findings imply that clearing decisions should be made on a case-by-case basis after quantifying on-site ecosystem service conditions and prioritising e.g. sites with high recreational value. Clearing method selection can be partially efficiency-based but is also context-dependent and affected by site conditions like density, substrate and depth. The findings also indicate ways of making Pacific oyster management more cost-efficient by utilizing private and commercial interest in the species.

Keywords: Invasive species management, ecosystem services, cost-efficiency analysis, habitat complexity, density, substrate, mechanical clearing methods

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1 Introduction

With 41% of the global population inhabiting areas close to the sea, coastal areas are among the most popular places for people to live (Martínez et al., 2007). Known for important benefits to people, such as fishing grounds, water purification, coastal protection and recreation (Liquete et al., 2013), coastal ecosystems have been found to provide 77% of the global value of ecosystem services (Costanza et al., 1997; Martínez et al., 2007). The concept of ecosystem services (ES) was described by the UN Millenium Ecosystem Assessment, defining ecosystem services as "the benefits people obtain from ecosystems" (Millenium Ecosystem assessment, 2003, p.57). Considering earlier definitions by Daily et al. (1997) and Costanza et al. (1997), the framework includes both direct and indirect (also called tangible and intangible) benefits that are sorted into 4 functional groups: supporting, regulating, provisioning and cultural services (Millenium Ecosystem assessment, 2003)[1]. Supporting services are recognized as indispensable for the production of all other ES (Figure 1, adapted from Millenium Ecosystem Assessment, 2003).

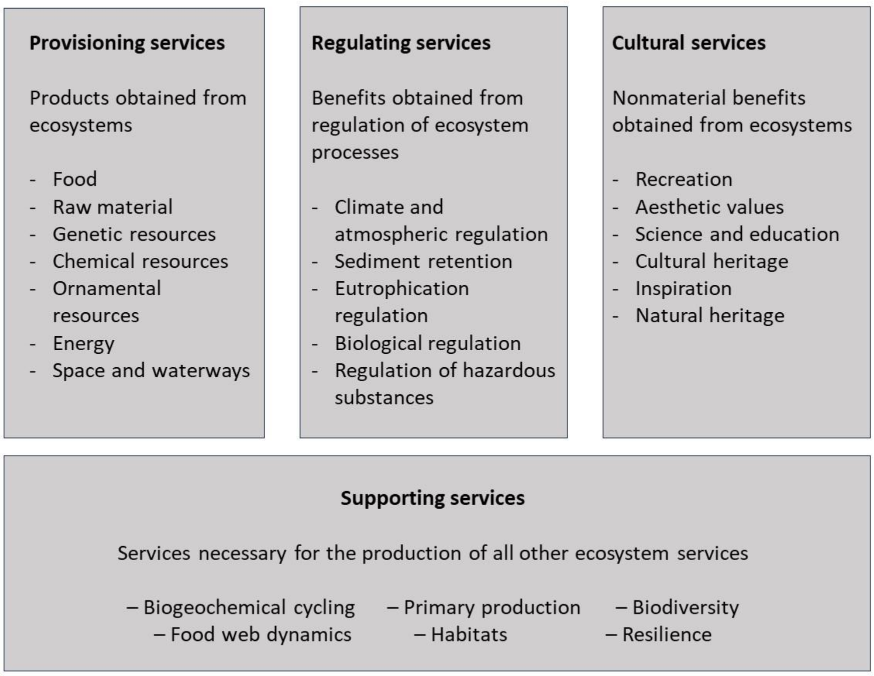

Figure 1 Illustration of the functional groups of ES. Figure adapted for marine ecosystems from Millenium ecosystem assessment (2003). p. 57

[1] Newer categorizations are available, such as CICES (Haines-Young & Potschin, 2018). However, given previous mappings of marine ecosystem services in Sweden, the categorization from Millennium Ecosystem Assessment 2003 is referred to in this thesis.

The maintenance and enhancement of ecosystems and their services is set as the second target of the EU's biodiversity strategy, and member states are required to map and assess ES in their specific geographical area (EU Communication COM 2011/244). In Sweden, marine ES have been described by the Environmental Protection Agency (Naturvårdsverket, 2008) and the Swedish Agency for Marine and Water Management (SwAm) (Bryhn et al., 2015).

Bivalves as so-called ecosystem engineers, organisms that "change the environment [alter its state] via their own physical structures" (Jones et al., 1994), support key ecosystem functions. They impact the ecosystem through three main functions: the creation of 3D structures, their filtration and their function as a resource, both to humans and as a biological resource. Bivalves perform major habitat modifications through their physical presence, which is beneficial in terms of shoreline protection and stabilising the sediment but also in providing (diversified) habitats to epibenthos and fish (Grabowski & Peterson, 2007; Laugen et al., 2016). Their water filtration and the following deposition of organic material lead to various positive impacts such as phytoplankton control, improved water clarity and nutrient and toxic substance regulation (Coen et al., 2007; Grabowski & Peterson, 2007). Bivalves are also known as a nutritious and protein-rich food source and are popular aquaculture species (Herbert et al., 2016; Laugen et al., 2016; Vaughn & Hoellein, 2018). The yearly contribution of non-food bivalve aquaculture services has been valued to be around 6.47 billion USD (van der Schatte Olivier et al., 2020), and estimates for the gain of ES from the restoration of native oyster reefs in America (*Crassostrea virginica*) range between 5,500 and 99,000 USD per hectare and year (Grabowski et al., 2012). Although it is relatively well-known what ES bivalve populations contribute with, it is less well explored how the contribution differs between different habitats and bivalve densities. Gaps in the documentation of cultural ES have also been identified.

The Pacific oyster (*Magallana gigas,* hereafter PO or oysters) is a bivalve species native to Japan/the Pacific ocean (Laugen et al., 2016). While being valued for important (esp. provisioning and regulating) services in its native range (Baek et al., 2024), it has also become a global invader that (despite being appreciated in aquaculture and of growing interest to fisheries (Shakspeare et al., 2024)) is especially known for its negative impacts on "host" ecosystems (Herbert et al., 2016).

Pacific oysters fulfil the Convention on Biological Diversity's (CBD's) definition of invasive alien species as "organisms that are non-native to an ecosystem, and which may cause economic or environmental harm or adversely affect human health" (CBD, 2021). In the EU however, according to Article 2 (5) and Annex IV in the EU regulation concerning use of alien and locally absent species in aquaculture (Regulation EC 708/2007), they are considered beneficial to aquaculture. According to Article 2 (2e) of the EU regulation on the prevention and management of the introduction and spread of invasive alien species (Regulation EU 1143/2014) they are therefore excluded from major measures against invasive species (Hansen et al., 2023), and they are exempt from the list of invasive alien species of Union concern (Union List, 2022).

A major invasion event in Swedish waters was first documented in 2006, when several sightings of wild PO populations were reported and the species has been colonizing new habitats ever since (Laugen et al., 2016; Mortensen et al., 2017). PO have increased in density along the Swedish west coast, reaching high densities and reef formations in three of 24, and well-established source populations in 13 of 24 municipalities (Figure 2, IVL working document, 2023).

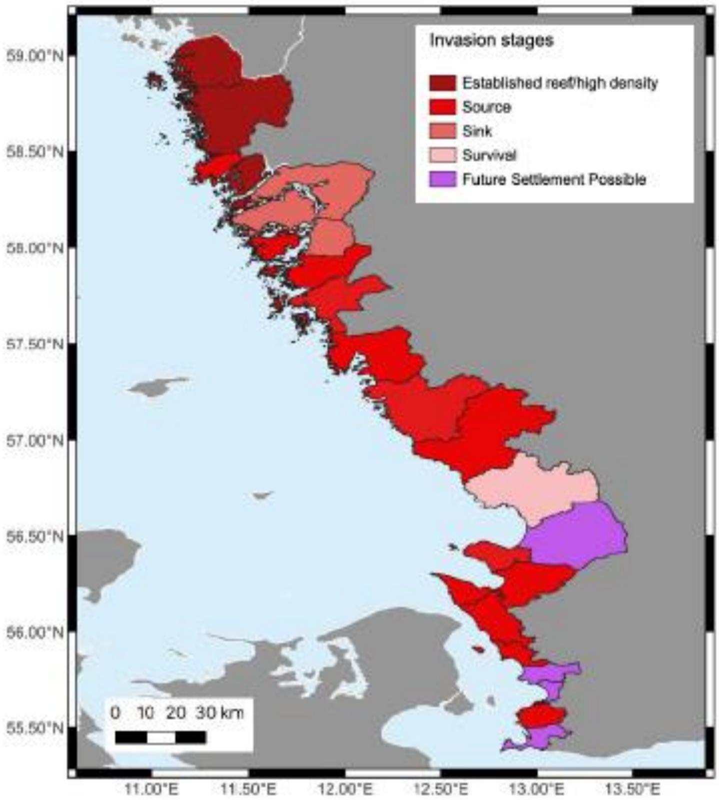

Figure 2 Pacific Oyster invasion stages along the Swedish West Coast (by municipality from Strömstad (north) to Vellinge (south)). Higher invasion levels (established reefs/high density and source populations) are reached in the northern municipalities. With the exception of Halmstad (survival) and Laholm (future settlement possible,) source populations continue southward including the municipalities of Landskrona and Malmö. IVL working document, December 2023

In Sweden, PO are included in the focus list on alien species for environmental monitoring (SwAm, 2019) and can be reported via the Swedish reporting portal Rappen (SLU, n.d.) but are neither covered by the Regulation on invasive species (SFS 2018:1939) - which is the implementation of EU regulations into Swedish law - nor are they included in the proposal for a national list of invasive species (that are not covered by EU regulations) by SwAm and the Swedish Environmental Protection Agency (SwAm, 2023). To conclude, no management measures for PO are currently in place in Sweden despite significant PO occurrence.

Successful management of invasive species requires the consideration of invasion stages and ranges from prevention before a species' introduction, eradication at early invasion stages, containment during expansion to the long-term management and mitigation of negative effects of fully established species (Geburzi & McCarthy, 2018). While early-stage management tends to be most cost-efficient (Geburzi & McCarthy, 2018), it is often hindered by a lag-phase between invasion and detection, leaving only a limited time-slot to establish management measures before significant population increases (Figure 3, from Roy et al., 2024).

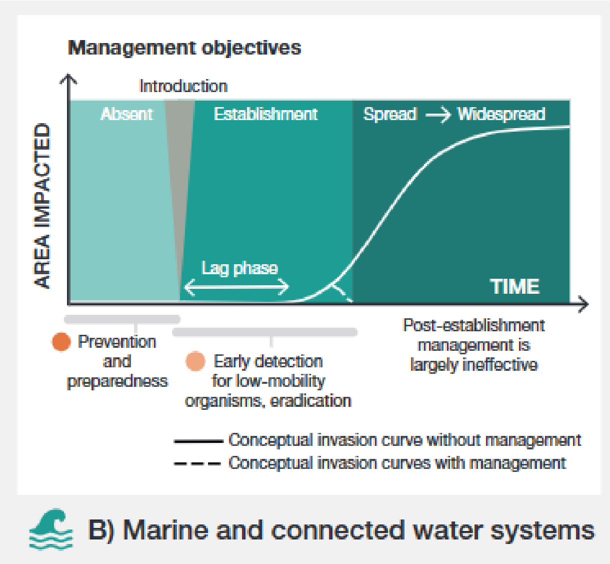

Figure 3 Management objectives in marine ecosystems according to invasion stage. From Roy et al. (2024). p. 570

The following potential management measures for invasive species have been proposed: physical removal, use of biocides, environmental remediation, biological control and genetic measures (Thresher & Kuris, 2004). For the containment of PO, evaluated management measures include mechanical control like dredging (Wijsman et al., 2008; Herbert et al., 2016; Hansen et al., 2023) and mechanical destruction in hard-bottom areas (Guy & Roberts, 2010; McKnight & Chudleigh, 2015; Herbert et al., 2016). Both dredging and mechanical destruction require a repetition every 5-7 years (Herbert et al., 2016). Both techniques have advantages and disadvantages, with large-scale dredging inferring a risk of habitat destruction (Herbert et al., 2016; Hansen et al., 2023) whereas mechanical destruction has proven to have low environmental effects but to be very labour-intensive (McKnight & Chudleigh, 2015). Hand-picking of PO is another promising approach, be it as volunteer work with the sole purpose of mitigating negative effects as done in Norway in so-called "dugnad" activities (Oslofjordens Friluftsråd, 2018; Asker kommune, 2021), for bivalve bed restoration purposes (Strand et al., 2023), for private consumption or with commercial intentions (Herbert et al., 2016; Hansen et al., 2023; Hjalager et al., 2018). Handpicking for commercial purposes as well as gastronomic tourism activities has also been initiated in Sweden (Iitembu et al., 2023). Problems can occur with food safety in such activities, but controlled harvesting of oysters is nevertheless proposed by Herbert et al. (2016) as an economically promising method for management.

Other proposed but not fully evaluated methods are choking and starving the PO by either covering the reefs with sand/gravel or adding a thick layer of blue mussels on top (Hansen et al., 2023), desiccation control – keeping the substrate out of water for a sufficient timespan to kill the oysters - (Ruesink et al., 2005) or the use of image-analysis-based robots to pick the oysters (Hansen et al., 2023). Genetic measures like creating reproductive sterility through triploidity are considered in aquaculture settings (Herbert et al., 2016; Hansen et al., 2023; Shakspeare et al., 2024). Despite partial effectiveness evaluations of clearing methods, an analysis of costs associated to clearing actions is lacking.

The management of invasive species and economic losses from invasive species are associated with a global cost of over 1 trillion $, out of which the costs for the management of invasive vertebrates are the highest at 29 billion $ (Roy et al., 2024). In general it is very difficult and often not successful to manage invasive marine species late in the invasion stages (Roy et al., 2024), and therefore it becomes important to prioritise what actions to take to mitigate specific negative impacts. Hence, management measures should be evaluated economically before using them on a larger scale with tools such as a cost-efficiency analysis (from here on CEA). Cost-efficiency is defined as "the ability to give the best possible profit or benefits in comparison with the money that is spent" (Oxford Dictionary, n.d.-a) and allows to compare the (incurred) costs per unit for different clearing alternatives, i.e. the costs associated to reaching a clearing goal. CEA should not be confused with an evaluation of effectiveness, i.e. if an intended result is reached (Oxford Dictionary, n.d.-b). Economic analyses can be performed in hindsight of the actually incurred costs (ex-post) or as a prognosis from an ex-ante perspective.

Aim of study and research questions

The overall goal of the thesis is to support informed management of the PO in Sweden, particularly when, and when not, to perform clearing actions. The work is part of the DynamO project (Dynamic management of the Pacific oyster), which is a project collaboration between IVL Swedish Environmental Institute, University of Gothenburg, KTH Royal Institute of Technology and University of Agder.

Mappings of ES and their economic valuation have been conducted for shellfish aquaculture and bivalve/ oyster reef restoration projects. Although negative impacts of PO are well described and singular potentially positive effects of PO in invaded areas have been suggested, a comprehensive, systematic overview of the context dependencies of impacts of PO as an invasive species on its "host ecosystem" and associated ES has not been performed. There is also a lack of knowledge of PO impacts on cultural ES. Moreover, studies like McKnight & Chudleigh (2015) have described the effectiveness of their removal method (hammering on chalk reefs) but no in-depth economic evaluation of different methods (i.e. cost-efficiency analysis) has been carried out for oyster clearings.

Therefore, the following research questions were posed in this project: How are ES along the Swedish west coast affected by PO in relation to habitat complexity and substrate type? Does the cost-efficiency of clearing activities vary between methods? And what are the combined implications of the mapping of impacts on ES and the cost-efficiency analysis for future PO management in Sweden?

The following hypotheses were evaluated:

H1: Impacts of Pacific oysters on ES are (are not) affected by oyster-mediated habitat complexity and/or substrate type.

H2: The cost-efficiency of oyster removal is (is not) affected by substrate and clearing method.

Limitations of the study

Recognizing that measures of prevention or eradication and containment in early invasion stages tend to show higher success rates at lower costs (Simberloff et al., 2013; Geburzi & McCarthy, 2018), this thesis focuses on the long-term management of already established oyster populations. While management efforts are often refrained from in fully invaded areas, impacts can be expected to increase at higher invasion stages; therefore it´s important to nevertheless identify and mitigate the most severe consequences in a cost-efficient way. As the northern part of Bohuslän displays fully established populations, this was the geographical scope of the study. Additional data on clearing actions was collected from southern Norway (Oslo fjord area) due to similar environmental and oyster population conditions.

2 Methods

Three different methods were used to explore the above-mentioned research questions; 1. A literature review (2.2), 2. stakeholder surveys (2.3), and 3. compilation of data from performed clearing activities and performance of field trials (2.5), with results from one method feeding into the others (Figure 4).

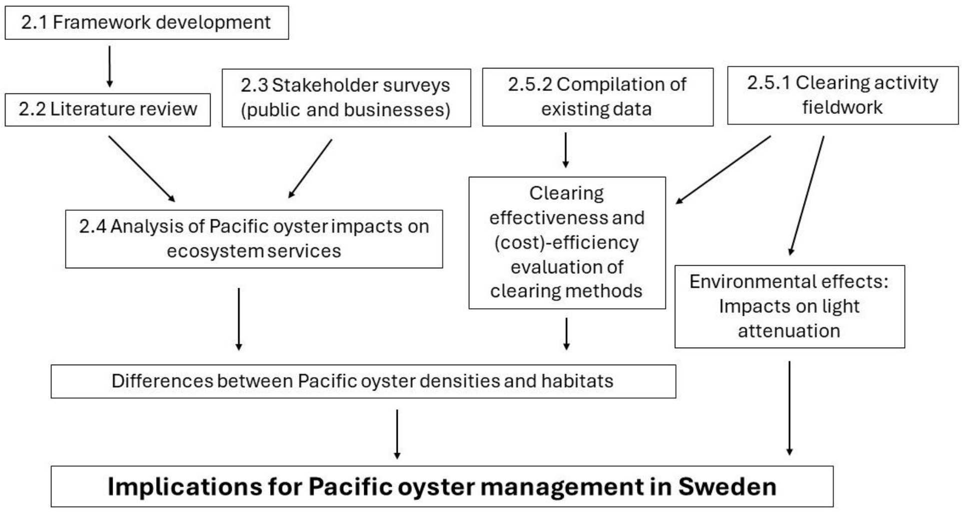

Figure 4 Structure of used methods and how they connect to Pacific oyster management in Sweden

2.1 Identification and description of ecosystem services

The framework to analyse impacts of POs on ES in relation to bottom substrate and oyster-mediated habitat complexity was based on Bryhn et al. (2015). The report (Byrhn et al., 2015) links ES (Table 1) to descriptors of good environmental status and respective indicators according to the applicable EU regulations:

- the Marine Strategy Framework Directive 2008/56/EC (MSFD) which was incorporated into Swedish legislation by Havsmiljöförordningen 2010:1341
- the Water Framework Directive 2000/60/EC (WFD) which applies in Sweden through Vattenförvaltningsförordningen 2004:660.

Table 1 Overview of ecosystem services, according to Bryhn et al. (2015).

Ecosystem service category	Ecosystem service
Supporting services	S1 Biogeochemical cycling S2 Primary production S4 *Biodiversity S3 *Food web dynamics S5 Habitats S6 Resilience
Regulating services	R1 Climate and atmospheric regulation R2 sediment retention R3 Eutrophication regulation R4 Biological regulation R5 Regulation of hazardous substances
Provisioning services	P1 Food P2 Raw material P3 Genetic resources P4 Chemical resources P5 Ornamental resources P6 Energy P7 Space and waterways
Cultural Services	C1 Recreation C2 Aesthetic values C3 Science and education C4 Cultural heritage C5 Inspiration C6 Natural Heritage

** the order of S3 and S4 was changed to better illustrate how changes in biodiversity will affect food web dynamics*

The indicators presented in Bryhn et al. (2015) are specified in national regulations, for the MSFD in HVMFS 2012:18 and for the WFD in HVMFS 2019:25. For the description of food web dynamics, biodiversity and habitat services, indicators from the EU Habitats Directive 92/43/EEC, Förordning (1998:1252) and Artskyddsförordning 2007:845 were used according to Bryhn et al. (2015). The Swedish environmental goal (miljömål) “a rich flora and fauna” is also considered in Bryhn et al. (2015). Other impacts of PO on the ES that were not mentioned in the regulations (i.e. were not described by indicators) but were deemed relevant were added as “other relevant impacts”. A list of descriptors that were excluded from further analysis for obvious irrelevance can be found in appendix 1.

2.2 Literature review

To identify the impacts of PO on the identified ES (see section 2.1), a semi-structured literature review was performed in three stages, using the database Scopus and filtering for English peer-reviewed articles only. The first step was scoping for reviews that provided an overview of ES provided by PO using the search terms **Oyster* AND (ecosystem OR "environmental impacts")**. The search terms were linked with Boolean operators. The results were scanned for relevance by title, abstract or reading the whole article and relevant articles were selected for further processing. Five articles that had been suggested for reading by a topic expert or that were referred to in the other reviews were added manually because of their high relevance for the topic. These reviews provided an overview of the ecological impacts of PO, the knowledge of which was then applied to describe how the corresponding ES are affected (section 2.4).

Targeted literature searches with search terms based on specific ecosystem services (table 1) were conducted in a second step and literature recommended by experts was added and scrutinized and references in identified reviews from stage 1 were consulted for more detailed information. Further efforts in stage 3 aimed at finding papers that discussed the effects of oysters in different densities and on hard-bottom substrate specifically (search terms **Oyster* AND "density-dependent effects"**), and as before, articles were added manually either according to literature recommendations by experts or because they had been referred to in other articles.

2.3 Surveys on stakeholders' perceived impacts of Pacific oysters

To complement the findings (section 2.2) of cultural and provisioning services from the literature reviews, two surveys were conducted among stakeholders on the Swedish west coast, one directed to private individuals and one directed to businesses. The goal of the surveys was to find out if, and how, people engaged in different marine activities were affected by PO. Both surveys were available in Swedish and English. The survey to the public consisted of four questions to discern the main costal related activity of the respondents, if the respondent had observed PO associated to their preferred activity, if the respondents felt affected by the occurrence of PO and if so, how they were affected. The full survey questions with answer options are available in appendix 2. The survey to businesses consisted of seven questions to discern the business area (including clarifications) of the respondents, if the respondent had observed PO associated to their business, if the respondents or their guests felt affected by the occurrence of PO and if so, how they were affected, and finally if the occurrence of PO resulted in any economic impacts on the business and if so, to what extent. The full survey questions with answer options are available in appendix 3.

To identify pathways to reach the desired stakeholder groups, marine activities potentially affected by PO occurrences were identified by parts of the DynamO project team in a brainstorming session. Using the municipality register of associations in Strömstad and Tanum, relevant stakeholder groups associated to the activities were identified and contacted with a request to share a link to the public questionnaire with their members (pre-selection of respondents). The public survey was also shared through the DynamO network, the university's social media pages, GU's Swedish Mariculture Research Centre (SWEMARC), Informationscentralen för Västerhavet, Naturum Kosterhavet and other relevant Facebook pages like municipality notice boards. For the business-related questionnaire, companies in tourism and harbour operators were filtered out on the tourism websites for all municipalities in Bohuslän. Actors in the oyster sector were identified through already existing networks established during previous applied aquaculture and ecology research projects at IVL. The branch organisation Svenskt vattenbruk och sjömat and the Blue Food Centre were contacted and asked to distribute the survey among their members; the survey was also promoted during the marine company fair organised by the University of Gothenburg.

To analyse the obtained data, responses that described how people were affected in their work rather than privately were filtered out from the public survey and were analysed together with the answers to the business survey. After this the answers on observed oyster occurrence (Q2) and perceived impacts of PO (Q3) were used to gain an overview of general PO observation frequency and if respondents felt affected (positively or negatively or both) by PO. Dependence between assignment to activities (Q1), observations of oyster occurrence (Q2) and respondents' perceived impacts of PO (Q3) was meant to be explored; however, it became clear when looking at the open-text responses to Q4 that respondents didn't always answer the questions in relation to the activity they had selected in Q1. To exemplify, hikers would comment on how they risk cutting their feet when going swimming, a typical beachgoers' activity. Consequently, activity group (Q1) was not analysed in relation to perceived impacts (Q3 and Q4). Dependence between observed oyster occurrence (Q2) and affectedness (Q3) was, however, analysed with a Fisher's exact test (3x3 contingency table), with answers of observed oyster occurrence ("Yes", "No", "Don´t know") being compared to responses of perceived impacts (positive, negative and mixed impacts grouped together (i.e. "all impacts") vs. "not impacted" vs. "don't know").

The open-ended question (Q4) was then analysed to find out in what ways respondents felt affected by PO. Answers to Q4 were coded manually by type of impact (based on, but not strictly following ecosystem service categories, new categories were added for recurring keywords) allowing several categories to be assigned to one response as various impacts were often mentioned in the same open answer. The coded impacts were divided in levels of main categories, subcategories and specific impacts depending on the responses' level of detail

(Appendix 4). Answers were assigned to the most specific level possible, allowing both a global analysis of the most-mentioned impacts and an in-depth analysis of the most prominent main categories. This was also followed by a statistical power analysis of the open-ended question, where the responses were randomized, after which the number of new aspects that were brought up per group of 25 responses were cumulated to see if/when a saturation of responses was reached.

The business survey was analysed in a similar way, looking first at the responses of observed oyster occurrence and perceived impacts without dividing by activity groups. The analysis of open-ended questions showed great overlaps of impact categories with the public survey, therefore the results were used to complement the finding of impacts of PO on private people with findings of economic impacts, and additional economic impact categories were added to the response categorisation structure.

2.4 Analysis of impacts of Pacific oysters on ecosystem services

The literature review findings and survey results were merged into a detailed analysis of PO impacts on ES (appendix 12), differentiating between soft and hard-bottom substrate and three different categories of PO growth mode, inferring different habitat complexity. Interlinkages between different ES were also explored. Soft bottoms were defined as clay, mud, sand (corresponding to MA 5 littoral sand and MA 6 littoral mud according to EUNIS habitat classification 2022) as well as fine gravel and shell hash, whereas hard bottoms were defined as boulders, rocks, pebbles and coarse gravel (corresponding to MA 1 littoral rock and MA 3 littoral coarse sediments of EUNIS habitats). The habitat complexity was delineated by a combination of oyster density and growth mode, i.e. if the oysters grew solitary, in clusters or in reefs (Figure 5), with increasing complexity with higher oyster densities and corresponding increasing occurrence of clusters until a reef starts to form (in this study defined as 75% coverage).

Figure 5 Habitat complexity (solitary oysters, clusters or reef formations) can be judged by a combination of oyster density and growth mode. Low density sites will be mostly made up of solitary oysters and few clusters and will consequently have low complexity. The occurrence of oyster clusters will increase with increasing oyster density until, at 75 % oyster coverage, an oyster reef can be assumed. Pictures: Svenja Heß and DynamO project.

The mapping of impacts was structured by ES, impacted descriptor (as described by the related legal frameworks) and indicators as defined in section 2.1. The impact classification of S1 to S5 (see 2.1) was based on all identified indicators per ES. No descriptors or indicators have, however, been identified for ES S6 to C6, hence the impacts on those ES were classified as an overall assessment, similarly to the ecosystem service analysis of the Swedish seas (Bryhn et al., 2015). The classifications used are summarised in Table 2, and include both confirmed (positive, negative or neutral (i.e. no impact expected)) and hypothetical (supposedly positive or negative) impacts. The hypothetical impacts were inferred from associated documented impacts based on ecological principles but were not specifically documented in the identified literature. For descriptors and indicators where no associated impact of PO was documented and nothing could be inferred from associated impacts, “Not known” was used as a category. The classification also included a class for situations when an impact could be expected but where the direction of the impact was context dependent (e.g. increase in species richness vs. changing the natural state of an ecosystem).

Table 2 Explanation of classification semantics

Impact classification	Explanation
Positive	Documented positive impacts of PO on ES
Supposedly positive	Positive impacts inferred from associated documented impacts but not specifically documented
Negative	Documented negative impacts of PO on ES
Supposedly negative	Negative impacts inferred from associated documented impacts but not specifically documented
Positive and negative	Documented positive and negative impacts of PO on ES
Changes will occur increasingly with increased density	Documented changes but no classification as positive or negative
Neutral	No documented impacts and impact seems unlikely
Not known	Impacts of PO on ES not known
Not applicable	Not applicable for various reasons; mostly because of bottom type (e.g. changes on sandbanks not applicable for hard-bottom substrate)

Impacts were classified in relation to the respective descriptor, meaning that both an increase of undesirable, and a reduction of desirable, effects would be classified as negative. For example, the impacts on the indicator "biomass of phytoplankton in coastal waters" under the descriptor "eutrophication" were labelled positive because PO will reduce the biomass of phytoplankton which is a positive effect in the mitigation of eutrophication effects. Under the descriptor "phytoplankton" for the ES "primary production", the loss of phytoplankton biomass was labelled negative because it presents a negative effect on primary production. In order to summarise and graphically illustrate the results from the impact analysis, the mapping was then condensed into a summary table that shows which ES are most and least, positively and negatively, respectively, affected by PO. For S1 to S5, the number of indicators classified in each way was counted, and for S6 to C6 the overall assessment was used. The table was colour-coded according to a heat map principle (Figure 6), using different colours for the categories <33%, 33–50%, >50% of the indicators being classified as positive or negative for each ES. The overall classification of indicators on soft vs. hard-bottom habitat was assessed in a similar way.

< 33 % positive	33-50 %	> 50 %	< 33% negative	33-50 %	> 50 %

Figure 6 Illustration of the colour-coding used to summarise major impacts of PO on ES.

2.5 Clearing activities

Data for comparison of clearing effectiveness, efficiency and cost-efficiency between different methods of oyster clearing was both collected through field work (section 2.5.1) and compiled from previously performed activities (section 2.5.2).

2.5.1 Fieldwork

To collect data related to dredging and excavating as clearing methods, four sites (dredging 1 Bofors: 58.8884° (N), 11.1388° (E), dredging 2 Kollholmen: 58.8623 ° (N), 11.1682° (E), excavating 1 Rundö hamn: 58.8538° (N), 11.1740° (E), excavating 2 Rundö östra 58.8554° (N), 11.1861° (E), Figure 9) of approximately 200 m^2 each on the Swedish West Coast (around Tjärnö) were selected based on previously performed surveys of oyster density and growth mode (clusters or reefs) as well as the permission for clearing actions from the land owners. The activities were licenced by the County Administrative Board Västra Götaland (excavating) and SwAm (dredging). The removal of PO was carried out via dredging and excavating on 2 sites respectively with cleared areas ranging between 60 and 160 m^2. The sites contained oyster clusters (densities 45.3 and 50.8 ind./m^2) or reefs (densities 761.6 and 1176.0 ind./m^2). In a pre-survey, the oyster area at each site was defined and marked, oyster density was counted in 10 randomly placed quadrats (only live individuals bigger than 20 mm were registered; quadrat size 0.5 x 0.5m at cluster sites and 0.25 x 0.25m at reef sites) and 100 oysters per site were measured. Loggers to measure light in 15-minute intervals were placed in one corner of each site and at 70 m distance on both sides of the site to gain data on the dredging and excavating impacts on light attenuation in the area. Dredging was performed in collaboration with the University of Gothenburg, using a custom-made, 0.5m wide steel dredge (Figure 7). The dredge was drawn from the shoreline or from one side of the site across the seafloor vertically to the coastline from a 9 m long boat using a winch, then the contents were unloaded and sorted on board the vessel. The dredge was transported from the boat to the shore or to the starting point to repeat the procedure using either a small boat or a raft. On site Bofors the winch broke, and the site was therefore only partially cleared (60m^2).

Figure 7 Dredging procedure. Clockwise (from left): 1: steel dredge filled with oysters. 2. The dredge was winched on board and 3. oysters were unloaded and sorted into leafbaskets.

Excavating was done in collaboration with the company Hamn&Sjö AB. An excavator with a custom-welded excavating shovel was placed on a barge next to a container and transported to site by a small boat (required water depth: 50 cm) (Figure 8). At site Rundö hamn, the entire pre-determined area (160 m²) was cleared whereas the excavating of the second site (Rundö östra) was limited to 60 m² by the high oyster density and a lack of container space. At both sites, a silt curtain was placed to minimize sediment transport and turbidity outside the clearing site.

Figure 8 Excavating setup, clockwise: 1. excavator and container placed on a barge from Hamn&Sjö Väst AB at the first excavating site. 2. Excavation shovel filled with cleared oysters. 3. Oysters were placed in a container for deposition.

In post-clearing surveys (January), the loggers were retrieved, the remaining PO density was evaluated again using the same method as before the trials (three sites in January and one in May), and all sites were inspected for visible traces of the dredging and excavating on the sediment (January and May). The light measurement data from the loggers was analysed semi-quantitatively to examine impacts on light transparency in the water during the clearing actions. Graphs were plotted to illustrate the light fluctuations over the entire logging period (52 days, daylight hours, 07:00 -17:00) in relation to SMHI's weather data of solar irradiation (hourly data) to get a trendline (average response) of the loggers to the radiation. In a second step, the logs of the respective clearing days were compared to the average response to see if effects were recorded that exceed the natural variation in light conditions.

A third clearing activity was performed at Getevik, Fiskebäckskil (58.2780° (N), 11.5037° (E), Figure 9) to collect data to assess the efficiency of handpicking at reef sites. Five groups of volunteers were asked to perform pre-surveys of PO densities (0.25 x 0.25m sampling quadrats within in 2x2m squares) and then clear the area, taking notes of the number of dead and alive oysters, size distribution, weight and the time it took to clear respective areas (instructions in appendix 5).

At all sites, the weight and number of PO in three leaf baskets (45l) with PO harvested from each site were documented to enable calculation of harvested number of individuals based on the total weight of the collected oysters at each site.

2.5.2 Compilation of previously performed clearing activity data and analysis of clearing effectiveness and efficiency

Members of the DynamO network had been involved in previously performed oyster clearings or had established contacts to actors in Norway where oyster clearings have been performed as "dugnad", a type of volunteer work similar to beach clean-ups. Data from these previous oyster clearings was obtained from different sources (see below) and compiled to document ranges of clearing and cost-efficiency in different contexts, e.g in different oyster densities, bottom types and for different clearing methods. The identified additional clearing activities included:

- hand-picking (volunteer work, wading and snorkelling) in Bærum municipality, Norway, 2023 (raw data)
- hand-picking (wading, snorkelling and diving) on mixed bivalve beds for the Bivalve project around Tjärnö and Grebbestad (Kämpersvik), year 2018 (Strand et al., 2023)
- clearing activities for the DynamO project
    - hand-picking (snorkelling and diving) on Hallands Väderö, year 2022 (raw data)

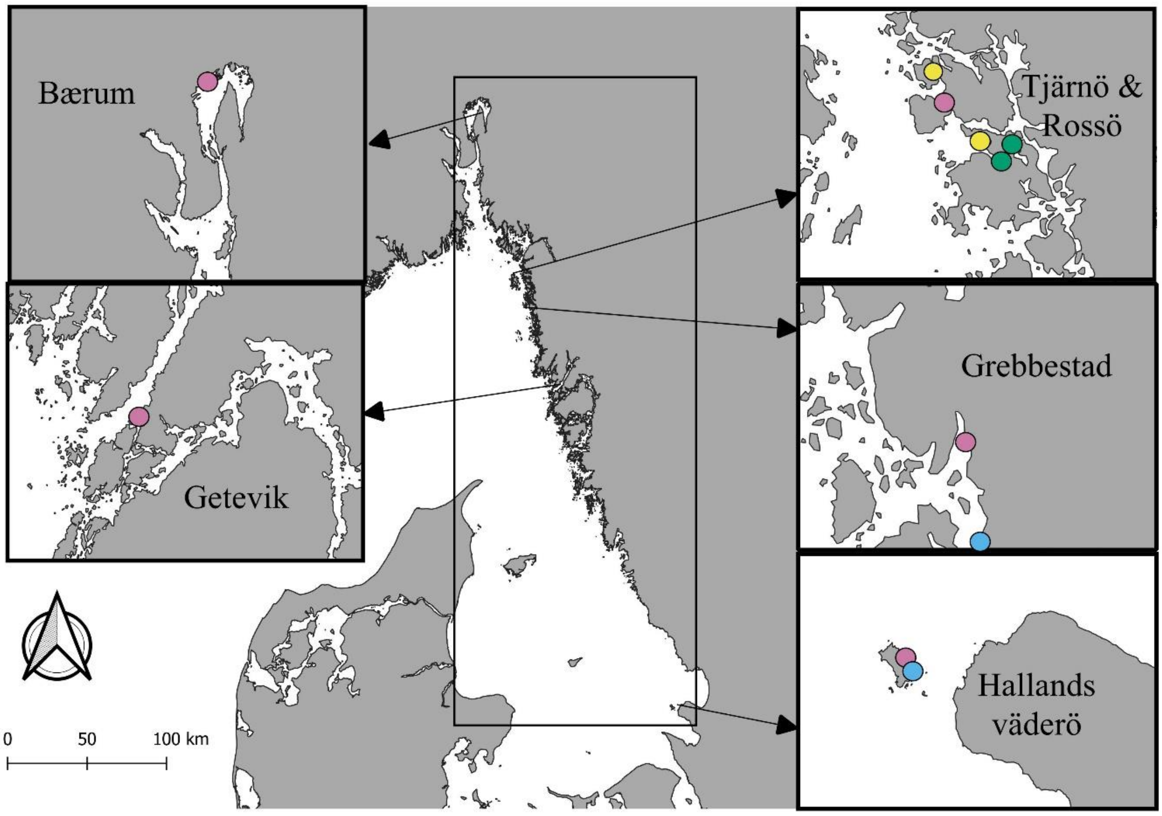

Figure 9 Map of the sites along the Swedish west coast and in the south of Norway where different oyster clearings were performed. Handpicking is marked in purple, diving in blue, dredging trials in yellow, excavating trials in green.

For the evaluation of methods, the clearing methods were divided into:

1) handpicking - wading and snorkelling
2) handpicking - diving
3) dredging
4) excavating

Data from the fieldwork on size distribution, lengths and weights at Getevik was used to calculate the weights from two clearing activities (Grebbestad 1 and 2, 2023) where individuals were counted and size distribution assessed but not weighed. The data from all clearing activities was compiled into an overview table (appendix 6) and was used to calculate indicators of effectiveness (clearance proportion) and clearing efficiency (equations 1-3).

Clearance proportion = removed oyster density / pre-survey oyster density (Equation 1)
Clearing efficiency 1 = cleared oysters (kg) / working hour (Equation 2)
Clearing efficiency 2 = cleared area (m^2) / working hour (Equation 3)

The dependence between clearing efficiency and oyster density was analysed (for both efficiency indicators) in scatterplots using Log10-transformed data for both oyster density and efficiency. As different substrates may influence clearing execution during handpicking (hard substrate requires oysters to be chiselled away, clay and mud cannot be walked on and require snorkelling), impacts of substrate (mud/clay, sand/fine gravel/shell hash, mixed substrate and hard bottoms) was first evaluated for handpicking before dependence of efficiency and oyster density was evaluated for all four clearing methods (handpicking with wader boots and snorkelling, handpicking through diving, dredging and excavating). To make clearing efficiency more comparable despite a high variation in clearance proportions, all clearings were also scaled up to 90 % effectiveness and clearing efficiency 2 was reanalysed[2]. It was assessed that a 90%-clearance goal was realistic based on already existing data from similar activities as those with low clearance effectiveness, and that extrapolation to that level may be achieved by merely scaling up the working hours accordingly.

2.5.3 Cost-efficiency analysis

For a comparison of cost-efficiency between different substrates and methods, a cost overview table was created (appendix 7) from the existing cost data of all handpicking activities, considering equipment costs per use, operational costs and volunteer compensation. All values were expressed in SEK without VAT. Pre- and post-clearing costs and revenues for post-harvest uses were excluded (Figure 10 and appendix 8). The costs were divided into equipment, operational costs, compensation for voluntary efforts by non-profit organisations, labour costs, and contracted costs and were identified as either fixed or variable costs (Figure 10).

[2] The hypothetical scaling-up of the clearing increased both working hours and weight of cleared oysters by the same factor, so efficiency-indicator 1 will remain the same. Extrapolating the clearing in this way most likely underestimated the time, because the time needed to pick the same weight of oysters will increase with decreasing oyster density during the clearing process.

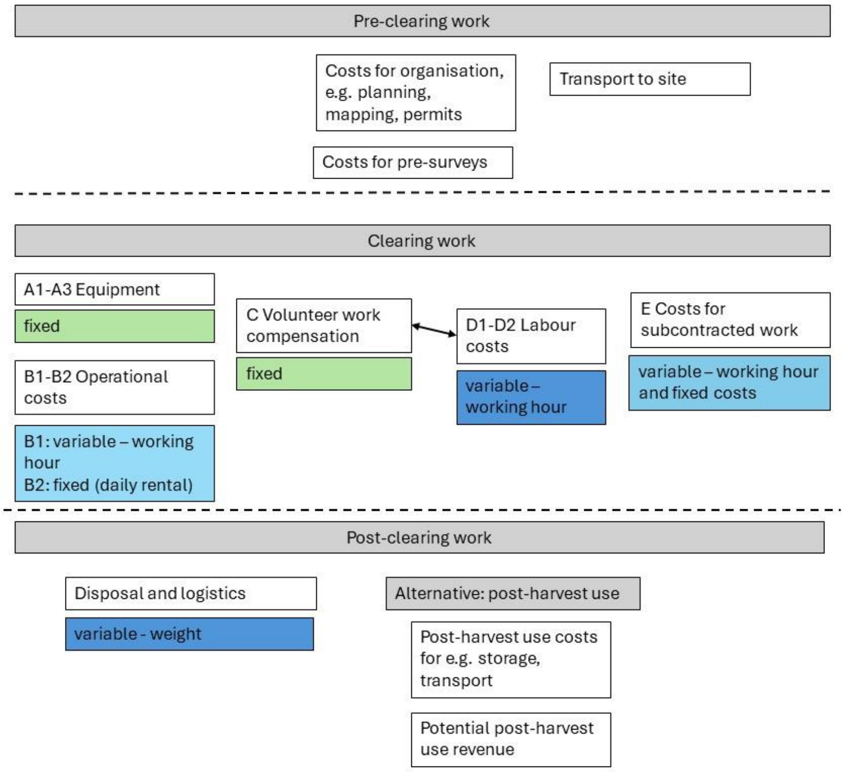

Figure 10 Overview of the costs incurred during the removal process. Costs for pre-clearing activities and costs and revenues from post-harvest uses or disposal are excluded from the calculation. Fixed costs are marked green, variable costs blue and a combination of the two is marked turquoise.

Calculations were done for three scenarios, the "real" (scenario 1) and "hypothetical" (scenario 2) costs for the determined clearance proportion (cleared PO density/pre-clearing density) as well as hypothetical costs for a 90%- clearance proportion scenario (scenario 3). "Real costs" were the actually incurred costs (ex-post perspective, e.g. for volunteer clearings volunteer compensation was considered) whereas the "hypothetical costs" excluded special agreements, i.e. volunteer compensation was replaced by labour costs. To compensate for the high variation in clearance rate, cost-efficiency indicators were also recalculated for a 90%-clearance proportion scenario by using an extrapolation of the site-specific clearing efficiency, with a resulting increase in working hours, boat rental days where applicable and weight of cleared oysters[3].

For the dredging and excavating activities, costs were split according to the respective invoices for each activity (appendix 9 and 10) and real and hypothetical costs were calculated. For

[3] Again, linear extrapolation may underestimate the increase in working hours, and costs per percent clearing may actually increase slightly with increasing clearance proportion. Again, this increase would occur especially between 90% and 100%, which is why the 90%-clearance target was set.

hypothetical costs it was assumed that special equipment (e.g. special oyster dredge and oyster excavation shovel) already existed.

All calculations of total costs per site were described as:

$$C_{site} = C_{fixed} + c_{var\_h} * h \qquad \text{(Equation 4)}$$

where C_{site} = total cost per site, C_{fixed} = total fixed cost per site, c_{var_h} = variable, working hour-dependent cost per unit (h), and h = working hour.

Indicators of cost-efficiency were defined as:

1) Cost-efficiency 1 = Costs (SEK) / cleared oysters (kg) (Equation 5)
2) Cost-efficiency 2 = Costs (SEK) / cleared area (m^2) (Equation 6)

Cost-efficiency indicators 1 and 2 were then plotted against oyster-density for handpicking on different substrates and for the different clearing methods. Determined relations were described by linear functions (Log10-transformed data) for which a linear regression analysis was performed. Confidence interval functions were plotted to evaluate the reliability of the functions.

Ethics compliance statement

Artificial Intelligence was not used for writing this thesis.

3 Results

3.1 Literature review

The first literature search resulted in 114 hits, of which nine were deemed relevant. Five articles were added manually (appendix 11). The second literature search resulted in a total of 41 articles with descriptions of specific ecosystem services, and the third literature search about density-dependent impacts resulted in six hits, out of which two were deemed relevant and another article was added manually. Two articles on PO effects on hard-bottom habitat were also added manually in stage three. Combining the searches and literature recommendations of all 3 stages, a total of 60 articles was included in the mapping of PO impacts on ES.

A majority of the articles described PO from an ecological perspective (in-depth explanations in appendix 12). The oysters' filtering capacity and physiological processes were highlighted, leading to an uptake of organic matter and increased sedimentation rate (benthic-pelagic coupling), phyto- and zooplankton reduction, general water quality and clarity improvements as well as the filtering of toxic substances from the water column. The facilitation of microbial processes through the benthic-pelagic coupling was also emphasised. The provision of 3D-structures was described with impacts such as sediment retention, reduced circulation, habitat provision, protection and habitat homogenisation. PO were furthermore highlighted as a biological resource both in terms of trophic subsidies and as a vector for non-native species. The knowledge of the ecological impacts of PO was then related to the corresponding ES and effects on the ES were described (section 3.3

3.2 Surveys on stakeholders' perceived impacts of Pacific oysters

3.2.1 Public survey

The survey directed to the public resulted in 493 responses, of which 482 were analysed. Four answers for commercial fishing and seven answers on work other than fishery were transferred and analysed in the business survey.

The respondent group comprised 10 marine-related activities and a group of respondents that stated multiple activities (Figure 11). The groups "beach guest" (n=141, 29.3%) and "leisure boating" (n=107, 22.2%) together made up more than half of the responses, closely followed by "hiking/walks along the shoreline" (n=104, 21.6%). Less than 10 answers respectively were received for the groups surfing, birdwatching and multiple activities.

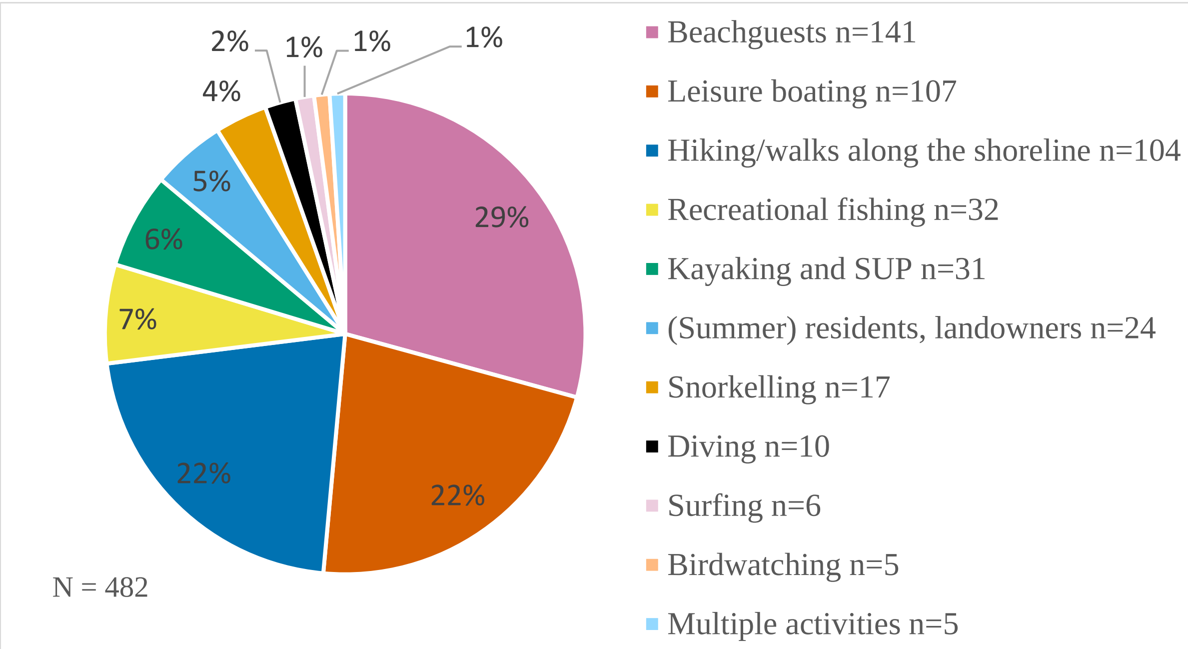

Figure 11 Respondent composition of the public survey. The total number of responses was 482, which are divided between 11 stakeholder groups (sorted by main marine-related activity).

The great majority (87.1%) of respondents stated that oysters occurred in the area they used for their marine related activity (9.3% “no” and 3.5% “I don’t know”). More than half of the overall respondents (54.6%) felt negatively affected by Pos only, followed by 19.3% that didn’t feel affected, 11.2% felt only positively affected, 8.7% felt both positively and negatively affected, and 6.2 % that didn’t know.

When comparing the perceived impacts of PO on respondents (Q3) that had observed oysters in the area that they were using to those that had not and to those that didn´t know if oyster were present in the area they used (Q2), people that had observed oysters in the area tended to be more affected by PO (positively, negatively or both) than people that had not observed oysters in the area or did not know if oysters were present (Fisher’s exact test, 3x3 contingency table, $p < 0.001$, Figure 12).

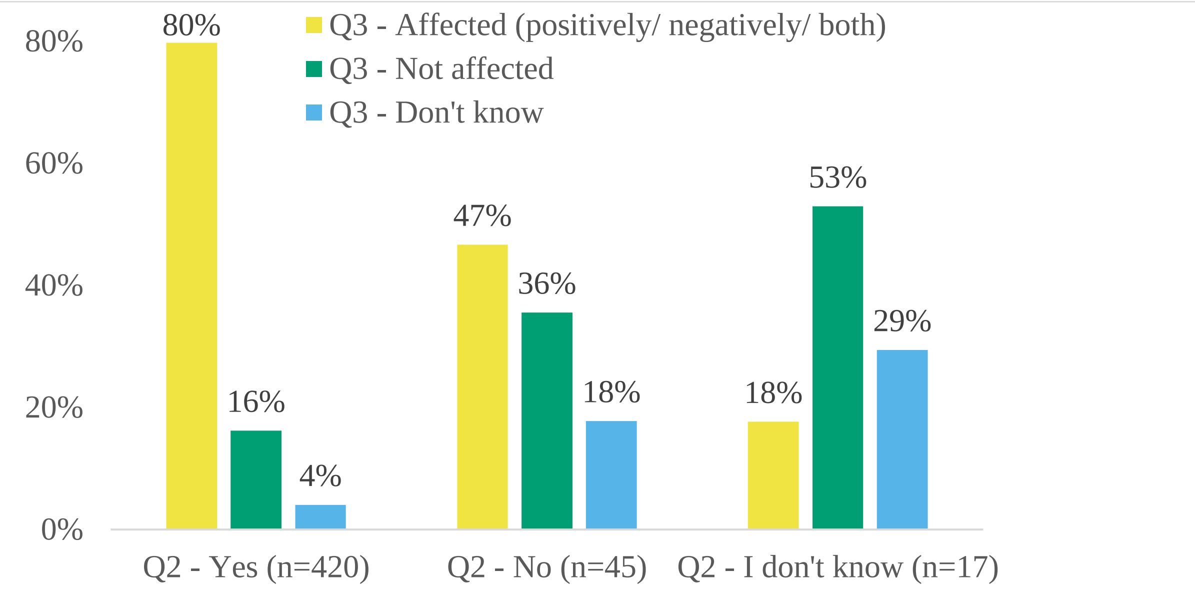

Figure 12 Relation between the responses to Q2 (observed occurrence of oysters in the used area) and Q3 (affectedness by oysters)

There were, however, also respondents who hadn’t observed oysters in their area or didn’t know if oysters were present and nevertheless felt negatively affected (affected despite no oyster occurrence n=21, of which negatively affected n=18, 85.7%; affected with oyster occurrence n=335, of which negatively affected n=242, 72.2 %). This was confirmed by the open answers where respondents indicated that they had heard about negative impacts (e.g. ”*I've heard that they can be very sharp, so I'm a bit afraid of cutting my feet when bathing*”[4]), that they felt emotionally affected (”*I don't feel personally affected, but I've heard that it's bad for the*

[4] Responses translated from Swedish into English using DeepL.

Swedish environment because it's an invasive species, so because of this I feel bad for my well-being, it's linked to stress about climate change and the environment […]"), or that they had changed their behaviour in response to negative experiences with oysters ("*They cut our feet and the pads of the dogs. [...] So now we have almost stopped bathing because of cut pads and feet.")*.

Out of the 482 respondents, 334 respondents answered the open question (Q4). The assignment of several categories to one response led to a total of 555 categorized answer aspects assigned to 37 different impacts in 10 main categories (appendix 4). A plateau in number of new aspects brought up was reached after 350 responses (power analysis, Figure 13).

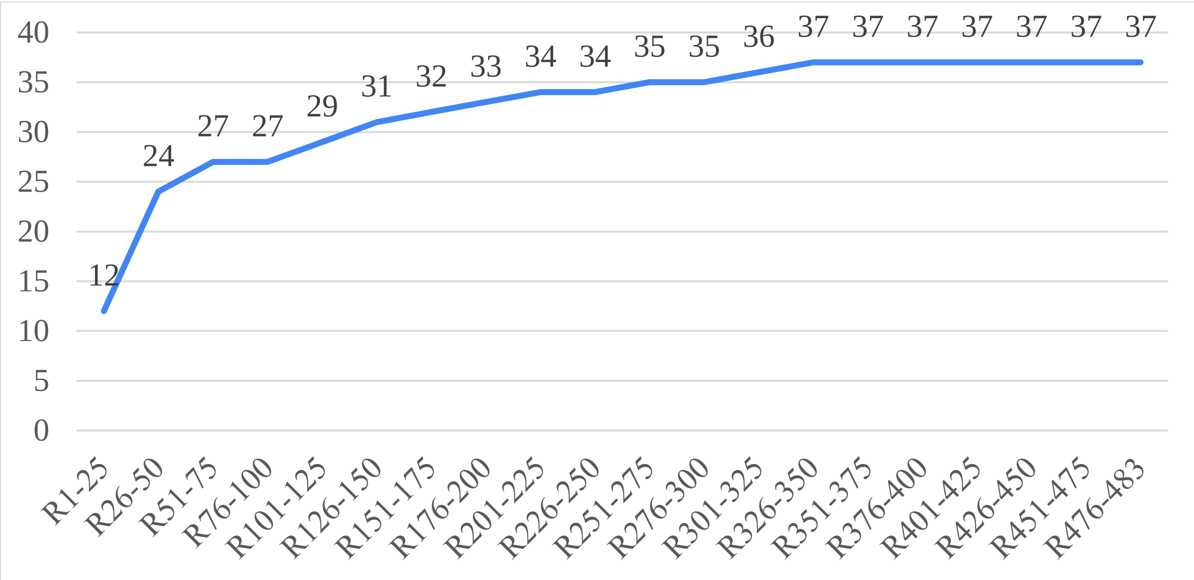

Figure 13 The number of new answer aspects per group of 25 randomized responses

The most common negative main categories mentioned were recreation (41.8%, n=232), followed by ecosystem impacts (17.7%, n=98) and what was classified as "negative emotional response" (15.0%, n=83). The most frequent positive category was impacts on recreation (12.4%, n=69), all other impacts were at a frequency <10.0% (Figure 14). The brought-up negative aspects were more diverse (5 main categories, 21 impacts) than the positive ones (5 main categories, 16 impacts).

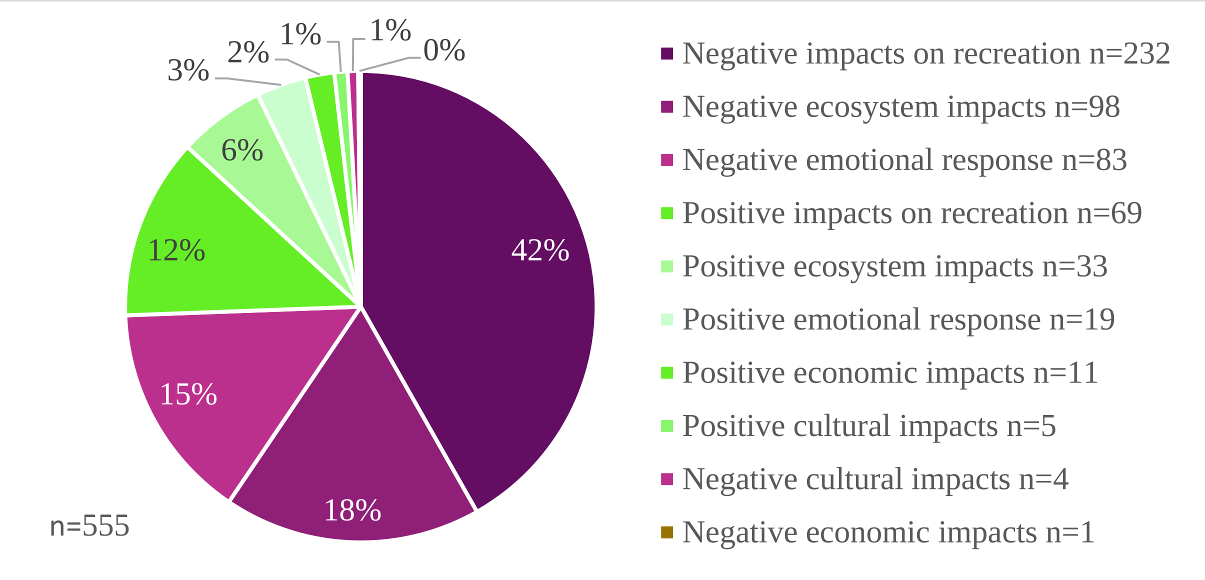

Figure 14 shows the distribution of categorized answer aspects between the main impact categories, i.e. in what way respondents feel affected by Pacific oysters.

The category "negative impacts on recreation" mainly referred to a limited access to, or use of, beaches (n=215), predominantly caused by a fear of cuts (n=210). Other impacts included impacts on recreational equipment (n=12), e.g. scratching of kayaks or biofouling on boat hulls and engines. The overgrowing of shallow passages and channels was also mentioned. The answers categorized as "negative ecosystem impacts" were dominated by negative impacts on biodiversity (n=88), e.g. the disappearance of blue mussels (n=43) or competition with native flat oysters (n=18) as well as general disappearance/outcompeting of other unspecified species (n=23) and in two cases to the appearance of other unwanted species (crabs, filamentous algae and jellyfish). The modification of substrate through creation of oyster reefs was mentioned as a negative ecosystem impact as well. The category "negative emotional response" contained responses that voiced respondents' concerns about the oysters' successful invasion (n=37), including both a fear of environmental destruction by PO but also that their success is an indicator of more profound environmental change, e.g.*"[...] On the other hand, I don't know what these oysters could be a sign of. We have to accept change; it has always been like that."* and "*It's great to have good oysters, but not if they are due to a poorer environment*". Many respondents also mentioned the omnipresence of oysters as a nuisance (n=27), the change of the costal environment over time (n=13), and the perception that PO were aesthetically displeasing and cluttering the coastline. Finally, the loss of income for landowners with a right to collect flat oysters was mentioned as a negative economic impact (n=1).

In terms of "positive impacts on recreation", only the picking of oysters as a food resource was mentioned (n=69). Positive ecosystem impacts included positive impacts on biodiversity (n=16), e.g. birds feeding on the oysters, a positive association with other species like the periwinkle and, in one case, blue mussels, and provision of substrate (n=6). The ability of the oysters to mitigate environmental challenges (n=7) by filtering the water, taking up nutrients, and mitigating ocean acidification was also mentioned. Less tangible are the impacts categorized as "positive emotional response", which consisted of responses identifying PO as aesthetically pleasing (n=10) or see them as an indicator of life in the sea. Example of this was "*Something in the sea lives and thrives*" and "*It's nice to see the shells at the shore sometimes. A reminder of wildlife underneath the surface* […]". Positive economic impacts were the potential of oysters as a source of income e.g. in tourism (n=6), the use as animal feed (n=2) and general provisioning. Positive cultural impacts comprised the use as an ornamental resource (n=3) and the replacement of blue mussels as a bait for the tradition of crab fishing (n=2), although PO causing the loss of blue mussels as a bait for crab fishing and therefore the loss of traditions was also mentioned as a negative cultural impact (n=4). The survey demonstrated that while some impacts of PO are unambiguously negative or positive (e.g. cuts or use as a food source), others are very much subjective (all impacts categorized as "emotional response", e.g. PO shells on the beach can be perceived as aesthetically pleasing or displeasing).

The open-question responses showed further that respondents didn't merely feel affected by PO but had also reacted by avoiding, adapting or even exploiting PO occurrence. Adaptation strategies were mentioned in 35 cases and ranged from adaptation on site, e.g. wearing bathing shoes (n=22) and being careful when swimming (n=4) to warning others and bringing a first aid kit (n=1). Other respondents explained how they avoided oysters, either by a change of swimming spots (n=3), partial or complete refrainment from bathing (n=6). Aspects of exploitation (n=70) are the aforementioned uses as a food and ornamental resource, use as bait in crab-fishing as well as an (unspecified) source of income.

3.2.3 Business survey

The 53 responses to the business survey were sorted into 10 activity categories, the most prominent being "recreational tourism" (n=12), commercial fishing (n=8), municipalities and environmental management (n=8) and non-oyster aquaculture (n=7) (Figure 15).

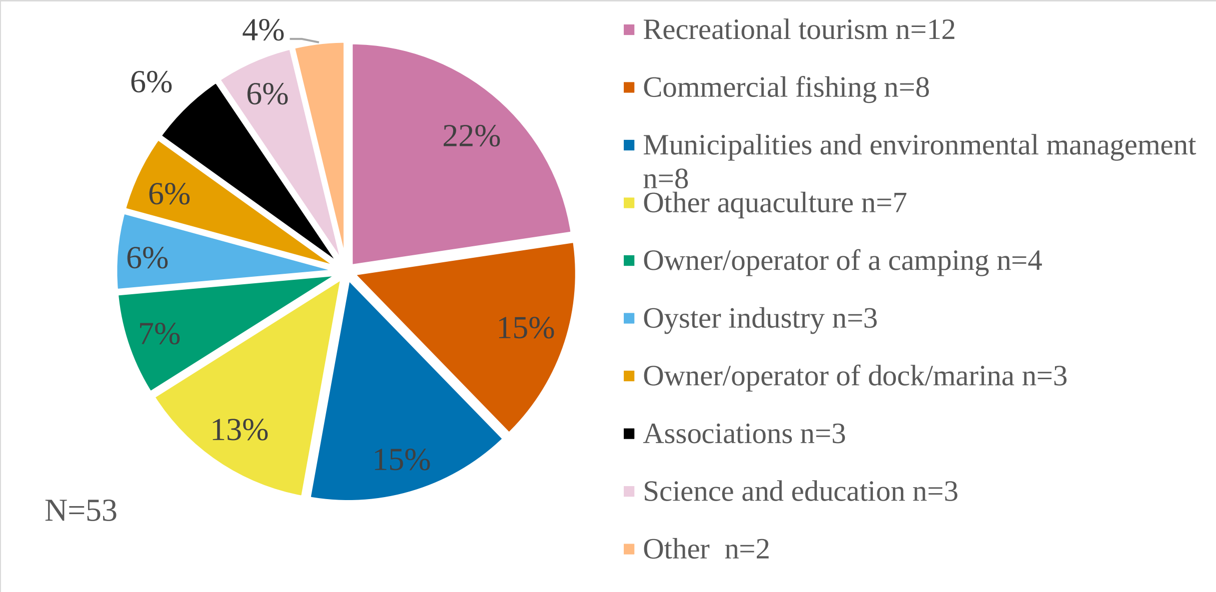

Figure 15 Respondent composition of the business survey. The total number of responses was 53, which are divided between 10 stakeholder groups (sorted by main marine-related activity). Group "other" includes the responses "work" and "manager of a seafood organisation".

A majority of the respondents (79.3%, n=42) had observed PO in the area they use for their business activities. 37.7% of the respondents (n=20) felt negatively affected, 22.6 (n=12) not affected, 18.9% (n=10) positively affected, 11.3% (n=6) registered both positive and negative impacts and 9.4% (n=5) didn't know. When asked to specify[5], 7 of 31 respondents (22.6%) responded that they were economically affected by the PO.

Out of the 53 respondents, 33 answered the open-ended question (description of perceived impacts) which led to 49 categorized answer aspects (appendix 4). Parts of these aspects dealt with how respondents were affected privately instead of in their business and are not repeated here as they were previously observed also in the private survey. The risk of cuts was mentioned from a tourist guide perspective as well as how oysters can raise an interest *("They are exciting, add spice to the guided tours")*. Economic aspects that were brought up were additional expenses, both in aquaculture for sorting out PO spat from flat oyster spat obtained from sea-based oyster seed collectors, and in terms of maintenance costs for destroyed material/removal of biofouling which was mentioned by a mussel farmer, a commercial fisher and a respondent from the "science and education" group. The limited financial resources for oyster removal were mentioned by two municipalities *("If oysters are present on municipal land, they can involve costs. The municipality does not actively control the oyster as it owns little land adjacent to the coast and the focus is instead on controlling land-based invasive species, which is very*

[5] Not mandatory question, hence a total of 31 instead of 53 responses

costly"), and the difficulties of getting an oyster fishing licence from a fishery perspective was highlighted, which implies economic interest in the species. Five respondents also mentioned how PO provide an additional/diversified source of income, deriving from sales and oyster safari events where tourists can pick oysters themselves. Cost estimates of impacts included 12,000 SEK for repairs of a boat's water jet due to biofouling and 50 working hours/year to sort out unwanted PO spat. Additional achieved or potential income was estimated by two different companies to 5,000 and 800,000 SEK/year. Another response estimated a nation-wide loss derived from unexploited aquaculture opportunities of 200-500 million SEK.

3.3 Analysis of impacts on ecosystem services

As found in the literature review (section 3.1), PO have various ecosystem functions and impacts which will often impact several ES simultaneously (Figure 16).

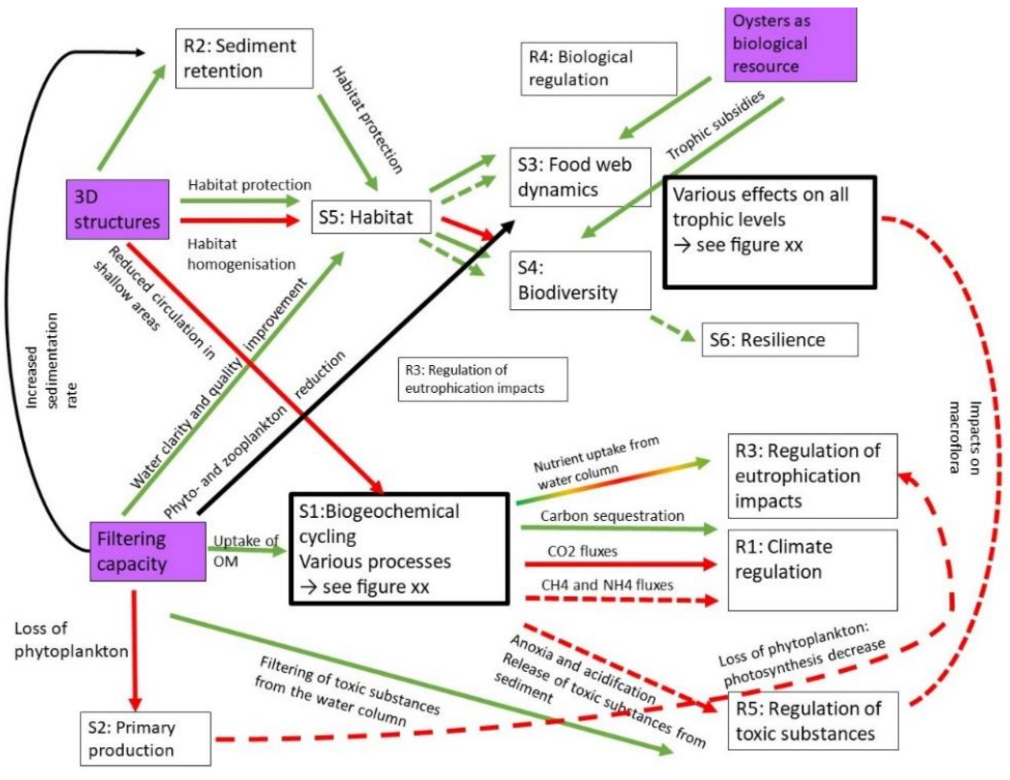

Figure 16 Overview of the interactions of supporting and regulating services. Boxes marked in purple show the oysters' three main functions. Green and red arrows illustrate positive and negative impacts, dashed lines indicate that effects are indirect.

The analysis of PO impacts on ES resulted in 50 indicators associated to 23 descriptors, which were divided among the first 5 ES, and a total assessment of 24 ES. Seven descriptors were excluded before the analysis because of obvious irrelevance (appendix 1). 13 indicators were added after the literature review for their high relevance. Those were:

- carbon cycling (S1 biogeochemical processes)
- occurrence of other [than cod] migratory and resident fish (both under S4 biodiversity and S3 food web dynamics)
- epifauna and infauna abundance, species richness and species composition (S4)
- species interactions with other bivalve species and recruitment potential of bivalve species (S4).

Effects of PO were identified on all ES in the literature review, except for energy production (S6). An in-depth analysis of PO impacts on each ES, including full references, is presented in appendix 12, and is therefore only briefly summarised here.

3.3.1 Short description of Pacific oysters' impacts on ES

Pacific oysters are efficient filter feeders. By filtering and the following physiological processes, they increase the turnover of nutrients in the ecosystem, contribute to benthic-pelagic coupling, and impact **biogeochemical cycling (S1)** in numerous ways. They also provide a habitat to bacteria with various functions in biogeochemical cycling (Figure 17).

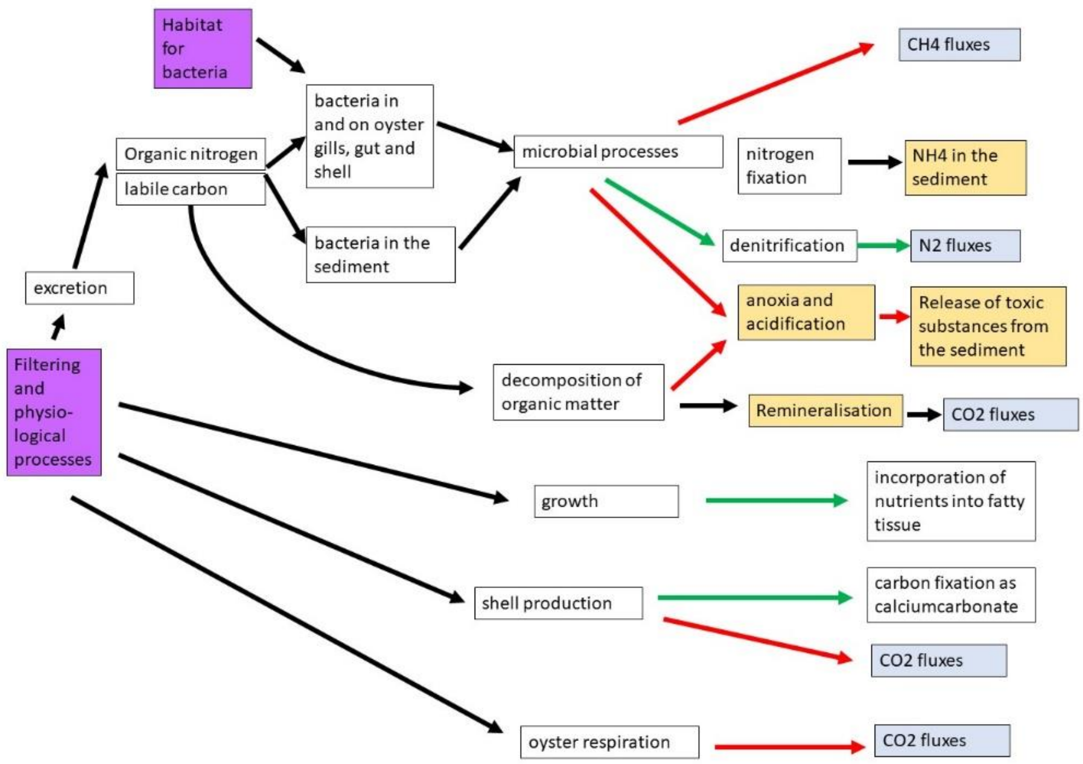

Figure 17 Impacts of Pacific oysters on biogeochemical cycling. The oysters' functions are marked purple, effects in the sediment orange and effects in the water column blue. Green and read arrows illustrate positive and negative effects.

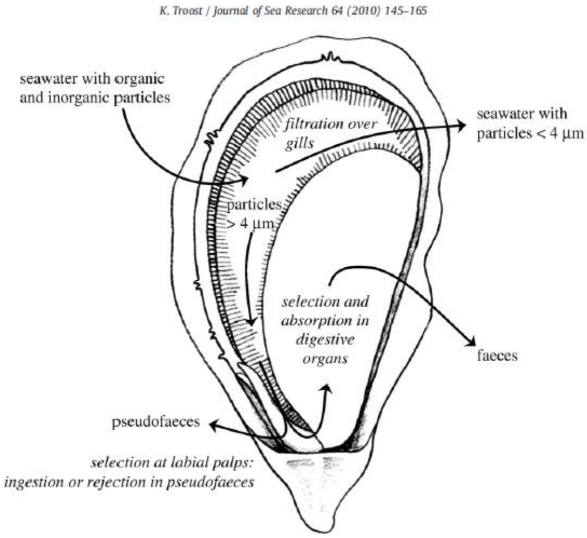

Figure 18 Filter feeding and excretion from: Troost (2010), p.3

During the process of filter feeding, PO will trap particles, some of which will be used as food and some which will be rejected and released as pseudofaeces (non-digested material) (Figure 18 from Troost, 2010), enabling benthic-pelagic coupling (Laugen et al., 2016; Vaughn & Hoellein, 2018). The increased availability of nutrients in the sediment will increase microbial activity which in turn will also alter biogeochemical cycles (Herbert et al., 2016). Through the biodeposition (faeces and pseudofaeces), nutrients are deposed into the sediment, increasing organic content and nutrient availability in the sediment (Green et al., 2012; Herbert et al., 2016). This promotes growth of the benthic flora and fauna, as well as microbial activity (Green et al., 2012; Herbert et al., 2016), unless the organic enrichment of the sediment is too high, at which point high rates of decomposition and microbial respiration may reduce the available oxygen and can lead to locally hypoxic or anoxic sediments (Ruesink et al., 2005; Green & Crowe, 2014; Troost, 2010; Laugen et al., 2016; Herbert et al., 2016). During microbial anaerobic respiration the sediment will become more acid and toxic substances such as sulphides may be released (Troost, 2010), and other microbial processes may also lead to fluxes of methane (CH_4) (Green et al., 2012; Herbert et al., 2016). The increased availability of organic matter as well as the oysters' excretion of dissolved inorganic nitrogen also lead to various nitrogen cycling processes by decomposition and bacterial activity (Ray et al., 2021), including denitrification (conversion of biologically available nitrogen into nitrogen gas in anoxic conditions). Additionally, the oysters also provide habitat for denitrifying bacteria in their gut, gills and shells as well as for nitrifying bacteria on their shells (Ray et al., 2021).

Moreover, as a result of aerobic respiration and during shell formation, the oysters will release CO_2 into the water column (van der Schatte Olivier et al., 2020). Through the production of calcium carbonate ($CaCO_3$), carbon is bound and sequestered in the shell, and if the shell is buried in the sediment after the oyster's death it therefore acts as a long-term carbon sink (Filgueira et al., 2015; van der Schatte Olivier et al., 2020).

In terms of **S2 primary production**, PO will filter phytoplankton from the water, reducing its biomass (Newell, 2004; Ruesink et al., 2005; Troost, 2010; Herbert et al., 2016; Vaughn & Hoellein, 2018) and potentially also change species composition, which can be considered negative in relation to the ES (Cognie et al., 2001). While the effects on macroalgae are positive, deriving mostly from the provision of attachment substrate (Ruesink et al., 2005; Markert et al., 2009; Padilla, 2010; Troost, 2010; Boëthius, 2022) and positive nutrient effects (Naldi et al., 2020), positive and negative effects have been shown for eelgrass. Oysters may infer a loss of soft substrate (Kelly & Volpe, 2007), along with a potential sulphide accumulation and hypoxic conditions (Kelly & Volpe, 2007; Padilla, 2010; Troost, 2010; Vaughn & Hoellein, 2018). At the same time, increases in Secchi depth and nutrient availability (Laugen et al., 2016; Vaughn & Hoellein, 2018) are beneficial to eelgrass. Limited intermix of eelgrass and oysters has been observed along the Swedish west coast (Bengtsson Kupcik, 2017).

Regarding **S4 biodiversity**, PO can impact the abundance or biomass, species richness and species composition of both flora, algae (see S2 primary producers) and fauna. The provision of habitat (nesting, nursery and foraging grounds) will have positive effects on both pelagic and demersal fish with resulting higher abundance and biomass (Ruesink et al., 2005; Grabowski & Peterson, 2007; Norling et al., 2015; Laugen et al., 2016; van der Schatte Olivier et al., 2020). Infauna abundance in the sediment under oyster reefs or bivalve beds has been documented to increase, whereas species richness seems less affected (Lejart & Hily, 2011; Hollander et al., 2015; Laugen et al., 2016; Herbert et al., 2016). In contrast, the biomass of zooplankton may be affected negatively by the oysters´ filtering (Ruesink et al., 2005; Troost et al., 2008; Herbert et al., 2016; Vaughn & Hoellein, 2018). Additionally, the oysters may also change both infauna and epifauna species composition (Kochmann et al., 2008; Markert et al., 2009; Troost, 2010; Green & Crowe, 2014; Norling et al., 2015; Laugen et al., 2016; Lejart & Hily, 2011). Epifauna will benefit from the provision of attachment substrate, especially on soft sediments, with documented higher abundance and species richness (Markert et al., 2009; Lejart & Hily, 2011; Norling et al., 2015). Epifauna also profits from organic attachment substrate on artificial hard bottoms; on natural hard bottoms, however, establishment of oysters may favour non-native epibiont species (Firth et al., 2021).

PO may also interact with other bivalve species, esp. through larviphagy (Troost et al., 2008) and competition for food and space (Laugen et al., 2016). Blue mussels seem, however, to benefit from the shelter and substrate provided by oysters, leading to the creation of so-called oyssel-reefs (Reise et al., 2017). For European flat oysters, the knowledge is more limited compared to blue mussels and the nature of interactions is unclear. Flat oysters occur in highest abundances at depths between 0.5-3m (but down to 6m) on sandy or gravelly, unvegetated substrate (Thorngren et al., 2019) which tends to result in spatial partitioning from PO, which prefer depths of around 0.5 m (Stagličić et al., 2020; Bergström et al., 2021). However, recent studies show a greater niche overlap than previously believed (Bergström et al., 2021), but in these cases, the provision of substrate may be beneficial to flat oysters (Christianen et al., 2018).

PO will impact **food web dynamics (S3)** on all trophic levels by the processes described in S1-S4 (Figure 19). PO will reduce the biomass and potentially species composition of both phyto- and zooplankton (see S1 and S4), thereby exerting bottom-up effects on the food web. They also provide habitat for fish (see S4) which will then exert top-down control on the other trophic levels. PO may also have positive effects on some seabird species that feed on oysters (Escapa et al., 2004; J. L. Ruesink et al., 2005; Cade´e, 2008b, 2008a; Markert et al., 2009; Troost, 2010) and negative effects on other bird species that typically feed on young bivalve beds only. The Red Knot for example which swallows bivalves whole, is dependent on bivalves under 20mm size and is therefore negatively affected by a predominance of comparably large (and often cluster-growing) PO (Waser et al., 2016).

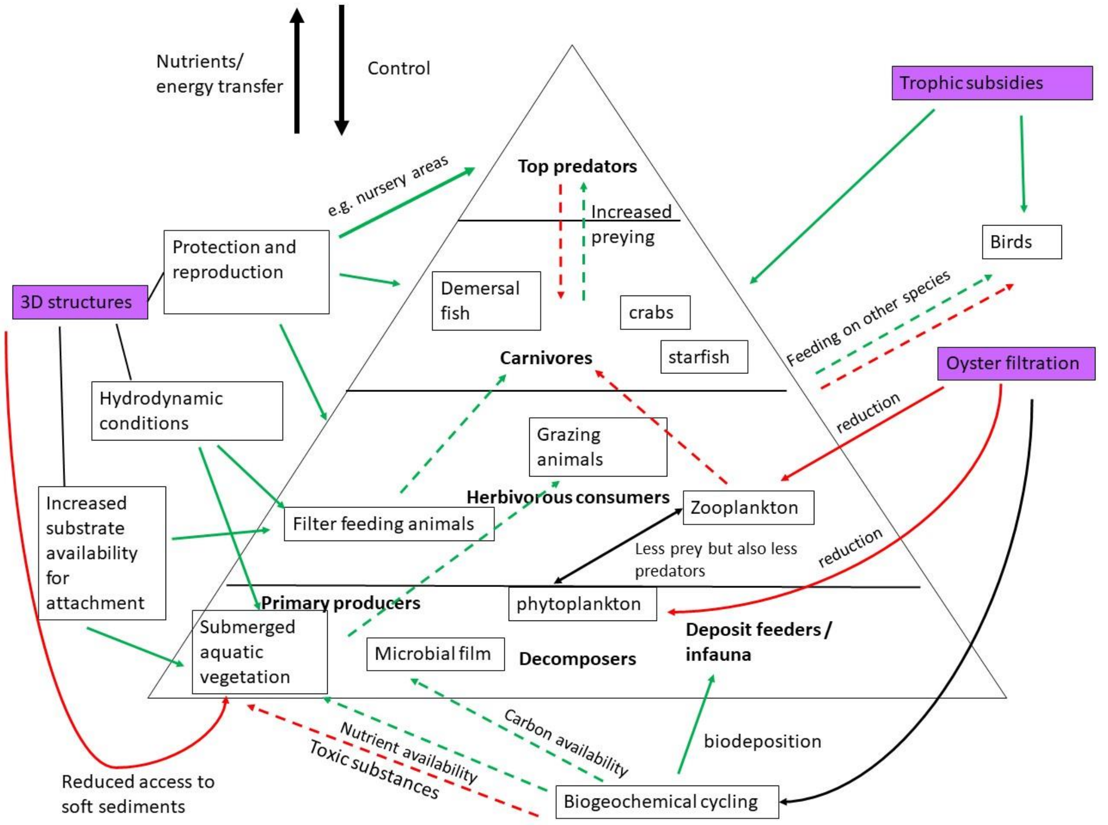

Figure 19 Pacific oyster impacts on the food web. The oysters' functions are coloured purple, red and green arrows present negative and positive impacts, dashed lines indicate indirect effects.

PO may create, enhance or modify **habitats (S5)** by stabilizing soft sediment and by adding new structures (habitat diversification, Ruesink et al., 2005), by impacting other ecosystem engineering species (e.g. eelgrass, see S2), and may counteract desiccation of species during low tide (Padilla, 2010; van der Schatte Olivier et al., 2020; Herbert et al., 2016). Reef formations may, however, also lead to increased sedimentation and a reduced water flow, initiating siltation process and therefore to a loss of soft-bottom habitats (Ruesink et al., 2005; Laugen et al., 2016).

No set indicators were associated to **resilience (S6)**. As resilience assessment is generic and very complicated, it was therefore not evaluated in this thesis. Changes in biodiversity, the food web and habitats (see S3-S5) are, however, considered to impact ecosystem resilience (Oliver et al., 2015). A functional similarity of PO to native bivalves is considered to in certain cases compensate for the loss of ecosystem functions caused by a decline of native species (Zwerschke et al., 2016, 2020; Shakspeare et al., 2024).

The oysters' carbon sequestration (see S1, Filgueira et al., 2015) may have positive effects on **climate and atmospheric regulation (R1)**, whereas CO_2 fluxes from respiration, the release of N_2O (see S1, Ray et al., 2021) and methane from associated bacteria (see S1, Green et al., 2012; Herbert et al., 2016) may affect this ES negatively. Regarding **sediment retention (R2)**, PO enhance sediment stability and retention as well as act as "living breakwaters" which reduces coastal erosion (Troost et al., 2008; Herbert et al., 2016; Laugen et al., 2016; Vaughn & Hoellein, 2018; Hansen et al., 2023; Shakspeare et al., 2024). The uptake and cycling of nutrients (see S1) also has positive impacts on the **mitigation of eutrophication effects (R3)**.

In terms of **biological regulation (R4)**, PO can be a vector for other non-native species and facilitate invasion by creating habitat (Ruesink et al., 2005; J. Ruesink, 2007; Troost et al., 2008; Lang & Buschbaum, 2010; Herbert et al., 2016). They can also be a cause of emerging diseases (Ruesink et al., 2005) whereas in other cases, where PO act as non-hosts/dead-end hosts to parasites and interfere with the parasites' life-cycle, the spread of diseases is suggested to be limited through the oysters' dilution effect (Krakau et al., 2006; Thieltges et al., 2008; Troost, 2010; Martínez-García et al., 2022). An adaptation of native parasites to PO can, however, not be ruled out (Krakau et al., 2006; Troost, 2010). The oysters' filtering may also reduce the likelihood of harmful algal blooms (Beck et al., 2009). By filtering chemicals, metals, pathogens and microplastics from the water, Pacific oysters contribute to **R5, the regulation of hazardous substances** (Vaughn & Hoellein, 2018; Paul et al., 2023).

Regarding **food provision (P1)**, oysters are a protein-rich and nutritious food source (Herbert et al., 2016; Laugen et al., 2016; Hallström et al., 2019). They also provide habitat to commercially important fish species (see S3 biodiversity). Negative effects on food provisioning can arise from negative interactions with commercial fisheries, e.g. the destruction of fishing gear and interference with the production of other shellfish species (see section 3.2). Ensuring food-safety for private oyster consumption requires frequent controls (Herbert et al., 2016).

Diverse uses of PO as a **raw material (P2)** include the shell use in construction, roadbuilding and coastline protection, as lime or as artificial stone material (Herbert et al., 2016; van der Schatte Olivier et al., 2020; Vaughn & Hoellein, 2018; Hellen et al., 2019; Linder, 2022). The meat can be used in fish and poultry feed (Laugen et al., 2016; van der Schatte Olivier et al., 2020) and both shells and meat can serve as fertilizer (van der Schatte Olivier et al., 2020; Vaughn & Hoellein, 2018). For more information see Linder (2022) and Nyqvist (2022).

In terms of **genetic resources (P3)**, wild oyster populations can serve as source of spat for farming and for restoration purposes (not relevant in Sweden) (Martínez-García et al., 2022). Other impacts on genetic resources could arise from the interactions with native species, see S4 biodiversity. There is no risk for hybridisation of PO with other mussels and oysters in Sweden.

As a **chemical resource (P4)**, PO shells can be used in healthy foods and medicine, e.g. as a calcium supplement (Fujita et al., 1990; Linder, 2022). Hydroxyapatite can be extracted for use in bone grafting (Hou et al., 2016) while calcium oxide can be used for its antibacterial and antifungal effects (Yao et al., 2014). Oyster meat can also provide a health and dietary supplement (Nyqvist, 2022). Oyster shells are also used as **ornamental resources (P5)** for artwork, jewellery, home decoration/handicraft and as garden decorations, e.g. as candleholders (see section 3.2). By blocking navigation channels and the fouling of boats, docks, drainage pipes, underwater constructs and cooling water inlets, PO affect **space and waterways (P7)** negatively (Herbert et al., 2016; Laugen et al., 2016, see section 3.2).

Negative impacts on **recreation (C1)** include the risk of injury from the shells, the fouling of boats and docks as well as material destruction and sanitary problems with decomposition after high mortality events (Herbert et al., 2016; Laugen et al., 2016, see section 3.2). However, the increase of bathing water quality and clarity, crab fishing for children, as well as recreational picking of the oysters should be highlighted as positive (Laugen et al., 2016; see section 3.2). Enhanced conditions for recreational fishing can be assumed from the habitat provisioning to different fish species (see S4, Grabowski et al., 2012). Regarding **aesthetic values (C2)**, PO are perceived as aesthetically pleasing by some and displeasing by others (see section 3.2). Because of their accumulation of contaminants, Pacific oysters can be used for **science and education (C3)** purposes, esp. in environmental monitoring and ecotoxicology (Vaughn & Hoellein, 2018). They are also easy to access and use as a model organism for education and communication purposes.

With regards to **cultural heritage (C4)**, archaeological records of bivalve shells from consumption, as tools and currency provide evidence of ancient bivalve use traditions (van der Schatte Olivier et al., 2020). Outside the PO's native distribution range, these traditions involved other, native species. Other aspects include seafood traditions, e.g. handpicking of oysters and seafood festivals (van der Schatte Olivier et al., 2020). The survey results (section 3.2) showed adaptation of traditions with PO being used as bait for crab fishing instead of blue mussels. Moreover, work opportunities in rural areas (harvesting and gastronomic tourism) aid in keeping previous fishing societies alive. The easily available PO can also provide **inspiration**

(C5) for culinary experiments, new business ideas and art (see section 3.2). Finally, PO occurrence has impacts on **natural heritage (C6)**, potentially affecting conservation and perceived natural beauty by changing ecosystems from, and preventing the return to, their "natural"/original state.

3.3.2 Summary of Pacific oysters' impacts

The extensive mapping of PO impacts on ES (appendix 12) was summarised to facilitate interpretation and analysis of the impacts (Table 4). For the 50 indicators and 19 indicatorless ES that were examined and associated to existing knowledge throughout the literature review, the impacts of the Pacific oysters were classified as positive, negative or other categories for soft-bottom and hard-bottom habitats as seen below (Table 3).

Table 3 Overview of the impact classification of all 69 indicators by habitat.

Impact classification	Soft-bottom habitat	Hard-bottom habitat
Positive	22	11
Supposedly positive	4	6
Negative	6	6
Supposedly negative	3	3
Both positive and negative	10	11
Changes (no classification as positive or negative)	11	1
Neutral	7	8
Not known	5	10
Not applicable	1	13
Total	**69**	**69**

Overall, more impacts on ES were classified as positive than negative. Positive (or supposedly positive) impacts of oysters on ES were more frequent on soft than on hard-bottom substrate while the number of negative and supposedly negative impacts were the same for both habitats. The number of indicators classified as not applicable (13), not known (10) or supposedly positive (6) were higher for hard bottoms than for soft bottoms.

The occurrence of PO was found to impact all supporting services both negatively and positively (but to different degrees), including changes that are expected to occur in different habitats but cannot be classified as positive or negative. Differences in provisioning services between hard and soft substrate occurred mainly in S4 biodiversity (more positive impacts on soft than hard bottom) and S5 habitats where changes are expected on soft bottom, whereas impacts on hard bottom are not known or not applicable. PO on both hard and soft substrate were found to have either fully positive, or positive and negative, impacts on all regulating services, except for sediment retention on hard bottoms (not applicable). The impacts on provisioning services were more diverse, but in most cases, oysters from hard substrate cannot be used for provisioning because they are attached and can only be removed with great difficulty. The only provisioning service that was indirectly impacted (both positively and negatively) by hard-bottom oysters was P1 Food. Cultural services were found to be impacted both positively and negatively by PO regardless of substrate.

Table 4 Overview of the classification of PO impacts on ES indicators. S1 to S5 are classified by several indicators, S6 to C6 as an overall assessment. A list of descriptors deemed not impacted by the oysters were excluded before the analysis (appendix 1). The numbers in the table show how many indicators were classified in each category. Blanks or – indicate categories that weren't used. The following colour coding was used to summarise major impacts of PO on ES, based on the percentage of impacted indicators per ES, orange indicates impacts that are both positive and negative and neutral effects are marked grey.

< 33 % positive	33-50 %	> 50 %	< 33% negative	33-50 %	> 50 %

Indicator classification per ecosystem service								
Ecosystem service		**(Supposedly) positive**	**(Supposedly) negative**	**Both positive and negative**	**Changes expected but not classified**	**Neu-tral**	**Not known**	**Not. appli-cable**
S1 Biogeo-chemical cycling, 13 indicators	Soft bottom	6	1	3	-	2	1	-
	Hard bottom	6	1	3	-	2	1	-
S2 Primary production, 4 indicators	Soft	1	2	1	-	-	-	-
	Hard	-	2	-	-	1	-	1
S4 * Bio-diversity, 18 indicators	Soft	5	3	-	5	3	2	-
	Hard	2	3	2	2	3	3	3
S3 Food web dynamics, 10 indicators	Soft	2	3	1	1	2	1	-
	Hard	2	3	-	1	2	1	1
S5 Habitats, 5 indicators	Soft	-	-	-	5	-	-	-
	Hard	-	-	-	-	-	2	3
General classification of ecosystem services without indicators								
S6 Resilience	Soft			x				
	Hard			x				
R1 Climate and atmospheric regulation	Soft			x				
	Hard			x				
R2 sediment retention	Soft	x						
	Hard							x
R3 Eutrophication regulation	Soft	x						
	Hard	x						
R4 Biological regulation	Soft			x				
	Hard			x				
R5 Regulation of hazardous substances	Soft	x						
	Hard	x						
P1 Food	Soft	x						
	Hard			x				

P2 Raw material	Soft	x						
	Hard							x
P3 Genetic resources	Soft						x	
	Hard						x	
P4 Chemical resources	Soft	x						
	Hard							x
P5 Ornamental resources	Soft	x						
	Hard							x
P6 Energy	Soft							x
	Hard							x
P7 Space and waterways	Soft		Clusters & reefs			solitary		
	Hard		Clusters & reefs			solitary		
C1 Recreation	Soft			x				
	Hard			x				
C2 Aesthetic values	Soft			x				
	Hard			x				
C3 Science and education	Soft	x						
	Hard	x						
C4 Cultural heritage	Soft	x						
	Hard	x						
C5 Inspiration	Soft	x						
	Hard	x						
C6 Natural Heritage	Soft		x					
	Hard		x					

** the order of S3 and S4 was changed to better illustrate how changes in biodiversity will affect food web dynamics*

3.4 Evaluation of clearing activities

3.4.1 Fieldwork data

A total of 16,692 kg of Pacific oysters were removed within 57 working hours during the trials of mechanical clearing (dredging and excavating) methods.

In terms of environmental effects, no light attenuation that exceeded natural variation of light conditions was observed for the excavating and dredging activities respectively on sites Rundö hamn, Rundö östra and Kollholmen (appendix 13). For the clearing at site Bofors, a temporary on-site increase in turbidity was recorded during the dredging (10:00 to 11:00) (logger 1), recognisable by the fact that the increase in solar irradiance was not picked up by the light logger (Figure 20). A sequence from 10:00 to 12:00, where the datapoints approached the trendline again, was clearly visible. The increased turbidity did, however, not exceed natural variation of the light conditions. The increase was also very short-lived and local as it was not registered by logger 2 (located downstream of the clearing); logger 3 (located upstream) was lost, so the local limitation upstream couldn´t be confirmed. The findings from the loggers aligned with on-site observations during the dredging. No deviations were detected on the days following the clearing (appendix 13).

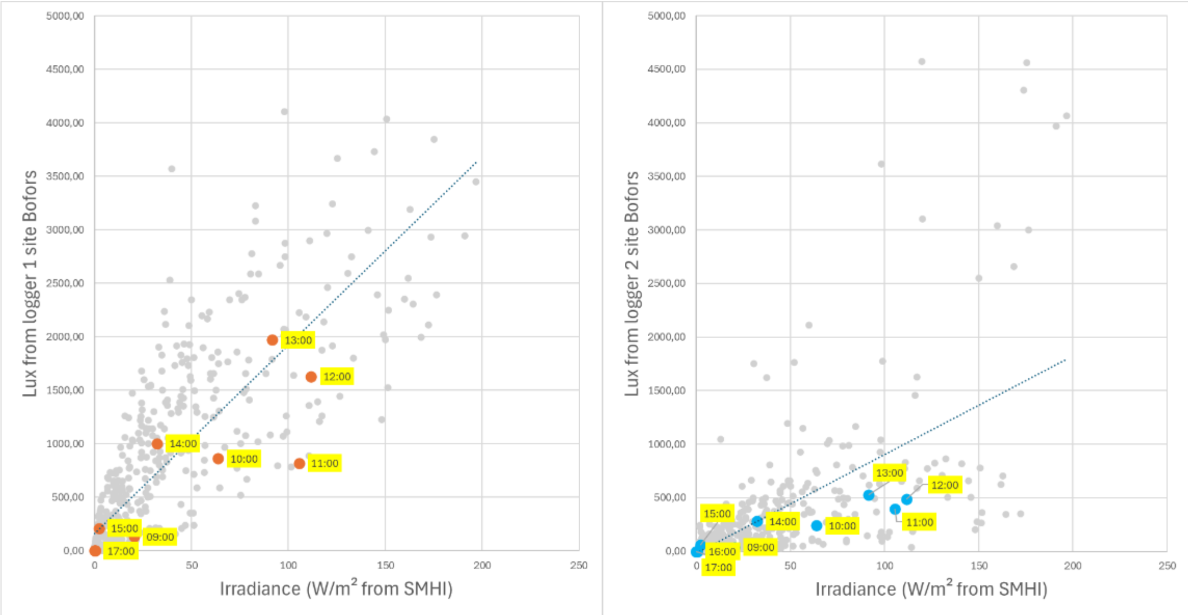

Figure 20 Logger data (lux) from logger 1 and 2 site Bofors plotted against solar irradiance (data from SMHI). The trendline shows the average response of the loggers to solar irradiance. Coloured dots illustrate the logged data on the dredging day.

Visual sediment inspections showed no traces of the dredging after 1 month (January), whereas excavating traces (ditches where the sediment was excavated) were still visible as deep trenches and sediment mounds after 6 months (May).

3.4.2 Compilation of previously performed clearing activity data and analysis of clearing effectiveness and efficiency

A total of 29 clearing activities was evaluated (appendix 6), out of which 20 used handpicking when wading or snorkelling, five used handpicking while diving and two sites respectively were excavated and dredged. 15 activities were performed on soft bottom, six on hard bottom and the remaining eight sites had a mix of soft and hard substrate.

The clearing method selection was dependent on site conditions, especially oyster density (Figure 21). Handpicking densities on soft-bottom ranged between 0.2 kg/m² (1-5 ind./m²) and 18.6 kg/m² (97.3 ind./m²), and on hard-bottom from 0.02 kg/m² to 6.7 kg/m². Diving was performed on three soft-bottom and two pebble/gravel sites with densities ranging from 0.02 kg/m² (0,1 ind./m²) to 2.1 kg/m² (8,6 ind./m²). The dredging trials took place on two sites with densities of 16.7 kg/m² (50.8 ind./m²) and 12.8 kg/m² (45.3 ind./m²) while excavating was performed on the highest density sites with 67.2 kg/m² (761.6 ind./m²) and 50.2 kg/m² (1176 ind./m²). All sites for mechanical removal were soft-bottom sites, as there are no large-scale clearing methods for high-density hard-bottom sites.

Figure 21 Pre-clearing oyster density on site by clearing method

3.4.2.1 Evaluation of clearing effectiveness

The clearing effectiveness (indicated by clearance proportion[6]) between the different sites ranged from 9.6% to 100%, with the highest range in effectiveness for handpicking activities and the highest effectiveness median (99.1%) for excavating (Figure 22).

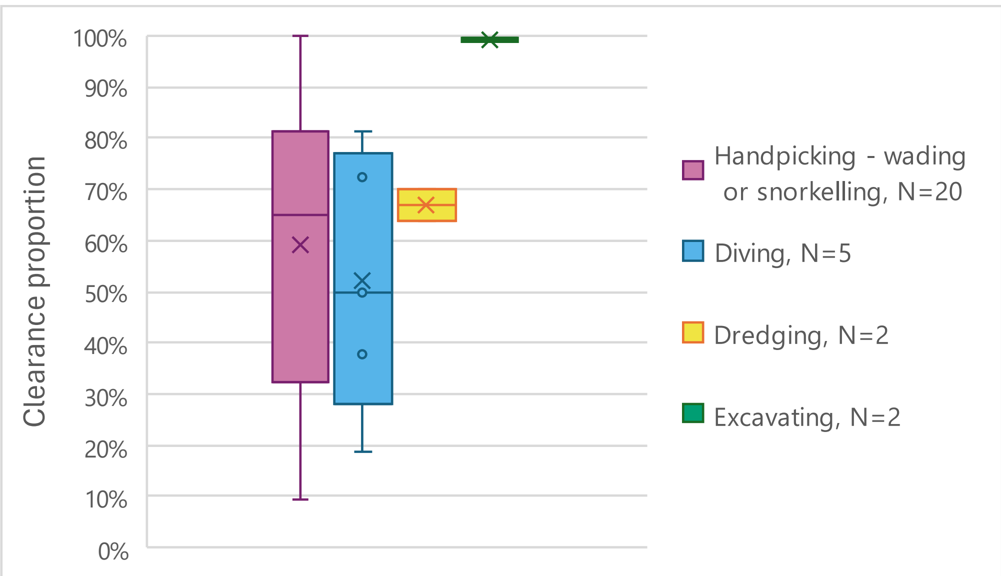

Figure 22 Clearance proportion by clearing method

The differences in effectiveness must be considered in the light of different clearing objectives. While clearing for research purposes always aimed at removing all oysters from a site (but was

[6] For the volunteer handpicking on all Norway sites, this was an estimate by the organisers which was then used to calculate estimated pre-clearing density (no pre-survey data). For all research projects, the clearance proportion was calculated from the difference in pre- and post-clearing densities.

sometimes limited by factors like time and budget), volunteer clearings were organised with the goal of removing as many oysters as possible within a 2-hour timeframe, resulting in a wide range of clearance proportion for the handpicking activities (which include volunteer and research activities) in particular. Consequently, clearance proportion was not considered as a measurement in evaluating different clearing methods, instead it presented a noise in the data to be aware of and that was compensated for in the following analysis by extrapolations to a 90%-clearance proportion scenario wherever needed and possible.

3.4.2.2 Evaluation of clearing efficiency

Substrate did not affect either efficiency-indicator (Figure 23). Handpicking was therefore considered without a distinction between substrates during the efficiency comparison between the different clearing methods.

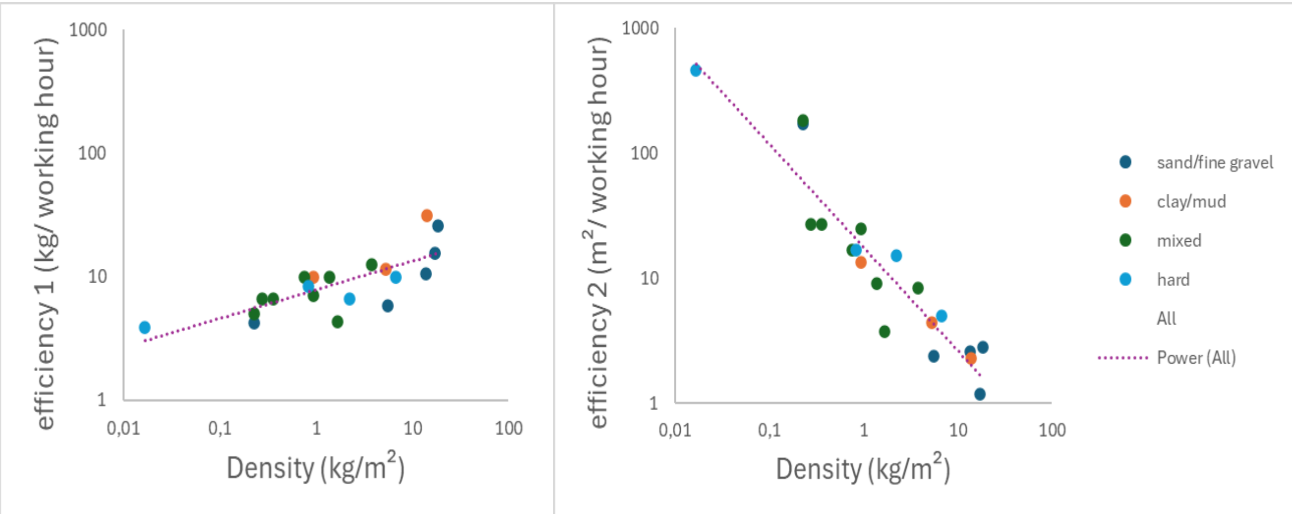

Figure 23 Relation between oyster density and efficiency 1 and 2 (removed kg/working hour and cleared area/working hour) for handpicking on different substrates. (Note: log:log-scales)

In comparison to substrate, the efficiency-analyses of different methods showed a less random distribution (Figure 24), suggesting different efficiency between methods at increasing oyster densities. For efficiency-indicator 1 (kg/working hour), both handpicking and diving showed a significant increase of efficiency with increasing density (Linear regression, Table 6), with diving resulting in a higher efficiency than handpicking in terms of cleared oysters/working hour, and dredging and excavating distributed above the diving trendline, indicating an even higher efficiency (Figure 24).

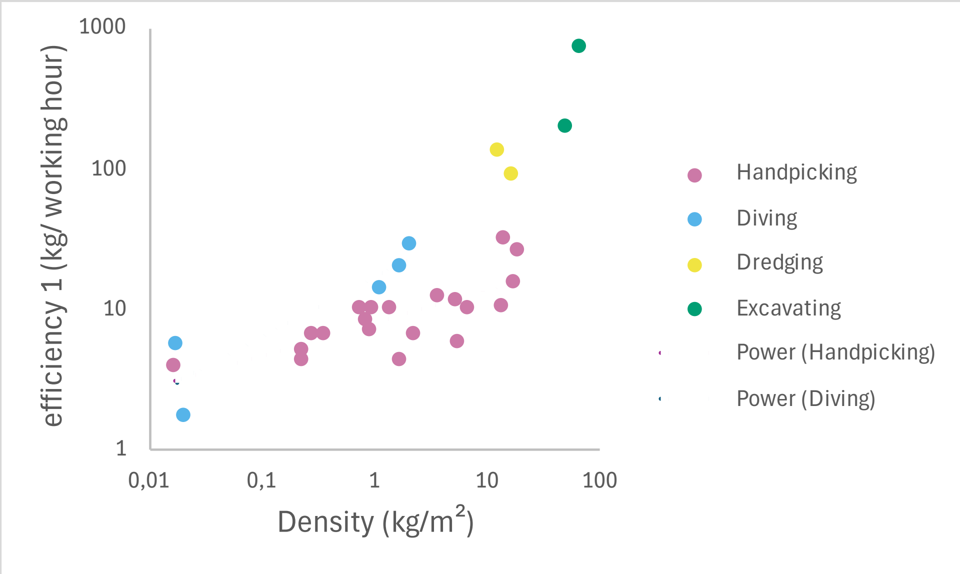

Figure 24 Relation between oyster density and efficiency 1 (removed kg/working hour) for different clearing methods. (Note: log:log scales).

For efficiency-indicator 2 (cleared area/working hour), the trendlines for handpicking and diving were rather aligned and both handpicking and diving showed a decrease of efficiency with increasing density (Linear regression, Table 5, Figure 25). Dredging and excavating were again distributed above the handpicking and diving values which illustrated also a higher efficiency in terms of cleared area/working hour (Figure 25).

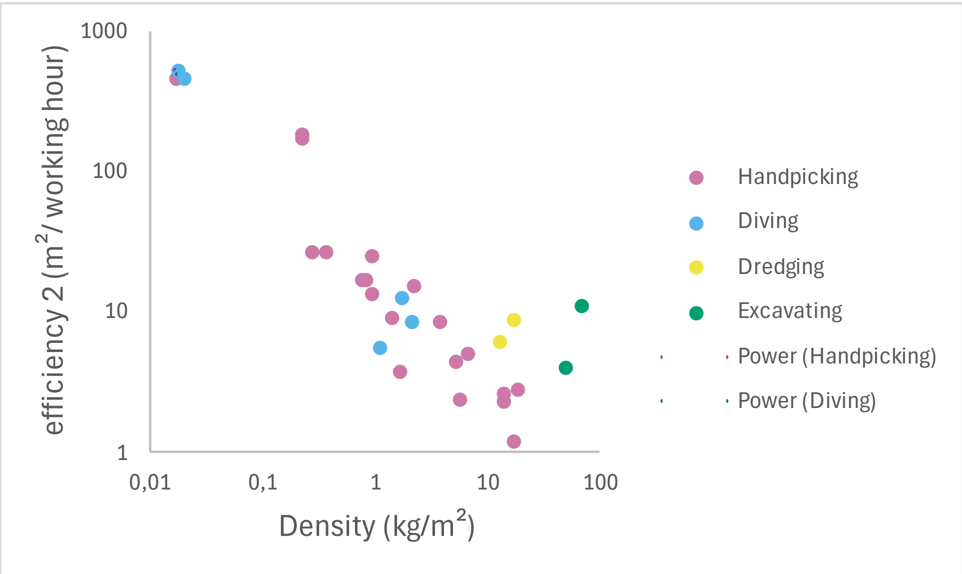

Figure 25 Relation between oyster density and efficiency 2 (cleared area/working hour) for different clearing method. Note: log-log scale.

Table 5 Linear regression analysis of the log-transformed data on clearing efficiency (a and b refer to the linear function) and the corresponding power function for untransformed data

Indicator	Method	N	R^2	p-value	a	b	Power function
Efficiency 1	Handpicking	20	0.57	< 0.01	0.90	0.23	$Y = 7{,}8755x^{0{,}2326}$
	Diving	5	0.83	0.03	1.22	0.42	$Y = 16{,}695x^{0{,}4246}$
Efficiency 2	Handpicking	20	0.88	< 0.01	1.25	-0.83	$Y = 17{,}623x^{-0{,}827}$
	Diving	5	0.96	< 0.01	1.11	-0.90	$Y = 12{,}917x^{-0{,}902}$

Efficiency-indicator 1 is not dependent on clearance proportion and will therefore not change in a 90%-clearance target scenario. For efficiency-indicator 2, when all data with lower clearance than 90% was recalculated to 90% clearance, similar patterns as for the original data were observed (Figure 26). However, as expected, the overall efficiency (the area cleared in one hour) decreased when assuming a 90%-clearance target (Figure 26).

The difference in efficiency between the two scenarios (original data with varying clearing proportions achieved and data recalculated to 90% clearing) is illustrated in Figure 27.

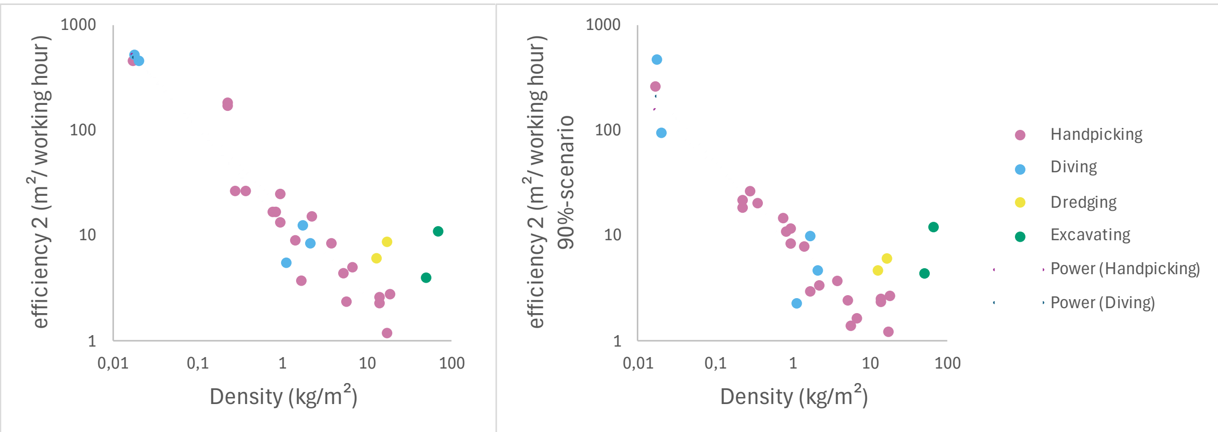

Figure 26 Comparison of efficiency 2 graphs for original data vs 90%-clearance scenario. (Note: log:log scale).

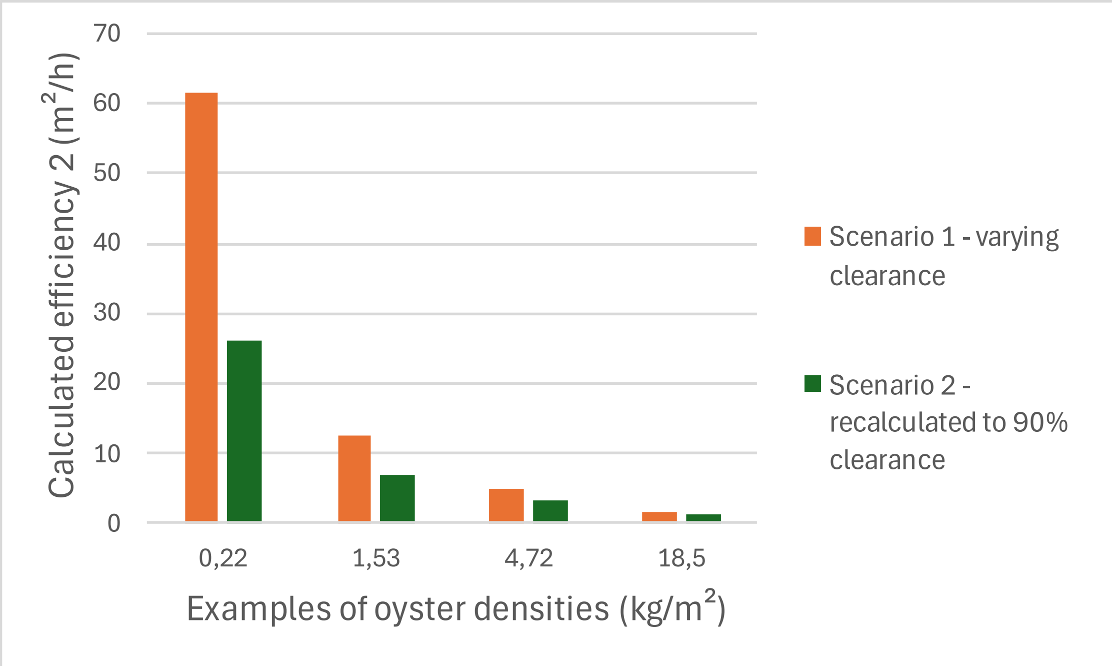

Figure 27 Efficiencies calculated by original and 90%-scenario functions.

3.4.3 Cost-efficiency analysis

3.4.3.1 Impact of substrate on cost-efficiency indicator 1 and 2 for hand-picking.

For scenario 1 (real costs), with the exception of a specific case of four clear clearing activities executed on mussel beds for bivalve bed restauration purposes (sand/fine gravel), substrate did not affect either cost-efficiency indicator for handpicking (Figure 28). The handpicking on mussel beds resulted in higher costs per kg and per m², which was a consequence of the increased effort needed to separate mussels from the PO during the activity rather than the substrate, and these datapoints were therefore excluded from the handpicking trendline.

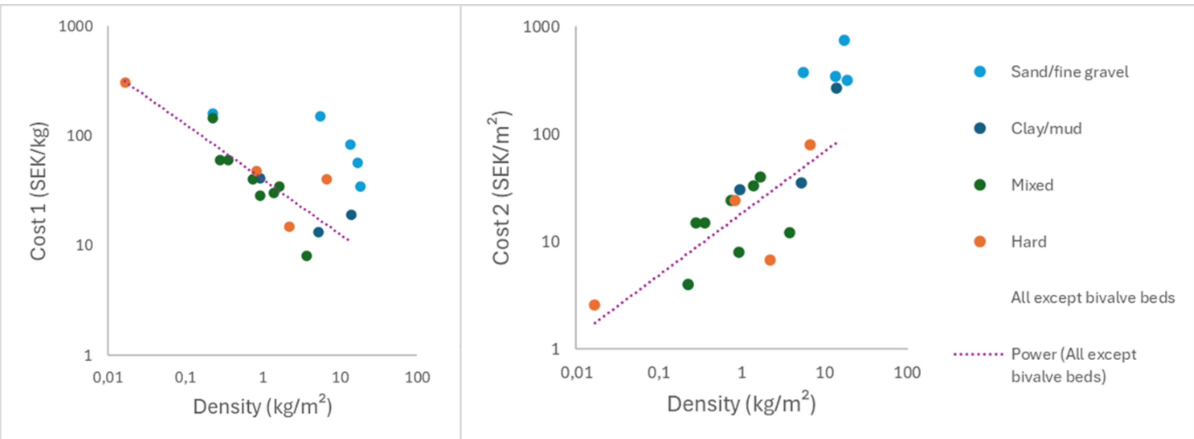

Figure 28 Relation between cost-efficiency indicators 1 (SEK/kg) and 2 (SEK/m²) and density (kg/m²) for handpicking by substrate. Note:log:log (Log 10) scale.

The same observations (cost-efficiencies weren't impacted by substrate, mussel beds excluded) were made for scenario 2 (hypothetical costs of paying an hourly wage to volunteers instead of volunteer compensation, appendix 14, figure 14.1) and scenario 3 (hypothetical costs at 90%-clearance proportion, appendix 14, figure 14.2).

3.4.3.1 Method comparison: Cost-efficiency indicator 1

In the comparison of clearing methods, cost-efficiency indicator 1 showed a relation between the clearing method and cost-efficiency with similar trends for all 3 scenarios (Figure 29). Handpicking was more cost-efficient than diving, although the diving and handpicking trendlines were closer together (i.e. differences in costs per kg decreased) when hourly wages were assumed for handpicking (scenario 2) instead of a fixed volunteer compensation (scenario 1). Both handpicking and diving showed a decrease in costs per kg with increasing oyster density in all scenarios (Table 6).

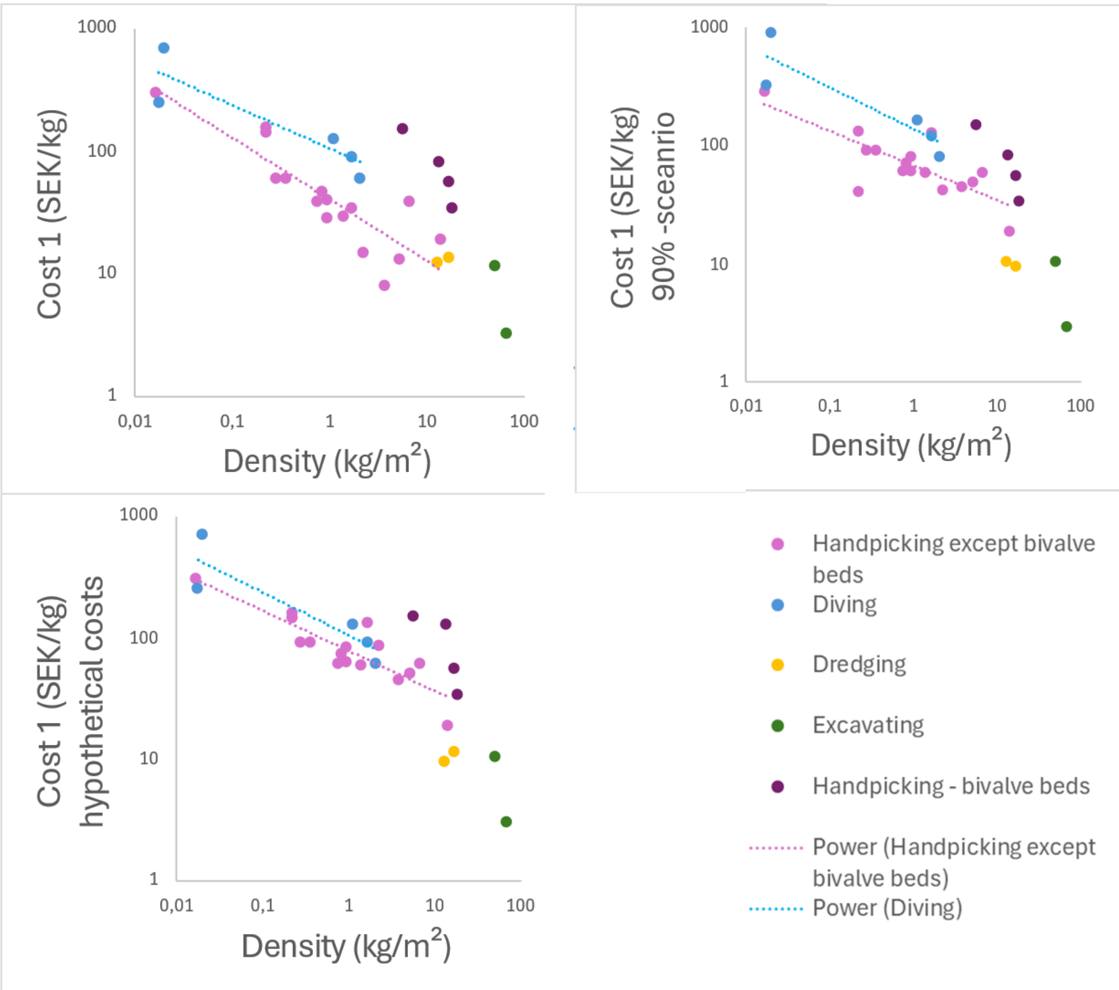

Figure 29 Relation between cost-efficiency indicator 1(SEK/kg) and oyster density between clearing methods and for three scenarios (real costs, hypothetical costs and hypothetical costs for 90%-clearance proportion). (Note: log:log scale)

Table 6 Linear regression analysis of the log-transformed data on clearing efficiency (a and b refer to the linear function) and the corresponding power function for untransformed data

Scenario	Method	N	R^2	P	a	b	Power function
1	Handpicking	16	0.74	<0.01	1.61	-0.50	$y = 40{,}287x^{-0{,}501}$
	Diving	5	0.81	0.04	2.02	-0.35	$y = 105{,}05x^{-0{,}353}$
2	Handpicking	16	0.75	<0.01	1.89	-0.33	$y = 78{,}288x^{-0{,}33}$
	Diving	5	0.81	0.04	2.02	-0.35	$y = 105{,}05x^{-0{,}353}$
3	Handpicking	16	0.60	<0.01	1.83	-0.29	$y = 68{,}281x^{-0{,}293}$
	Diving	5	0.80	0.04	2.14	-0.35	$y = 139{,}59x^{-0{,}351}$

Handpicking was found to be cheaper than diving which had higher fixed costs to begin with (visible also by the higher intercept of the diving function, Table 6). The handpicking functions also displayed a less steep slope in scenario 2 and 3 compared to in scenario 1, indicating a slower cost decrease with increasing density for those scenarios. No interception of the diving and handpicking trendlines was visible within the data range, meaning that diving was consistently more expensive than handpicking regardless of density.

The difference in cost-efficiency between the three scenarios (actual costs with different clearing achieved, hypothetical costs based on hourly compensation, and hypothetical costs recalculated to 90% clearing) is illustrated in Figure 30.

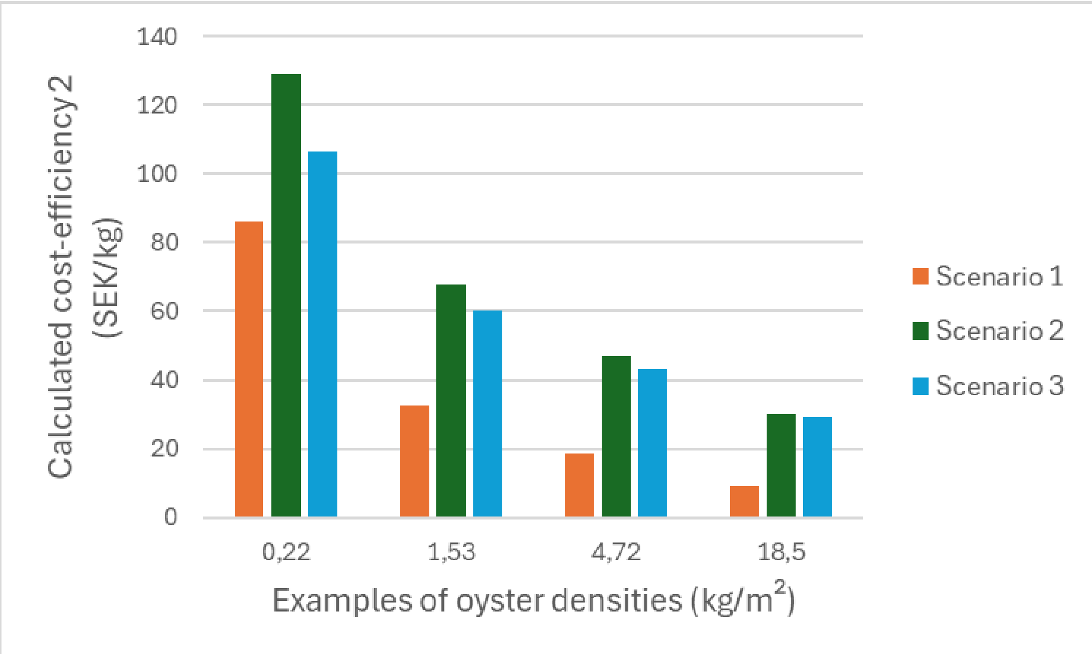

Figure 30 Cost-efficiencies 1 (SEK/kg) calculated from scenario 1-3 functions.

Using the upper and lower 95% confidence interval (best case lower 95% intercept and upper 95% slope, worst case *vice versa*) in the developed regressions provided an estimation of the uncertainties in the data (Figure 31). At e.g. PO density 20 kg/m² and 29.1 SEK/kg, a cost range of -11.4 SEK/kg to +18.6 SEK/kg can be inferred, i.e. for clearing 1 ton of oysters, costs could range between 17,763 SEK and 47,775 SEK.

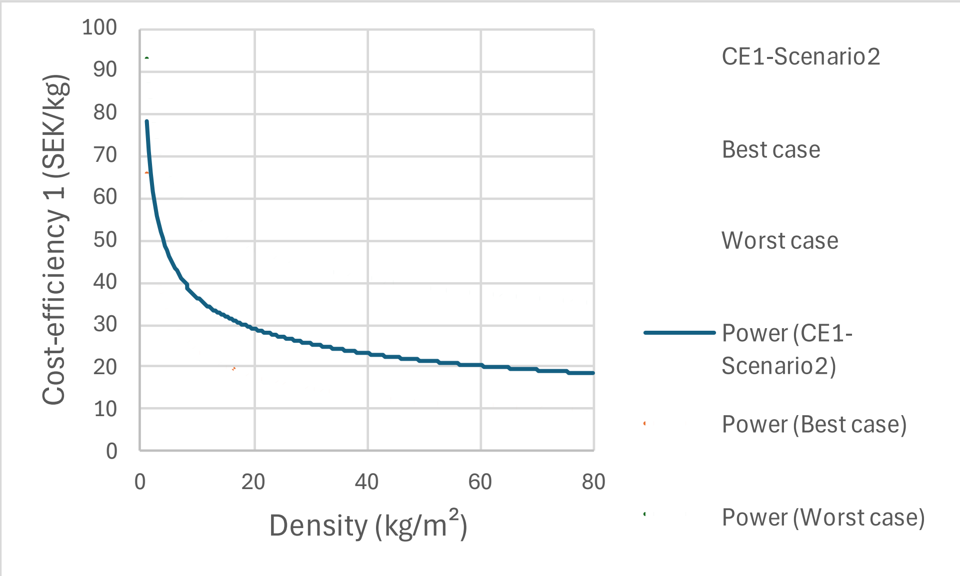

Figure 31 Cost-efficiency function, compared to best-case and worst-case 95% confidence interval functions.

Dredging densities were situated at the outer range of the handpicking data and excavating densities exceed all other densities, so it was not possible to make a direct comparison without extrapolating the handpicking data, using the handpicking trendline functions. Under the assumption that the handpicking functions can accurately describe the cost-efficiency also at higher PO densities than evaluated in the actual trials, extrapolated hypothetical costs for handpicking at high-density sites similar to excavating sites (average density of 58.7 kg/m²) were found to range between 11.1 SEK/kg and 37.6 SEK/kg (average ± 95% CI). In comparison, excavating at a density of 67.2 kg/m² was estimated to cost 3.0 SEK/kg, and 10.5 SEK/kg at a density of 50.2 kg/m². At sites similar to dredging sites (average density of 14.7 kg/m²), handpicking costs were found to range between 20.3 SEK/kg and 51.1 SEK/kg (average ± 95% CI) in comparison to dredging costs of 9.6 SEK/kg (density 12.7 kg/m²) and 11.6 SEK/kg (density 16.7 kg/m²).

3.4.3.2 Method comparison: Cost-efficiency indicator 2

Cost-efficiency indicator 2 also showed a relation between the clearing method and cost-efficiency with similar trends for all 3 scenarios (Figure 32). Handpicking was more cost-efficient than diving, although differences in costs per kg decreased when hourly wages were assumed for handpicking (scenario 2) instead of a fixed volunteer compensation (scenario 1).

Both handpicking and diving showed a decrease in costs per kg with increasing oyster density in all scenarios (Table 7).

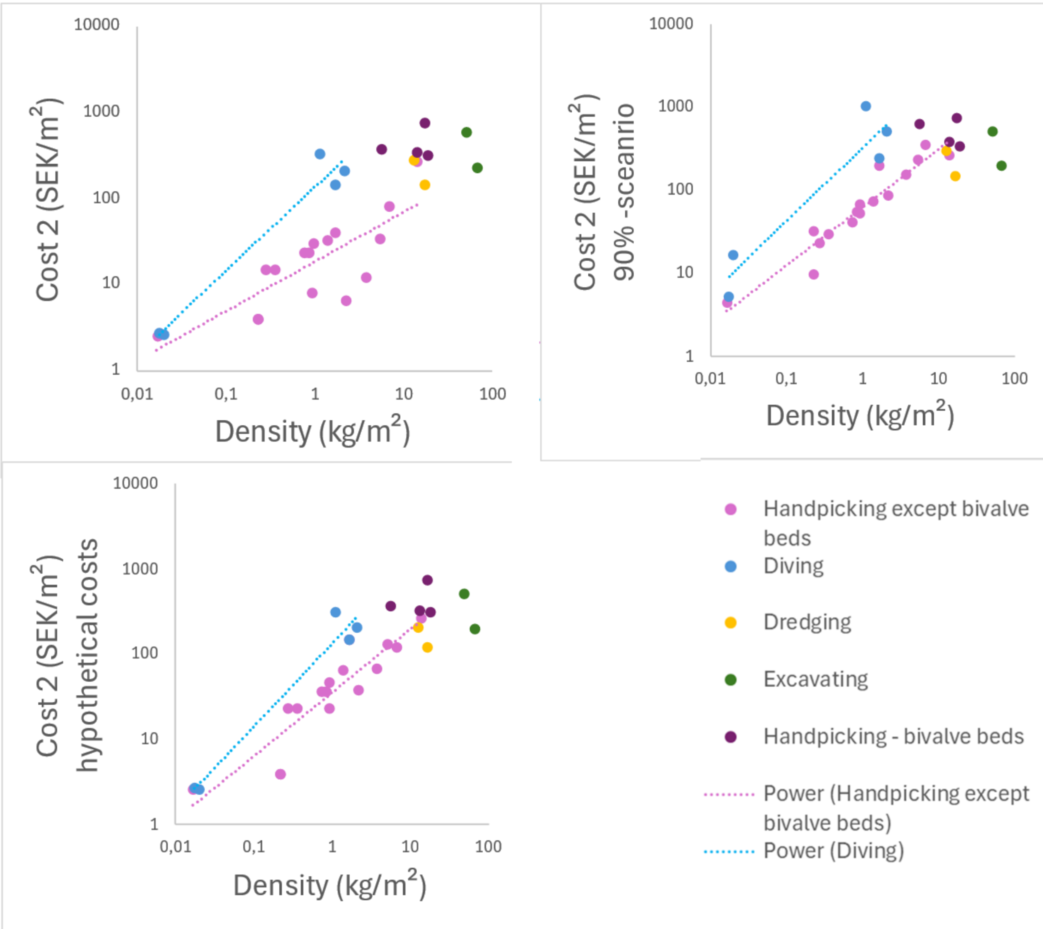

Figure 32 Relation between cost-efficiency indicator 2(SEK/m²) and oyster density between clearing methods and for three scenarios (real costs, hypothetical costs and hypothetical costs for 90%-clearance proportion). (Note: log:log-scale).

Table 7 Linear regression analysis of the log-transformed data on clearing efficiency (a and b refer to the linear function) and the corresponding power function for untransformed data

Scenario	Method	N	R^2	p-value	a	b	Power function
1	Handpicking	16	0.62	<0.01	1.26	0.58	$y = 18{,}395x^{0{,}5759}$
	Diving	5	0.96	<0.01	2.13	0.97	$y = 135{,}78x^{0{,}9738}$
2	Handpicking	16	0.82	<0.01	1.55	0.75	$y = 35{,}745x^{0{,}747}$
	Diving	5	0.96	<0.01	2.13	0.97	$y = 134{,}32x^{0{,}9715}$
3	Handpicking	16	0.91	<0.01	1.80	0.70	$y = 62{,}936x^{0{,}7042}$
	Diving	5	0.89	0.02	2.52	0.88	$y = 328{,}73x^{0{,}8816}$

Again, handpicking was found to be cheaper than diving which has higher fixed costs to begin with (visible by the higher intercept of the diving function, Table 7). The handpicking functions displayed a steeper slope in scenario 2 and 3 than in scenario 1, indicating a higher cost increase with increasing density. No interception of the diving and handpicking trendlines was visible within the data range, meaning that diving was consistently more expensive than handpicking regardless of density.

The difference in cost-efficiency between the three scenarios (actual costs with different clearing achieved, hypothetical costs based on hourly compensation, and hypothetical costs recalculated to 90% clearing) is illustrated in Figure 33.

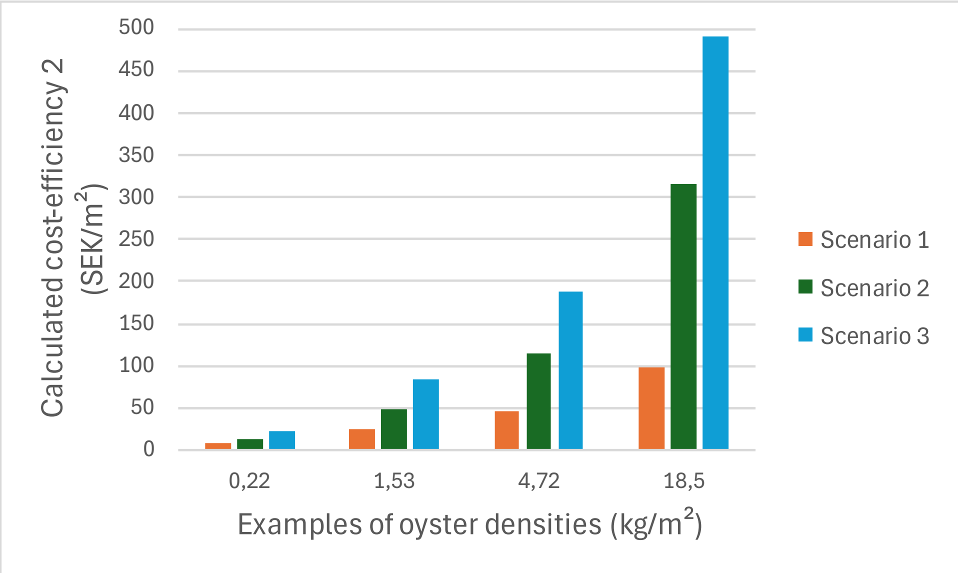

Figure 33 Cost-efficiencies 2 (SEK/m²) calculated from scenario 1-3 functions.

Using the upper and lower 95% confidence interval (best case lower 95% intercept and slope, worst case upper 95% intercept and slope) in the developed regressions provides an estimation of the uncertainties in the data (Figure 34). At e.g. PO density 20 kg/m² and 335.0 SEK/m², a cost range of -202.3 SEK/m² to +510.3 SEK/m² can be inferred, i.e. for clearing a 100 m² site with 20 kg/m², costs could range between 13,276 SEK and 84,537 SEK.

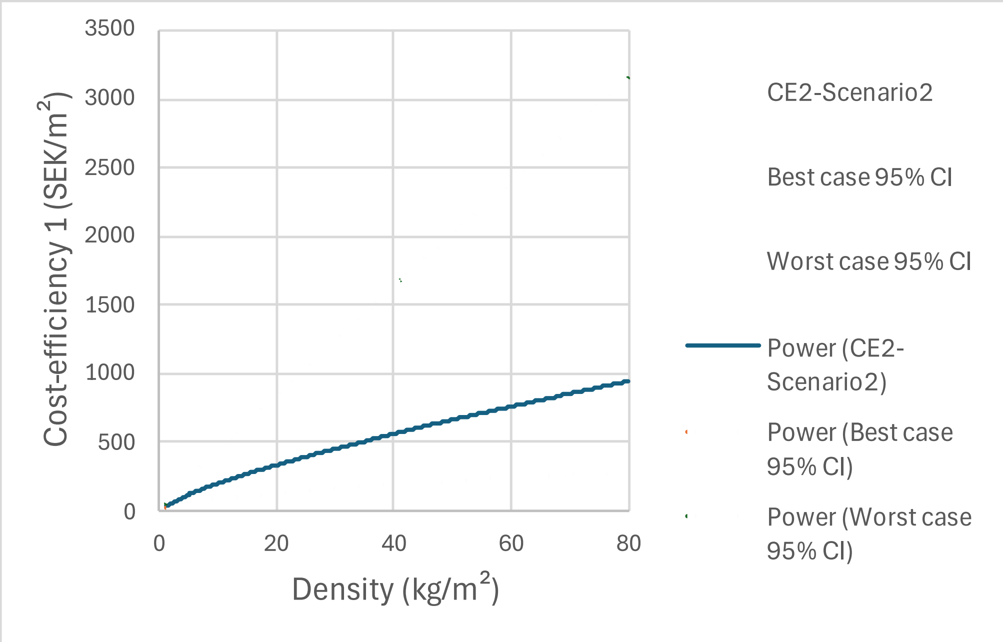

Figure 34 Cost-efficiency function, compared to best-case and worst-case 95% confidence interval functions. Note: log:log scale.

Again under the assumption that the handpicking functions can accurately describe the cost-efficiency also at higher PO densities than evaluated in the actual trials, extrapolated hypothetical costs for handpicking at high-density sites similar to excavating sites (average density of 58.7 kg/m²) were found to range between 238.7 SEK/m² and 2349.0 SEK/m² (average ± 95% CI). In comparison, excavating at a density of 67.2 kg/m² was estimated to cost 202.7 SEK/m², and 523.9 SEK/m² at a density of 50.2 kg/m². At sites similar to dredging sites (average density of 14.7 kg/m²), handpicking costs were found to range between 112.4 SEK/m² and 633.0 SEK/m² (average ± 95% CI) in comparison to dredging costs of 213.6 SEK/kg (density 12.7 kg/m²) and 123.6 SEK/kg (density 16.7 kg/m²).

Excluded additional costs

Appendix 8 provides an overview of costs that were not included in the evaluation but that should be taken into account when planning future oyster clearings.

4 Discussion

This thesis set out to explore how marine ES along the Swedish west coast are affected by the invasive PO in relation to habitat complexity and substrate type. Differences in cost-efficiency of clearing activities between methods were investigated with the goal of describing the combined implications of the mapping of impacts on ES and the cost-efficiency analysis for future PO management in Sweden. It was found that soft substrates were impacted more than hard substrates, although primarily positively in terms of number of positively impacted indicators, and that reef formations had the strongest impacts. Large knowledge gaps about PO on hard substrates and in varying densities were also found. Both clearing- and cost efficiency of clearing activities were impacted by oyster density rather than by substrate. For weight-dependent indicators, increasing oyster density had a positive effect, allowing more kg of oysters to be picked per working hour and at a lower cost. Area-dependent indicators were affected negatively by increasing density, decreasing the area that could be cleared per working hour and at a higher cost. Although the different methods were applied at different oyster densities, extrapolations of hand-picking data indicated that large-scale mechanical methods are more cost-efficient at high PO densities.

4.1 Context-dependent impacts of Pacific oysters on ecosystem services

In this study, impacts of PO on ES were found to be affected by both oyster-mediated habitat complexity and substrate type. Previous studies have observed stronger impacts (both positive and negative) on soft substrates than on hard-bottom substrates (Ruesink et al., 2005; Lejart & Hily, 2011; Laugen et al., 2016; Mortensen et al., 2017) and from oyster reefs rather than from solitary oysters (Green & Crowe, 2014; Mortensen et al., 2017). This is in accordance with the results of this study, where positive (or supposedly positive) impacts of oysters on ES were found more frequently on soft than on hard-bottom substrate while the numbers of negative and supposedly negative impacts were the same for both habitats. The higher number of benefits of PO on soft substrates was partly found to be a consequence of the easier access to provisioning services such as food, raw material, chemical and ornamental resources as the oysters are easier to harvest than oysters attached to hard substrate. Some of the indicators that were classified as positive on soft bottoms were also not applicable to hard bottoms, e.g. sediment retention and the abundance of infauna, hence further enforcing the differences in observed impacts. Consequently, the observation of higher benefits on soft substrates compared to on hard substrates may be biased by an overrepresentation of soft-substrate indicators which were classified as not applicable on hard substrates. It is not surprising that the ES framework (Millenium Ecosystem assessment, 2003) has a greater emphasis on indicators for soft substrates as most of the habitats covered by the EU Habitats Directive while also being relevant in Sweden are soft-bottom habitats. Moreover, the analysis also revealed uncertainties in terms of classification of impacts as positive or negative, which was especially true for the impacts on different habitats and changes in species composition of infauna and epifauna and the expected shift to larger zooplankton. Such impacts may be considered both positive as well as negative depending on context and perception of the evaluator. Knowledge gaps about the impacts of PO on hard-bottom substrate were also identified, causing more impacts to be classified as “not known”. Finally, some indicators were found to reoccur in several ES descriptors which may distort the overall picture of effects of PO on ES. However, excluding the indicators after the first use would also infer errors, especially as the impacts on indicators were assessed in relation to the ES and in some cases classified differently under different ES. An alternative framework that better encompasses both services and disservices (in contrast to the ES concept that only addresses services) is the Nature’s contributions to people framework (Diaz et al., 2018).

The literature on density-dependent effects of Pacific oysters was found to be limited to primarily the effects on eelgrass, biodiversity and habitats, with e.g. exponential decreases in eelgrass density and growth from 20% oyster cover (Kelly & Volpe, 2007; Wagner et al., 2012). Biodiversity on the other hand seemed to be impacted positively by higher PO densities, especially in comparison to formerly bare bottoms (Green & Crowe, 2014, Norling et al. 2015) although high densities are also associated to a shift in community structure from soft substrate to hard substrate communities and therefore a risk of taxonomic and habitat homogenisation (Markert et al., 2009; Herbert et al., 2016; Lejart & Hily, 2011). Habitat changes, increased 3D structures and an increased filtering explain why higher PO densities – especially reef structures in comparison to solitary oysters and clusters – will have higher impacts on ES. With regards to management, PO impacts on ES turned out to be rather ambiguous (higher impacts are to be expected on formerly soft bottoms and for reef formations, but those include both positive and negative impacts), therefore no clear prioritisations for oyster clearings based on either substrate or habitat complexity were identified. Consequently, instead of a focus on substrate and PO density for management action selection, the conservation of sites with high/special nature values should be prioritised for mitigation of PO (as implemented in Norway, Oslofjordens Friluftsråd, 2023). These could be e.g. bivalve- (Strand et al., 2023) or eelgrass beds, although for both habitats PO impacts, occurrence of intermix, and impacts of mitigation measures seem ambiguous (Kelly & Volpe, 2007; Wagner et al., 2012; Bengtsson Kupcik, 2017; Strand et al., 2023) and more research is needed to fully understand the implications of PO on these perspectives.

In terms of provisioning, positive PO impacts derived mainly from post-harvest uses, so provisioning ES would potentially benefit from oyster clearings on soft substrates. On hard substrates, provisioning services were found to be limited due to the difficulty to remove oysters from the substrate. In fact, the only references found that mentioned clearing activities on hard substrates referred to the use of manual destruction as a method (Guy & Roberts, 2010; McKnight & Chudleigh, 2015). It is, however, important to keep in mind that the removal and use of PO as a resource might counteract any positive impacts on ES and will prevent future impacts on ES. An example is the use of oysters in animal feed which leads to feedback of nutrients into the nutrient cycle and a loss of achieved carbon sequestration effects (van der Schatte Olivier et al., 2020), although the removal of nutrients from the sea and feedback to a land-based nutrient cycle may still be considered a benefit. This relates to the question if mere "non-nativeness" can justify management measures (Shakspeare et al., 2024) and there are suggestions to manage (rather than act against) novel ecosystems (Hobbs et al., 2006; Truitt et al., 2015).

Cultural services were found to be impacted both positively and negatively by PO occurrence. In agreement with the provisioning services results, business owners identified income opportunities in relation to PO occurrences in the survey addressed to businesses. However, both business owners and private individuals also identified a range of negative impacts, with impacts on recreation (cut risk) being the most prominent. A relation between observed PO occurrence and perceived impacts on activities was found, however, the cause-relation between the two aspects is unclear. It is plausible that in areas with high oyster occurrence, people feel more affected, but it is also possible that respondents who already felt affected tended to observe PO more often (perception bias (Oxford Reference, n.d.)). Nevertheless, some respondents still felt affected by PO even when they had not observed them in their area, indicating that attitudes towards the oysters can also be impacted by e.g. representation in the media or by PO being perceived as a symbol of greater environmental changes. In a previous survey among municipality representatives, the knowledge level about Pacific oysters was classified as low to medium (Roesch, 2023). In the survey to the public, it became obvious (especially from the positive responses; examples include mentioning of the provision of hard substrate, filtration and positive effects on biodiversity) that some of the respondents had a high information level about Pacific oysters. A much greater share of respondents, however, showed misconceptions about PO, most commonly that the disappearance of blue mussels and flat oysters are unquestionably linked to PO occurrence and competition. In accordance with the municipality survey, the findings from the public survey show that there is a lack of objective, up-to date information around the positive impacts of PO which contributes to the commonly negatively perceived impacts (Roesch, 2023). More nuanced information about the PO's ecological role and exploitation potential is needed and should therefore be a priority in any information campaign.

During the attempt to map the cultural ES impacts of PO in a public survey, the survey was distributed among associations specialised in one specific activity and among the public through social media. It is important to consider that a pre-selection of potential respondents (individuals that felt affected by PO in some way) was made (thus inferring a risk of selection bias), to fulfil the purpose of recording as many impacts as possible. As the purpose of the survey was to map the actual perceived impacts and not necessarily the distribution between positive and negative impacts, the approach is still valid. The success of this approach was also confirmed by the performed power analysis, indicating that enough answers were obtained to ensure coverage of most perceived impacts.

4.2 Clearing- and cost-efficiency of oyster removal

As expected, oyster density impacted both PO clearing- and cost-efficiency. With increasing oyster density, it took longer to clear an area of oysters but at the same time the oysters were situated closer together and often clustered at higher densities, hence becoming more practical to pick. Consequently, the area-based efficiency (m^2 cleared/h) and weight-based costs (SEK/kg harvested oysters) decreased, while the density-based efficiency (kg harvested/h) and area-based costs (SEK/m^2 cleared) increased (because of higher labour requirements per area unit cleared), with increasing oyster density. Considering a potential commercialisation of oyster clearings, clearing at high densities hence provides greater commercialisation potential due to lower per kg harvest costs. However, currently, solitary (low density) oysters aimed at the high-end market obtain a higher price and are easier to market compared to oversized and cluster oysters (Marinho et al., 2022; Nielsen et al., 2022), which constitutes the majority of the product in high-density site harvest. In the future, this may change as oysters as a product (both the shells and the meat) may be considered for a range of uses (Nyqvist, 2022; Linder, 2022).

In contrast, substrate did not affect clearing- or cost-efficiency. This was surprising as substrate will impact accessibility of the oysters (i.e. if it is possible to walk on the substrate or not in shallow areas, or if snorkelling is required) and how/if the oysters can easily be removed from the site (oysters on hard substrates must be smashed or chiselled away). In this study, records of hard substrate clearings were only obtained from low-density sites (highest oyster density 6.7 kg/m^2, with 30.0% clearance proportion) compared to the soft substrates (highest oyster density 18.6 kg/m^2). Future studies should therefore focus on obtaining data from high-density, hard substrates to further evaluate this perspective. Difficulties in removing the oysters from hard substrate may have been partially compensated for by the use of appropriate equipment, the additional fixed costs of which are very low (30.3 SEK/clearing) and therefore didn't change the cost-efficiency analysis results.

PO clearing-efficiency and cost-efficiency were, however, found to vary between methods. Evaluated methods in this study were handpicking (or smashing on hard substrates), which is also most commonly mentioned in the literature (Guy & Roberts, 2010; McKnight & Chudleigh, 2015; Herbert et al., 2016; Hansen et al., 2023) and mechanical removal, similar to experiments which have been conducted in Denmark (Nielsen et al., 2022). Diving was more efficient than handpicking in terms of the amount of oysters harvested per time unit (kg/h), while the two methods were very similar in terms of the area cleared per time unit (m^2/h). At the same time, diving costs (both SEK/kg and SEK/m^2) were higher than for handpicking. For dredging and excavating the data was very limited (two sites each), hence the results only allow for limited extrapolation and generalization. At high densities, dredging and excavating seemed, however, more efficient than extrapolated handpicking in terms of both cleared area per unit time (m^2/h) and cleared amount per unit time (kg/h). Dredging and excavating were also cheaper in terms of costs (SEK/kg harvested oysters) than the extrapolated cost-range from the handpicking functions (assuming labour costs).

The high variation of the extrapolated handpicking costs made it hard to compare the costs to the mechanical removal costs, and generalisations should therefore be done with caution. In order to narrow down the cost interval and allow for more reliable cost estimations for future clearings as well as a confident comparison between methods, more handpicking would need to be performed, especially in high oyster-density sites. Similarly, more data is needed on dredging and excavating efficiencies and costs. The function model for handpicking should also be verified by comparing it with data from other sites, where density, size of the area, cleared amount of oysters (kg) and actual costs are known. As mentioned, the linear extrapolations to the 90%-clearance target present a simplification that should be considered. Once refined and verified, the cost-functions could be used to calculate the break-even point for commercial oyster clearing/ harvesting. For that, more data on processing costs and post-harvest use revenues is also needed. Finally, it would be interesting to extend the comparison of cost-efficiency to other experimental methods that haven't been tried in Sweden yet.

Despite all aforementioned uncertainties, it seems like dredging and excavating do present efficient and cost-efficient alternatives to handpicking PO in high-density sites. In terms of environmental effects, the impacts of mechanical methods on light attenuation were observed to be negligible in this study (but see below), but excavating showed long-term effects in terms of sediment traces and other potential environmental impacts in concurrence with results by Herbert et al. (2016), Nielsen et al. (2022) and Hansen et al. (2023). At the same time, some problems in the analysis of the light logger data occurred, including unlogged periods for various reasons. During one activity the on-site logger had to be removed during the excavating but was redeployed directly after the excavating stopped which limited the possibility to detect short-lived impacts. The surrounding light loggers, however, did not record any major deviations in light attenuation during the clearing activity, again confirming the local range of impacts. The other excavating activity took place partly after nightfall which thwarted the attempt of measuring impacts on light attenuation. Consequently, more efforts should go into exploring environmental impacts of excavating as a clearing method.

4.3 Combined implications for PO management

As shown in this thesis, the impacts of PO are both positive and negative, and the magnitude of the impacts are context-dependent, complicating decisions about mitigation actions. Due to the PO's advanced stage of invasion in the northern part of the Swedish west coast, it would be inappropriate to set eradication as a management target (Hansen et al., 2023), instead, established populations call for targeted local management to mitigate negative impacts (Geburzi & McCarthy, 2018).

As proposed, site selection could be based on prioritising the conservation of sites with high/special nature values (see 4.1) or focus on recreational aspects, with a prioritisation of popular swimming areas as is done in Norway (Asker kommune, 2023; Oslofjordens Friluftsråd, 2023). The mapping of ES in this study did not weigh indicators against each other or quantify the potential PO impacts. It is possible to apply such an approach, however, this requires significant integration of stakeholders in a co-creation process where different perspectives and priorities from different stakeholder groups can be integrated into a consensus decision about what impacts to prioritise. A useful tool for quantifying and valuing said impacts would also be a cost-benefit analysis, including economic valuation of impacted ES, which would also allow for a site-dependent prioritisation in terms of management actions.

In terms of clearing method selection, site conditions need to be considered. As evident from the data, different methods were selected for different conditions with handpicking and diving covering similar oyster densities, followed by dredging at higher densities and finally excavating at reef formations. Other factors than oyster density may also impact method selection, e.g. depth, which allows wading down to 1.5 m, snorkelling down to 3-4 m depth, dredging being limited to deeper water (>1 m) as a boat is required, and excavating to the shallowest areas where the reef formations are mainly found (0.5 m, pers. observation Å. Strand) but also to high water levels to allow the working barge to approach the site. For deeper reef sites the excavator is limited by the depth range of the shovel. This illustrates that clearing method selection can be partially efficiency-based, but also depends on site-specific conditions like density, substrate and depth. The cost-efficiency analysis shows that e.g. dredging and excavating could be promising clearing methods in high density sites, but all clearing methods are accompanied by costs that should not be underestimated. At the same time, mentioned positive impacts like the private and commercial interest in harvesting PO present an opportunity that can, and should, be utilised, as this could help in reaching cost-efficiency of clearing actions (see 4.2, Herbert et al., 2016; Hjalager et al., 2018; Hansen et al., 2023). To ensure food safety, monitoring of selected areas for PO harvest may be required. The cost-efficiency of performing monitoring to enable low-cost, publicly or privately driven mitigation (clearing) activities in comparison to governmentally funded mitigation actions (where funding is typically a limiting factor) should therefore be evaluated.

It was noted that handpicking of PO on blue mussel beds was very time-consuming due to the time required to remove mussels attached to the oysters. This illustrates two aspects of special notion; 1. that targeting specific valuable habitats for management (as suggested above) may result in higher costs and/or reduced efficiency compared to harvest for commercial purposes due to a greater need for caution during the clearing action, and 2. that commercial harvest should be directed towards sites with low intermix of other valuable species, unless efficient measures for species separation (like a sorting drum, Nielsen et al., 2022) can be developed.

Apart from that, there is a need for further investigation of long-term effects of oyster clearings regardless of clearing method. As shown in this thesis, PO fulfil various ES functions, so impacts both deriving from the actual clearing activity but also from the loss of PO from the ecosystem and associated impacts on e.g. organic content in the sediment, infauna and epifauna diversity, recolonisation and return to former state should be examined (as partly done in Nielsen et al., 2022). Furthermore, the need for, and impacts of, repeated clearing (Herbert et al., 2016; Oslofjordens Friluftsråd, 2023) should be evaluated.

This thesis was limited to analysing clearing activities in established oyster populations but for a creation of comprehensive management strategies, it would be highly beneficial to extend the analysis to management measures in earlier invasion stages and containment of further invasion should be taken into consideration (Guy & Roberts, 2010). Previous research has found that especially consolidated (hard natural and artificial) substrates, and marinas in particular, can act as stepping stones for PO invasion (Hedensjö, 2024) which indicates that handpicking in hard-bottom, currently low-density, areas could help in containing a further spread to soft-bottom habitats. Combined with the knowledge of habitat preferences and the mapping of source and sink populations (Laugen et al., 2016), the implications of oyster-mediated habitat complexity and substrate effects allow for better site selection for effective management. For that, the evaluation of management methods should be extended to sites with earlier invasion stages. Education, public awareness and good monitoring practice are additional key components of a PO management strategy (Hansen et al., 2023, Palmqvist 2023).

Moreover, the findings of this thesis open a wide variety of research opportunities and questions to investigate further (Figure 35).

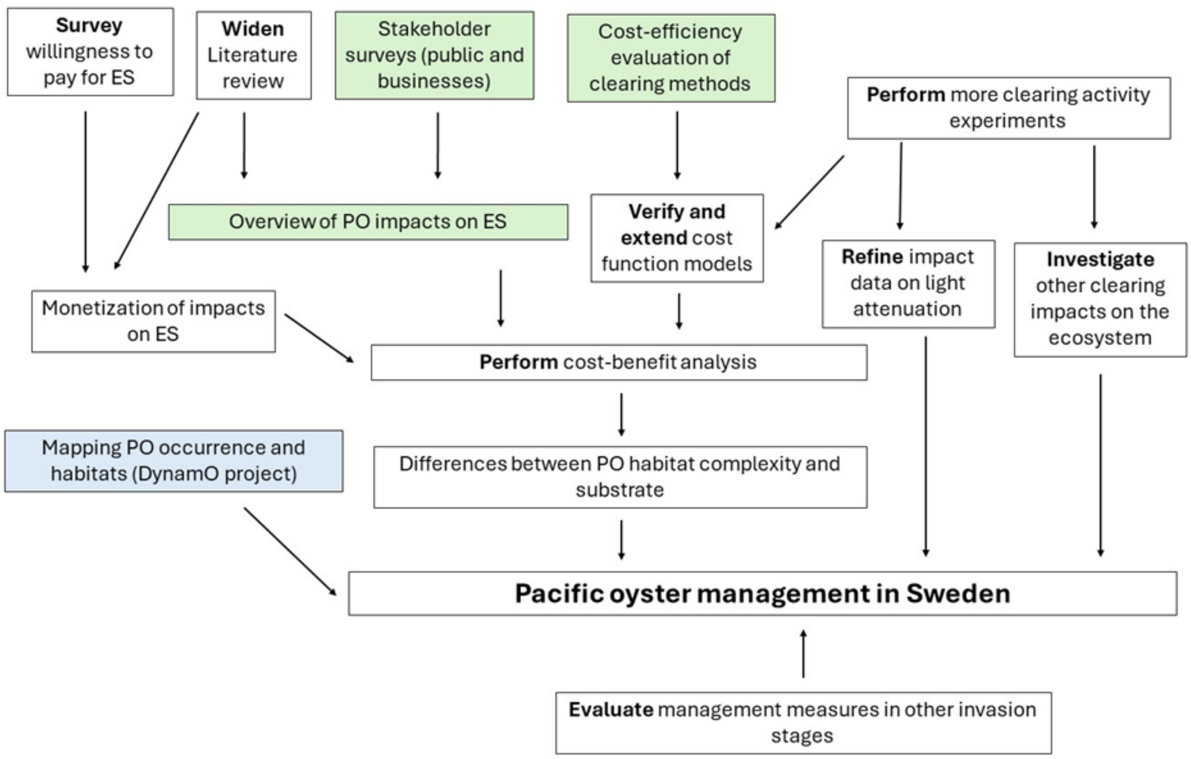

Figure 35 Overview of further research and refining opportunities. Fully performed analyses from this thesis are marked green, existing analyses from other sources blue. The white boxes show research potential.

Research opportunities range from refining and complimenting the existing results of the cost-model functions and ecosystem impacts of oyster clearing to integrating the findings into a cost-benefit analysis and looking into commercial viability of oyster clearings using business models. Cost-benefit work should include both a quantification and monetization of PO impacts on ES. Willingness to pay for shell-free beaches could be explored as recreational impacts were identified as the main cause of problems to private individuals.

5 Conclusion

This project provided a systematic overview of the impacts of PO as an invasive species on its "host ecosystem" services. It was shown that PO have both positive and negative impacts which brought up the question if mere "non-nativeness" can be used as an argument for management interventions. Instead, the systematic overview of both the ES and their linkages can aid in quantifying PO impacts for site-to-site management decisions. The surveys on perceived PO impacts by both the public and businesses built knowledge around the less investigated cultural and economic effects of PO, identifying impacts on recreation (cut risk) as the main cause for perceived negative impacts but also revealing ways in which both the public and businesses may benefit from PO occurrence. Moreover, the cost-efficiency analysis presents a first attempt of an economic evaluation of different clearing methods and provides valuable insights into density and method impacts on cost-efficiency. A variety of questions still need to be explored before efficient management of mixed impact invasive alien species can be achieved through a dynamic management approach including both nature management, societal-, as well as commercial interests. Nevertheless, the results in this thesis have clarified some questions, while raising others, and given enough commitment, there are possibilities to achieve management for the benefit of both nature and society ahead.

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Appendices

Appendix 1 Descriptors that were excluded from the ecosystem service table for obvious irrelevance

Ecosystem service	Descriptor
S 1 Biogeochemical cycling	Ice propagation Salinity
S 3 Food web dynamics	Sea eagle Seals
S 5 Habitats	1180 submarine structures made by leaking gases 1650 Boreal Baltic narrow inlets 8330 Submerged or partially submerged caves

Appendix 2 Survey questions- Public survey

Stillahavsostron har spridit sig till stora delar av den svenska västkusten. Som en invasiv art har de olika positiva och negativa effekter på ekosystemet men också på människorna som bor eller tillbringar sin fritid vid kusten. Med den här korta enkäten vill vi ta reda på din personliga uppfattning om stillahavsostron. Undersökningen består av 4 frågor och kommer att ta cirka 4 minuter att besvara. Ditt svar kommer att bidra till en masteruppsats vid Göteborgs universitet och DynamO-projektet, som är ett projektsamarbete mellan IVL Svenska Miljöinstitutet, Göteborgs universitet, KTH Kungliga Tekniska Högskolan och Universitetet i Agder om dynamisk förvaltning av stillahavsostronet. Alla uppgifter samlas in anonymt, de kan inte hänföras till dig personligen. Tack för din tid!

***

Pacific oysters have spread successfully to large parts of the Swedish West Coast. As an invasive species, they have various positive and negative effects on the ecosystem but also on people living or spending their leisure time by the coast. With this short survey, we would like to find out your personal perception of Pacific oysters. The survey consists of 4 questions and will take about 4 minutes to answer. Your answer will contribute to a master thesis at the University of Gothenburg and the DynamO project, which is a project collaboration between IVL Swedish Environmental Institute, University of Gothenburg, KTH Royal Institute of Technology and University of Agder on dynamic management of the Pacific oyster. All data is collected anonymously, it cannot be attributed to you personally. Thank you for your time!

Question 1: Vilken aktivitet är din huvudsakliga användning av kustområdet? Välj endast ett alternativ och besvara enkäten i enlighet med detta; du kan också fylla i enkäten flera gånger för olika användningsområden.

What activity is your main use of the coastal area? Please choose only one option and answer the survey accordingly; if applicable, you can fill in the survey several times for different uses.

[*multiple choice – only one box could be ticked*]

- Fritidsbåtliv (omfattar t.ex. användning av marinor, naturhamnar) *** Leisure boating (includes e.g. use of marinas, natural harbours)
- Kajak- och stand-up paddling *** Kayaking and Stand-up paddling
- Snorkling *** Snorkelling
- (Vind)surfing / kitesurfing *** (Wind)surfing / kitesurfing
- Fritidsfiske *** Recreational fishing
- Fågelskådning *** Birdwatching
- Strandgäst (simning, etc.) *** Beachguest (swimming, etc.)
- Vandring/promenader längs kusten *** Hiking/walks along the shoreline
- Other:

Information about Pacific oysters

Hur man skiljer mellan europeiska platta ostron och stillahavsostron

Det europeiska ostronet hör hemma på den svenska västkusten och är vanligtvis rundare och plattare. Stillahavsostron brukar vara större, avlångt formade och växer ofta i kluster. Denna undersökning behandlar endast stillahavsostron.

***

How to distinguish between European flat oysters and Pacific oysters

The European oyster is native to the Swedish west coast, it is typically rounder and flat. Pacific oysters tend to be bigger, are oblong-shaped and often grow in clusters. This survey deals only with Pacific oysters.

Question 2: Finns det ostron i området som du använder för din havsbaserade aktivitet?

Are there any oysters in the area that you're using for your marine-related activity?

- Ja / Yes
- Nej / No
- Jag vet inte / I don't know

Question 3: Känner du dig på något sätt (positivt eller negativt) påverkad av förekomsten av stillahavsostron när du utför din aktivitet?

Det är möjligt att vara såväl positivt som negativt påverkad.

***

Do you feel affected by the occurrence of Pacific oysters in any way (positively or negatively) when you perform your activity?

It is possible to be both positively and negatively affected.

[*checkboxes: several boxes could be ticked*]

- Ja, positivt påverkad / Yes, positively affected
- Ja, negativt påverkad / Yes, negatively affected
- Nej / No
- Jag vet inte / I don't know

Question 4: Om du har svarat ja (positivt eller negativt), beskriv gärna på vilket sätt du känner dig påverkad.

If you answered yes (positively or negatively), please describe in what way you feel affected.

[*Long-answer text, open question]*

Appendix 3 Survey questions- Business survey

Stillahavsostron har spridit sig till stora delar av den svenska västkusten. Som en invasiv art har de olika positiva och negativa effekter på ekosystemet men också på människorna som bor eller tillbringar sin fritid vid kusten. Med den här korta enkäten vill vi ta reda på din uppfattning som verksamhetsansvarig om stillahavsostron . Undersökningen består av 7 frågor och kommer att ta cirka 6-7 minuter att besvara. Ditt svar kommer att bidra till en masteruppsats vid Göteborgs universitet och DynamO-projektet, som är ett projektsamarbete mellan IVL Svenska Miljöinstitutet, Göteborgs universitet, KTH Kungliga Tekniska Högskolan och Universitetet i Agder om dynamisk förvaltning av stillahavsostronet. Alla uppgifter samlas in anonymt, de kan inte hänföras till dig personligen. Tack för din tid!

***

Pacific oysters have spread successfully to large parts of the Swedish West Coast. As an invasive species, they have various positive and negative effects on the ecosystem but also on people living or spending their leisure time by the coast. With this short survey, we would like to find out your perception of Pacific oysters as a business owner/operator. The survey consists of 7 questions and will take about 6-7 minutes to answer. Your answer will contribute to a master thesis at the University of Gothenburg and the DynamO project, which is a project collaboration between IVL Swedish Environmental Institute, University of Gothenburg, KTH Royal Institute of Technology and University of Agder on dynamic management of the Pacific oyster. All data is collected anonymously, it cannot be attributed to you personally. Thank you for your time!

Question 1: Vilket är ditt verksamhetsområde? Välj endast ett alternativ och besvara enkäten i enlighet med detta; du kan också fylla i enkäten flera gånger för olika användningsområden.

What is your area of business? Please choose only one option and answer the survey accordingly; if applicable, you can fill in the survey several times for different uses.

- Ägare/verksamhetsansvarig av en hamn/marina *** Owner/operator of dock/marina
- Ägare/verksamhetsansvarig av en campingplats *** Owner/operator of a camping site
- Företag inom fritidsturism *** Recreational tourism business
- Kommersiellt fiske *** Commercial fishing business
- Ostronindustrin *** Oyster industry business
- Företag inom vattenbruk *** other type of aquaculture/mariculture
- Förening *** association
- Vetenskap och utbildning *** Science and education
- Other:

Question 2: Om du har svarat "företag inom fritidsturism" eller "förening", ange gärna mer information om de erbjudna aktiviteter här.

Om du har svarat "företag inom vattenbruk", ange gärna vilka arter som odlas här.

***

If you answered "recreational tourism business" or "association", feel free to specify your offered activities here.

If you answered "aquaculture business", feel free to specify your cultivated species here.

[*open question, short-answer text*]

Information about Pacific oysters

Hur man skiljer mellan europeiska platta ostron och stillahavsostron

Det europeiska ostronet hör hemma på den svenska västkusten och är vanligtvis rundare och plattare. Stillahavsostron brukar vara större, avlångt formade och växer ofta i kluster. Denna undersökning behandlar endast stillahavsostron.

***

How to distinguish between European flat oysters and Pacific oysters

The European oyster is native to the Swedish west coast, it is typically rounder and flat. Pacific oysters tend to be bigger, are oblong-shaped and often grow in clusters. This survey deals only with Pacific oysters.

Question 3: Finns det ostron på din egendom/ i området som du använder för din verksamhet?

Are there any oysters on your property/ in the area that you're using for your business?

- Ja / Yes
- Nej / No
- Jag vet inte / I don’t know

Question 4: Känner du eller dina gäster sig på något sätt (positivt eller negativt) påverkad av förekomsten av stillahavsostron ?

Det är möjligt att vara såväl positivt som negativt påverkad.

***

Do you or your guest feel affected by the occurrence of Pacific oysters in any way (positively or negatively)?

It is possible to be both positively and negatively affected.

[*checkboxes: several boxes could be ticked*]

- Ja, positivt påverkad / Yes, positively affected
- Ja, negativt påverkad / Yes, negatively affected
- Nej / No
- Jag vet inte / I don't know

Question 5: Om du har svarat ja (positivt eller negativt), beskriv gärna på vilket sätt du eller dina gäster känner sig påverkad.

If you answered yes (positively or negatively), please describe in what way you or your guests feel affected.

[*open question, long-answer text*]

Question 6: Om du har svarat ja, upplever du särskilda positiva eller negativa **ekonomiska** effekter av ostronen på ditt företag?

If you answered yes, do you experience any particular positive or negative **economic** impacts of the oysters on your business?

- Ja / Yes
- Nej / No
- Jag vet inte / I don’t know

Question 7: Om du har svarat ja, kan du uppskatta den ekonomiska effekten (i monetära termer) och beskriva varifrån de extra intäkterna eller kostnaderna härrör?

If you answered yes, can you please estimate the economic impact (in monetary terms) and describe how the additional revenues or costs are derived?

[*open question, long-answer text*]

Appendix 4 Structure of response categorization

Positive/Negative

- Main category
    - Subcategory
        - impact

Negative

- Negative ecosystem impacts
    - Unspecified
    - Substrate modification
    - Negative impacts on biodiversity
        - Disappearance of blue mussels
        - Disappearance of European flat oysters
        - Disappearance of other species
        - Appearance of other unwanted species
- Negative impacts on recreation
    - Unspecified
    - Limited access to/use of beaches
        - Unspecified
        - Risk of cuts
    - Space and waterways
    - Impacts on recreational equipment
        - Unspecified
        - Material destruction
        - Biofouling
- Negative economic impacts
    - Unspecified
    - Loss of income
- Negative cultural impacts
    - Unspecified
    - Loss of traditions
        - Unspecified
        - Loss of blue mussel traditions
- Negative emotional response
    - Unspecified
    - Omnipresence is considered a nuisance
    - Aesthetically displeasing/cluttering
    - Change of (archipelago) environment / coastline/ landscape compared to former status
    - Knowledge/ concern about invasive species
        - unspecified
        - Viewed as cause for environmental destruction
        - Viewed as indicator of negative environmental changes

Positive

- Positive ecosystem impacts
    - Unspecified
    - Reef formation / provision of substrate

  - Positive impacts on biodiversity
    - Unspecified
    - Food resource for birds and other wildlife
    - Positively associated with other species
  - Positive impacts on man-made problems
    - Mitigation of ocean acidification
    - Filtering
    - Nutrient uptake
- Positive impacts on recreation?
  - Unspecified
  - Oyster picking as a food resource
- Positive economic impacts
  - Provisioning/Resource (unspecified)
  - Feed resource
  - Source of income
- Positive cultural impacts
  - Unspecified
  - Replacement of traditions
    - Unspecified
    - Replacement of blue mussel traditions
  - Ornamental resource
- Positive emotional response
  - Unspecified
  - Aesthetically pleasing
  - Indicator of life in the sea

Appendix 5 Instructions for oyster survey and clearing at Getevik, March 2023

Instruktioner för bortrensning av stillahavsostron

Syftet med aktiviteten är att genomföra en rensningsaktivitet för att ta bort stillahavsostron från en lokal där ostronen etablerat sig. Arbetet är kopplat mot DynamO projektet, https://www.ivl.se/projektwebbar/dynamo.html.

Ansvarig för arbetet är Ane T. Laugen, UiA (ane.t.laugen@uia.no) och Åsa Strand, IVL Svenska Miljöinstitutet (asa.strand@ivl.se).

I arbetet ska endast stillahavsostron tas upp, inte det inhemska platta ostronet (*Ostrea edulis*). Det europeiska ostronet är vanligtvis cirkulärt och platt och har regelbundna, fina åsar på skalet. Stillahavsostron brukar vara större, avlångt formade eller droppformade, har ofta lila/bruna ränder på skalet, har stora vågor längs skalkanten och växer ofta i kluster.

Förinventering

- Mät upp en provruta om är 2 x 2 m med en tumstock och markera hörnen med pinnar.
- Placera en liten (0.25 x 0.25 m) provruta på 3 slumpmässigt utvalda platser inom rutan.
- Dokumentera alla levande och döda ostron i varje ruta:
  - räkna alla levande och döda ostron var för sig.
  - mät längd (från umbo till längsta skalkanten) på alla levande ostron inom en ruta med ett skjutmått, ange endast hela mm. Mät minst 100 levande individer. Tänk på att små ostron kan sitta på stora ostron. Om det inte finns 100 levande individer inom en ruta, fortsätt mäta längd på levande ostron också i nästa ruta.

- Lägg alla levande ostron i en lövkorg och alla skal/döda ostron i en annan lövkorg.
- Väg levande ostron för sig (inklusive lövkorgen) och döda för sig (inklusive lövkorgen) från varje ruta.
- Töm korgarna i anvisat uppsamlingskärl.

Rensning

- Notera hur många personer som deltar i rensningen (exklusive den som antecknar).
- Notera starttid för rensning.
- Börja plocka ostron i den stora rutan ni markerat med pinnarna. Börja längs med en sida i rutan och arbeta er framåt mot motstående sida. Försök hålla plockytan som en expanderande rektangel, om ni inte hinner klart med hela ytan kommer ni vara tvungna att mäta hur stor yta ni lyckats rensa.
- Lägg alla levande ostron i en lövkorg och alla skal/döda ostron i en annan lövkorg.
- Väg varje full lövkorg och töm den sedan i anvisat uppsamlingskärl. Notera vikten och om ostronen är levande eller döda.
- Fortsätt plocka tills ni får slut på tid eller ni har tömt hela rutan.
- Notera sluttid för rensning.
- Om ni inte lyckas tömma hela rutan, mät upp området ni har rensat med en tumstock och notera arean.
- Om ni lyckas tömma hela rutan och vill göra mer, ta ett nytt papper, märk upp en ny ruta och upprepa processen från förinventeringen.
- OBS. Skriv ner om ni tar en paus så att vi kan dra bort den tiden från den totala tiden.

Efterinventering

Eftersom uppdraget är att ta alla ostron i en specifik ruta behövs ingen efterinventering, det ska inte vara några ostron kvar i området ni rensat när ni är klara. Skriv en notering om att detta kriterie är uppfyllt.

Appendix 6 Overview of evaluated clearing sites

Site	Method	Substrate	Density (kg/m^2)
Naturiststranda på Kalvøya, Bærum 2023	Handpicking	Clay/mud	0,94
Snarøykilen, Bærum 2023	Handpicking	Clay/mud	5,26
Getevik, Lysekil 2024	Handpicking	clay/mud	14,00
Høvikstranda fra Veritas til Sarbuvollen, Bærum 2023	Handpicking	Hard	2,22
Kalvøya søndre del, Bærum 2023	Handpicking	Hard	6,67
Storøyodden sydøst, Bærum 2023	Handpicking	Hard	0,83
site A shallow, Hallands Väderö, 2022	Handpicking	Hard	0,02
Henie Onstad-området, Bærum 2023	Handpicking	Mixed	1,67
Kalvøya Lille og store badebukt, Bærum 2023	Handpicking	Mixed	1,39
Borøya, sørvestre deler, Bærum 2022	Handpicking	Mixed	3,75
Storøya badestrand, Bærum 2023	Handpicking	Mixed	0,75
Koksa, Bærum 2023	Handpicking	Mixed	0,36
Holtekilen, Bærum 2023	Handpicking	Mixed	0,93
Kadettangen, Bærum 2023	Handpicking	Mixed	0,28
Grebbestad 2, Tanum 2023	Handpicking	Mixed	0,22
Grebbestad 1, Tanum 2023	Handpicking	sand/fine gravel	0,22
Site 328A, Tjärnö, Strömstad 2018	Handpicking	sand/fine gravel	18,57
Site 115B, Tjärnö, Strömstad 2018	Handpicking	sand/fine gravel	5,60
Site 100 A, Tjärnö 2018	Handpicking	sand/fine gravel	17,12
Site Saltösund B, Tjärnö 2018	Handpicking	sand/fine gravel	13,65
Site 87 Kämpersvik, Grebbestad, 2018	Diving	sand/fine gravel	1,11
Site 89 Kämpersvik, Grebbestad, 2018	Diving	sand/fine gravel	2,09
Site 79 Kämpersvik, Grebbestad, 2018	Diving	sand/fine gravel	1,69
site A deep, Hallands Väderö, 2022	Diving	Hard	0,02
site A shallow **follow-up**, Hallands Väderö, 2022	Diving	Hard	0,02
Kollholmen, Strömstad 2023	Dredging	clay	16,72
Bofors camping, Strömstad 2023	Dredging	mud	12,77
Kurt/Rossö hamn, Strömstad 2023	Excavating	mud	67,23
Åsa/ Rossö östra, Strömstad 2023	Excavating	mud	50,18

Appendix 7 Cost overview table for handpicking

Based on dugnad reports by Asker kommune and personal communications Åsa Strand, Ingvild Tandberg, Alice Hedensjö.

Costs were calculated under the following assumptions: Number of personal equipment sets was estimated based on volunteer numbers, average 19 people. Gloves, knives and waders are needed for each volunteer, baskets can be shared by 2 people. 1 pair of water binoculars and 4 corner markings are sufficient per site. Hammer, chisel, hoes and digging bar are needed for hard-bottom sites only, shared by 4 people.

All values in SEK without VAT.

A1 Equipment - all sites						
Equipment	Price (SEK without VAT)	Lifetime	Estimated number of uses	Cost per unit and use	Amount needed	Total cost per use
Cut-protective gl	64,00	1 year / 10	10,00	6,40	19,00	121,60
Waders	616,00	2 years	30,00	20,53	19,00	390,13
Knife	99,00	1 year	15,00	6,60	19,00	125,40
Baskets	72,00	1 year	15,00	4,80	10,00	48,00
Water binocular	520,00	10 years	150,00	3,47	1,00	3,47
Corner marking	23,00	2 years	30,00	0,77	4,00	3,07
Garbage bags	4,00		one use		depends on amount	
					Total	**691,67**
A2 Additional equipment for hard-bottom sites						
Hammer	48,00	5 years	75,00	0,64	5,00	3,20
Chisel	40,00	5 years	75,00	0,53	5,00	2,67
Hoe	159,00	5 years	75,00	2,12	5,00	10,60
Digging bar	207,00	5 years	75,00	2,76	5,00	13,80
					Total	**30,27**
A3 Additional equipment for snorkelling						
Wetsuit + gloves + boots + hood	1496,00	5 years	75,00	19,95	9,00	179,52
Fins, mask and snorkel	480,00	5 years	75,00	6,40	9,00	57,60
Weight belt	236,00	10 years	150,00	1,57	9,00	14,16
					Total	**251,28**

B1 Operational costs

Supervision (own effort): hourly wage 650 SEK

B2 Additional operational costs if site is reached by boat

Boat rental (daily): 2000 SEK/day

C Volunteer compensation

10000 NOK (≙ 10.000 SEK)

D1 Labour costs

Hourly wage 550 SEK

D2 Diving costs

Hourly wage (including diving equipment) 1100 SEK

Appendix 8 Excluded costs incurred by clearing activities

All values in SEK without VAT.

Cost item	Approx. costs	Comment
Pre- and post-surveys	varying	To establish oyster density and allow post-clearing evaluation. Include labour costs, equipment, journey to site.
Planning/management	varying	Labour costs for planning to allow systematic PO management
Journey to site	Depends on amount of people and distance	Excluded because highly site-dependent, consists of fuel costs and additional labour costs
Boat rental	1000 – 2000 SEK/day + fuel	To reach secluded sites, was not included in any handpicking costs
Machine preparation time and journey (excavating)	Total for two sites: 24 720 SEK	Includes loading and moving of barge and excavator (rental and labour costs)
Subcontracted machine transport (excavating)	Total for two sites: 6 980 SEK	Machine transfer and crane lorry
De-establishment (excavating)	Total for two sites: 3 025 SEK	Labour costs
Disposal logistics (excavating)	Total for two sites: 9 700 SEK	Includes working hours, container transport and crane lorry rental
Disposal logistics	Weight-dependent	Would include trailer rental, fuel, labour costs
Deposition	232 SEK for a trailer (small amounts); 1 150 SEK/ton (large amounts)	Small amounts (car with a trailer) can be disposed of at municipal waste treatment facility, otherwise disposal at waste plant.

Appendix 9 Dredging costs – included for two sites

Cost items	Costs	Comments
Labour costs (sub-contracted): For building dredge and actual dredging activities	9,106 SEK	Working hours for building dredge excluded in hypothetical costs
Labour costs (own effort): testing and dredging	15,400 SEK	Working hours for testing excluded in hypothetical costs
Boat rental Incl. fuel and skipper	13,480 SEK	
Material: Dredge material, personal equipment, site markings, water binoculars	729 SEK	Material for building the dredge excluded in hypothetical costs
Total	**38,715 SEK**	

Additional/excluded costs, see appendix 8.

Appendix 10 Excavating costs – included for two sites

Cost item	Costs	Comments
Labour costs: Establishing site, deploying silt curtain, excavating activities, checking and unloading oysters	25,990 SEK	Working hours for welding excavator shovel excluded in hypothetical costs
Boat, barge and container rental – during the actual excavating activities	21,205 SEK	
Material: Silt curtain and log mat rental	23,944 SEK	
Total	**71,139 SEK**	

Additional/excluded costs (e.g. preparation, journeys to site, deestablishment, deposition), see Appendix 8.

Appendix 11 Articles selected in step 1 and 3 of the literature review

Stage and search number	Author	Title	Geographical area
1	Herbert et al. 2016	Ecological impacts of non-native Pacific oysters (Crassostrea gigas) and management measures for protected areas in Europe	Europe
1	Martinez Garcia et al. 2021	Socioecological factors related to aquaculture introductions and production of Pacific oysters (Crassostrea gigas) worldwide	Worldwide
1	Vaugh & Hoellein 2018	Bivalve Impacts in Freshwater and Marine Ecosystems	USA
1	Smith et al. 2023	Meta-analysis of ecosystem services associated with oyster restoration	
1	Ruesink et al. 2005	Introduction of non-native oysters: Ecosystem effects and restoration implications	USA
1	Troost, 2010	Causes and effects of a highly successful marine invasion: Case-study of the introduced Pacific oyster Crassostrea gigas in continental NW European estuaries	NW European estuaries
1	Van der Schatte et al. 2020	A global review of the ecosystem services provided by bivalve aquaculture	Global
1	Hansen et al. 2023	Too late for regulatory management on Pacific oysters in European coastal waters?	Europe
1	Ray et al. 2021	A review of how we assess denitrification in oyster habitats and proposed guidelines for future studies	
1 Manually added	Grabowski & Peterson 2007	Restoring oyster reefs to recover ecosystem services	USA
1 Manually added	Green et al. 2013	Effects of Non-indigenous Oysters on Ecosystem Processes Vary with Abundance and Context	Ireland
1 Manually added	Laugen et al. 2016	The Pacific Oyster (Crassostrea gigas) Invasion in Scandinavian Coastal Waters: Impact on Local Ecosystem Services	Scandinavia
1 Manually added	Mortensen et al. 2017	Effects of a bio-invasion of the Pacific oyster, Crassostrea gigas (Thunberg, 1793) in five shallow water habitats in Scandinavia	Scandinavia

1 Manually added	Padilla 2010	Context-dependent Impacts of a Non-native Ecosystem Engineer, the Pacific Oyster Crassostrea gigas	USA
3 - Density (and habitat)	Green & Crowe 2014	Context- and density-dependent effects of introduced oysters on biodiversity	Ireland
3 - Density	Wagner et al. 2012	Density-dependent effects of an introduced oyster, Crassostrea gigas, on a native intertidal seagrass, Zostera marina	USA
3 Manually added - density	Kelly & Volpe 2007	Native eelgrass (Zostera marina L.) survival and growth adjacent to non-native oysters (Crassostrea gigas Thunberg) in the Strait of Georgia, British Columbia	Canada
3 Manually added - habitat	Firth et al. 2021	Do positive interactions between marine invaders increase likelihood of invasion into natural and artificial habitats?	UK
3 Manually added - habitat	Ruesink 2007	Biotic resistance and facilitation of non-native oyster on rocky shores	USA

Appendix 12 Systematic mapping of Pacific oyster impacts on ecosystem services

Unless mentioned in the table, the differences in impacts between the densities could not be quantified.

PO functions: F= filtering S= 3D structures R= (biological) resource						Population structure: S = solitary oysters C= clusters R=reefs						Legal framework: A = MSFD and HVMFS 2012:18 B = WFD and HVMFS 2019:25 C= HD (Habitats Directive) and Förordning (1998:1252) om områdesskydd D = Miljökvalitetsmålen O = Other relevant impacts
						Impact classified in relation to the descriptor						
						Soft bottom			Hard bottom			
ES	**PO function**	**Descrip-tor**	**Legal framework**	**Indicator**	**Current status (Väster-havet)**	**S**	**C**	**R**	**S**	**C**	**R**	**Explanation**
S1 Bioge	F	Oxygen	A	Oxygen deficiency in bottom waters	Tempo-rary hypoxia	Negative and positive impacts						(+) oxygen deficiency can be a result of eutrophication, oysters mitigate eutrophication effects (1, 2, 3; see also descriptor eutrophication and R3) and could therefore decrease oxygen deficiency. (-) organic enrichment of the sediment, high rates of decomposition and microbial respiration can lead to local anoxia (1, 4, 5, 6, 7, 8).

ochemiCal cycling		Oxygen (coastal waters)	A, B	Dissolved oxygen in the water column (oxygen content)	High to moderate oxygen content	Neutral		Negative effects because of loss of primary producers (see S2 primary production) and increase in community respiration (6,8) but local oxygen availability depends also on water circulation of the specific site. Since the current status for oxygen content is high to moderate, no negative impacts are to be expected except maybe locally on sites with low water circulation but oysters are unlikely to be present there in high densities (1). The circulation (esp. in shallow areas) might further be impacted by the physical structures created by oysters (1, 5).
		Eutrophi-cation	A, B, D	N-/P-concen-trations in coastal waters	nutrient status good to moderate	Positive: increase of NH4-content in sediment at 10% cover compared to 0% cover; highest increase of NH4- content in sediment at 40% cover, less at 80% (7)	positive	Cycling of nutrients through growth/feeding (nutrient intake and excretion), shell production and biodeposition. Increased nutrient availability in the sediment which leads for example to microbial denitrification (6,7,8,9). Sediment impact only on soft sediment, not hard substrate
				Biomass of phytoplankton in coastal waters (chlorophyll a and biovolume)		positive		Phytoplankton reduction (4, 10).

				occurrence of harmful algae in Västerhavet		positive	Filtering can decrease the likelihood of algal blooms (11)
				secchi depth in coastal waters	moderate	positive	Filtering of particles will increase water clarity and light penetration (1, 2, 4, 12, 13)
				oxygen balance in coastal waters		see indicator dissolved oxygen (above)	
				Depth distribution of macro-vegetation in coastal waters		supposedly positive	positive effects on secchi-depth will supposedly lead to positive impacts on depth distribution of macrofauna, positive impact on eelgrass depth distribution was shown for Eastern oysters (14)
				Benthic fauna in coastal and territorial waters: abundance		negative and positive impacts	Mitigation of eutrophication effects (see indicator oxygen deficiency in bottom waters) will have indirect positive effects on the benthic fauna. Potentially local negative effects from biodeposition and organic enrichment.

				Benthic fauna in coastal and territorial waters: species composition		not known, changes may occur	Mitigation of eutrophication effects (see indicator oxygen deficiency in bottom waters) may have indirect effects on the benthic fauna species composition as different species have different tolerance to varying oxygen conditions (34). Potentially also local effects from biodeposition and organic enrichment in soft substrate which favours meiofauna (35). Biodeposition increases local nutrient availability in the sediment which leads to increase in deposit feeders (8). Other (more prominent, 36) changes in benthic fauna species composition are caused by physical presence of the oysters -> see S4 biodiversity
		Secchi depth	A		moderate	positive	see indicator Secchi depth for descriptor eutrophication
		pH	B	Acidity Index ACID	pH decrea-sing	Not known, supposedly negative	Pacific oyster biodeposition increases microbial activity (6,8): release of hydrogen ions (H+) during microbial anaerobic respiration. During calcification process, hydrogen carbonate is taken up, calcium carbonate is formed, releasing CO_2 into the water (16), which when dissolved in water becomes carbonic acid, releasing H+ ions into the water.
		Carbon cycling	O			Positive and negative	(+) Carbon sequestration during shell production (16), burial of organic material (16), increased organic matter in the sediment increases microbial carbon cycling (6, 8) (-) carbon fluxes (16) from respiration
S 2	F	Phyto-plankton	A, B	biomass	Not good-good	negative	Phytoplankton is filtered from the water column (2, 4, 5, 8, 12), biomass loss depends on oyster density

Primary production				Species composition		Not known, supposedly negative		Selective filterfeeding (17) could have a negative effect on species composition
	F,S	Macro-algae	A,B		Decrea-sed areas since 1900	increasingly positive effects on both biomass and species richness (31)	neutral	(+) providing attachment surfaces (4, 5, 15, 18; esp. on soft sediments but also on boulders: 38), increase in water clarity (see secchi depth), increase in nutrient availability: oysters take up particulate nutrients but through their feeding process release dissolved nutrients into the water column which are fed on by both phytoplankton and macroalgae. Release of dissolved nutrients and reduction of phytoplankton are beneficial to macroalgae (19). For the Wadden Sea, invasion facilitation by the oysters to the seaweed Sargassum muticum (see also R4 biological regulation) has been suggested to abolish the otherwise positive effects on macroalgae (50).
	F, S	eelgrass	A,B		Significantly reduced areas since the 1980s	Positive and negative effects; on site, negative effects might dominate while surrounding areas might be affected positively. Increasing impacts with increasing oyster density	not applicable - no eelgrass on hard substrate	(+) increase in water clarity (see secchi depth) and nutrient availability in the sediment from benthic-pelagic coupling (1,2), stabilizing the sediment (4) (-) loss of soft substrate to root in: 20 % oyster density threshold for exponential decreases in eelgrass, oyster density > 50 % is impenetrable by eelgrass (20, 51); potential sulphide accumulation (2, 5, 18, 20) and hypoxic conditions (5), increase of foraging predators/grazers (15). Intermix of eelgrass and Pacific oysters observed along the Swedish west coast (32).

S4 Biodiversity	F,S	(submerged) aquatic vegeta-tion	A,B	Species composition + biomass	High - good	see S2 primary producers - changes will occur increasingly with increased density	Neutral	Changes. Is an increase in species richness and biomass of macroalgae positive or negative?
	S	Habitats	C,D		Unsatisfactory - poor	See S5 habitat		In general, habitat homogenisation and esp. loss of protected habitats can lead to biodiversity loss. Habitat diversification (e.g. adding substrate to formerly bare bottoms) can improve biodiversity (8,15,22)
	S	Fish	A	Occurrence of key fish species - large cod	Weak stocks and size composi-tion indica-ting disturbance	neutral - different habitat		
			O	occurrence of other migratory fish		neutral		Impacts on resident rather than migratory fish
			O	ocurrence of resident fish		positive	Supposedly positive	Provision of habitat to fish (nesting, nursery and foraging grounds) (1,4,13,23,33). Impacts are primarily documented for soft-bottom substrate.

			A	Spawning stock biomass for pelagic and demersal fish species		positive	Supposedly positive	Provision of habitat to fish (nesting, nursery and foraging grounds) (1,4,13,23). Impacts are primarily documented for soft-bottom substrate.
		Red-listed species	D			Not known		470 species in the marine environment are red-listed. Their occurrence in oyster habitats is unclear/ needs further research.
	F,S	Epifauna	O	abundance		positive	Positive and negative	Soft bottom: Provision of 3D substrate which can be used for hiding, foraging, attachment surface -> higher abundance than on bare sediments (1,8,22,33) and on blue mussel beds (15). Secondary invasion effects from invasive seaweed (see S2 macroalgae, R4 biological regulation) are suggested to have negative effects on epifauna -> high S. muticum seaweed coverage leads to significant epifauna reduction on the oyster shells (50). Hard bottom: Can act as a basibiont and reduce competition pressure also on hard substrate, mostly beneficial to invasive epibionts on natural hard bottom (increased abundance of invasive species is considered negative) and to native epibionts on artificial hard bottom (+) (37).

				Species richness		positive	Positive and negative	(+) Provision of 3D substrate which can be used for hiding, foraging, attachment surface -> higher species richness than on bare sediments (1,8,22,33) and blue mussel beds (15). Can act as a basibiont and reduce competition pressure also on hard substrate, mostly beneficial to invasive epibionts on natural hard bottom (-) and to native epibionts on artificial hard bottom (+) (37).
				Species composition		Changes will occur increasingly with increased density.		Examples for potential changes: Pacific oyster reef favours anthozoans, hydrozoans and barnacles (15) and larger invertebrates (33) compared to blue mussel bed and sandy sediment; occurrence of shore crab and littorina (15). Impacts on other filter feeders on hard bottoms (38).
			O	species interactions with other bivalve species		Changes will occur increasingly with increased density.	Not known	blue mussels: (-) larviphagy (see S4 recruitment of bivalve species), competition for food (1); (+/-) Co-existence in "oyssel-reefs": Pacific oysters provide shelter which is (+) for blue mussel survival but take up best feeding spots which is (-) for blue mussel fitness (41). European flat oysters: (-) larviphagy; (neutral to negative) differences in ecological distribution (58,59) but local interference possible (1) and niche overlap bigger than previously believed (60); (+) may facilitate return of flat oysters by substrate provision where their distribution overlap (40).
	F,S	Infauna	O	abundance/ biomass		positive	Not applicable	Higher infauna abundance/biomass documented on bivalve beds/in mud under oyster reefs than bare sediment (1,8,22,42).

				Species richness		neutral	Not applicable	No effect on infauna species richness detected for oyster densities < 120 ind./m^2 (31), infauna species richness generally less affected than abundance (42)
				species composition		Changes will occur increasingly with increased density.	Not applicable	changes in dominant infauna species compared to mussel beds (5, 43), infauna community on oyster reefs dominated by predators and deposit feeders compared to suspension feeders on bare sediment (1, 15, 22)
	F	Zoo-plankton	A			Not known, changes may occur increasingly with increased density. Potential shift to larger zooplankton.		Direct: Selective filterfeeding (shown for phytoplankton (17)) could potentially have an effect if filtering esp. small zooplankton. No knowledge on size or species preferences for zooplankton. Indirect: Oysters will impact microbial assemblage; bacterivory of small zooplankton and therefore increase in ratio of large zooplankton (21)
			A	Biomass	Reduced biomass	Negative		Zooplankton is filtered from the water column (2,4,5,8), biomass loss depends on oyster density
	F		O	recruitment potential of bivalve species		Negative		Larviphagy = "feeding on bivalve larvae by adult bivalves" (28). M. gigas larvae observed to be filtered out about 50 % less than M. edulis larvae, larvae (both M. gigas and M. edulis) reduction by larviphagy of M. gigas documented in Oosterschelde estuary (28a)
		Phyto-plankton	A	Species composition	High-good	see S2 Primary production - phytoplankton		
	F	Phyto-plankton	A,B	Biomass	High - good	see S2 Primary production - phytoplankton		
				Species composition		see S2 Primary production - phytoplankton		phytoplankton is filtered out -> bottom-up control of food web dynamics

S 3 Food web dynamics		Zoo-plankton	A	size		See S4 - phytoplankton		
				biomass	Reduced biomass	see S4 zooplankton		zooplankton is filtered out -> bottom-up control of food web dynamics
		Habitats	C		Unsatis-factory - poor	see S 5 habitat for description of impacts by habitat		
	R,S	Fish	A	Occurrence of key fish species - large cod	Weak stocks and size compo-sition indica-ting distur-bance	See S3 – large cod		
			O	occurrence of other migratory fish		See S3 – migratory fish		
			O	ocurrence of resident fish		See S3 - resident fish	See S3 - resident fish	Provision of habitat to fish (nesting nursery and foraging grounds) (1,4,13,23) who exert top-down control on the food-web
			A	(SSB) for pelagic and demersal fish species		positive		Provision of habitat to fish (nesting nursery and foraging grounds) (1,4,13,23)

	R		A,B	abundance of breeding and wintering seabirds		positive and negative (bird species-dependent)	not applicable - attached to substrate and therefore not available to birds	Food source for herring gull (5, 24, 25), Eurasian curlew (15) and other shorebirds (4, 26). Negative impacts on common gull and knot that depend on bivalve sizes < 20mm (27). Contradictory findings on whether a food source or negative impacts for Eurasian oystercatcher (15, 24, 25, 27)
S5 Habitats	S		C	1110 Sublittoral sandbanks		changes may occur increasingly with increased density, high densities are unlikely (29)	Not applicable	(+) Stabilizing soft sediment (4), habitat diversification with positive impacts on biodiversity, e.g. epifauna, fish (4, see S4 biodiversity). Stronger impacts on soft-bottom habitats than hard bottoms (1,29). Neutral: habitat modification. (-) Loss of soft-bottom habitat, reef formations restricting waterflow -> increased sediment deposition and retention (1,4)
	S			1130 Estuaries		changes may occur increasingly with increased density,	Not applicable	
	S			1140 Mudflats and sandflats not covered by seawater at low tide		changes may occur increasingly with increased density	Not applicable	As above. Additionally, refuge for species during low tide because of retained water -> reduced desiccation (8,18,23)
	S			1160 Large shallow inlets and bays		changes may occur increasingly with increased density	Not known	As above.
	S,F			1170 reefs		changes may occur increasingly with increased density	Not known	Effects on other bivalve species, see S4 biodiversity. Highest risk of C. gigas invasion (28, 29)

S 6	Resilience	F,S,R	no set descriptors or indica-tors	moderate	Positive and negative		Changes in biodiversity (see S4 biodiversity), food web (see S3 food web dynamics) and habitats (see S5 habitats) impact ecosystem resilience (28). Functional similiarity to native bivalves -> compensate for loss of ecosystem functions caused by a decline of native species (52, 53, 54).
R 1	Climate and atmospheric regulation		Not set	moderate	Positive and negative		(+/-) carbon (see S1 carbon cycling). (-) release of N2O during denitrification in oxic conditions (9) and methane in anoxic conditions (6,8) (see also S1 N/P concentrations)
R 2	Sediment retention	S	Not set	moderate	positive	Not applicable	sediment retention and stability reduce erosion -> coastal protection (1,2,5,8,25)
R 3	Eutrophication regulation	F	See S1	moderate	positive		see S 1 biogeochemical cycling - eutrophication
R 4	Biological regulation	S,F	Not set	moderate	Positive and negative impacts		(-) vector of other non-native species (5,8,30) and invasion facilitation by habitat creation (4, 37, 38, 50), oyster introduction a major cause of emerging diseases (4) (+) suggested to in other cases reduce spread of other diseases by dilution effect (5,30, 55, 56) but parasite adaptation can't be ruled out (55), reducing likelihood of HABs (see S1 - eutrophication)
R 5	Regulation of hazardous substances	F	Concen-trations of different toxic substances	moderate	positive		Bivalves as biofilters for chemicals, metals and pathogens -> can be used for removal of contaminants (2) and biofilters for microplastics (39)

P 1	Food	S,R	Not set	poor	Mostly positive	not applicable for direct food use (hard to harvest because oysters are attached to substrate), negative and supposedly positive impacts from leaving the oysters in	collecting the oysters: oysters as a protein-rich, nutrient-dense food source (1,8, 57 survey results); leaving the oysters in: positive effects on commercially important fish populations through habitat provision and changes in food web (see S4 and S3- fish), potentially negative interactions with commercial fisheries and production of other species (survey)
P 2	Raw material	R	Not set	poor	positive	not applicable, hard to harvest because oysters are attached to substrate	Use of shells in construction, as lime or quicklime (calcium oxide) (8,23), used in concrete/cement/as road building material (2,23), potential creation of artificial stone material (44,45) construction material in coastline protection (23,25), potential use of oyster meat in fish and poultry feed (1,23, survey), use of shells and ground meat as fertilizer (2,23).
P 3	Genetic resources	R	Not set	good	Not known		Wild populations can serve as source of spat for farming (30) and for restoration purposes (not relevant in Sweden). Potential interactions with native species, see S4 biodiversity.
P 4	Chemical resources		Not set	good	positive	not applicable, hard to harvest because oysters are attached to substrate	use of shells in healthy foods and medicine (44): calcium supplement (46), hydroxyapatite extraction for use in bone grafting (47), calcium oxide with antibacterial and antifungal effects (48). Use of oyster meat as dietary and health supplement (49)

P 5	Ornamental resources	R	Not set	good	positive		not applicable, hard to harvest because oysters are attached to substrate.		decorations on walls and in gardens, e.g. as candleholders (survey)
P 6	Energy	R	Not set	good	Not applicable				
P 7	Space and waterways	R	Not set	Not classified	neutral	negative regardless of substrate	neutral	negative regardless of substrate	Potential blockage of navigation channels (8, survey), fouling of boats, docks, drainage pipes, underwater constructs, cooling water inlets (1, survey)
C 1	Recreation	S,R, F	Not set	moderate	Positive and negative impacts				(-) Potential injury of the public from shells (8, survey), fouling of boats and docks (1, survey), and destruction of material (survey), sanitary problems with decomposition after high mortality (1) (+) hand-picking oysters as recreational/ tourist activity (1, survey), increasing bathing water quality/ clarity (survey), increased recreational fishing opportunities (61). Individually different perception (survey).
C 2	Aesthetic values		Not set	moderate	subjectively positive or negative based on personal perception				oysters are perceived as aesthetically pleasing by some and displeasing by others (survey)
C 3	Science and education	R	Not set	good	positive				Accumulation of contaminants (e.g. metals, pharmaceuticals, nanomaterials and microplastics) -> can be used for environmental monitoring and ecotoxicology (2). Shell growth (aragonite deposition) of bivalves indicates temperature, hydrology and food availability (2). Easy to access for education and communication purposes.

C 4	Cultural heritage	R	Not set	moderate	positive	Archaeological records of bivalve shells in piles and as tools and currency (23), seafood traditions, e.g. handpicking of oysters and seafood festivals (23), use as bait for crab fishing (survey). Work opportunities in rural areas (harvesting and gastronomic tourism) and keeping fishing societies alive.
C 5	Inspiration	R	Not set	good	positive	culinary inspiration, business ides, art (survey)
C 6	Natural heritage		Not set	moderate	not known, supposedly negative	potential impacts on conservation and perceived natural beauty, change from and preventing return to natural state

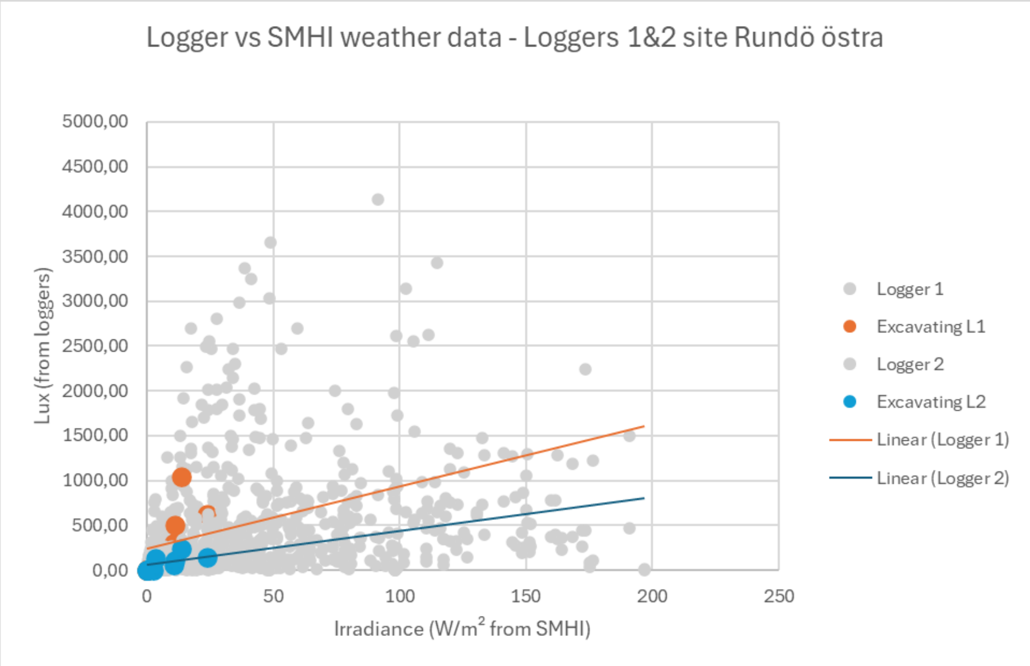
Table references

1) Laugen et al. (2016) - 2) Vaughn & Hoellein (2018) - 3) Smith et al. (2023) - 4) Ruesink et al. (2005) - 5) Troost (2010) - 6) Green et al. (2012) - 7) Green & Crowe (2014) -8) Herbert et al. (2016) - 9) Ray et al. (2021) - 10) Wheat & Ruesink (2013) - 11) Beck et al. (2009) - 12) Newell (2004) - 13) Grabowski & Peterson (2007) - 14) Newell & Koch (2004) - 15) Markert et al. (2020) - 16) Filgueira et al. (2015) - 17) Cognie et al. (2001) - 18) Padilla (2010) - 19) Naldi et al. (2020) - 20) Kelly & Volpe (2007) - 21) Caillibotte et al. (2020) - 22) Lejart & Hily (2010) - 23) Van der Schatte et al. (2020) - 24) Cadée (2008a, b) - 25) Hansen et al. (2023) - 26) Escapa et al. (2004) - 27) Waser et al. (2016) - 28) Troost (2008) – 28a) Troost (2009) - 29) Mortensen et al. (2017) - 30) Martinez-Garcia et al. (2021)- 31) Boëthius (2022) - 32) Bengtsson Kupcik (2017) - 33) Norling et al. (2015) - 34) Rosenberg et al. (1991) - 35) Castel et al. (1989) - 36) Norling & Kautsky (2007) - 37) Firth (2021)- 38) Green & Crowe (2013) - 39) Paul et al. (2023)- 40) Christianen et al. (2018) - 41) Reise et al. (2017) - 42) Hollander et al. (2015) - 43) Kochmann et al. (2009) - 44) Linder (2022) - 45) Hellen et al. (2019) - 46) Fujita et al. (1988) 47) Hou et al. (2016) - 48) Yao et al. (2014) - 49) Nyqvist (2022)- 50) Lang & Buschbaum (2010) - 51) Wagner et al. (2012) - 52) Zwerschke et al. (2016) - 53) Zwerschke et al. (2020) - 54) Shakspeare et al. (2024) - 55) Krakau et al. (2006) - 56) Thieltges et al. (2008) - 57) Hallström et al. (2019)- 58) Thorngren et al. (2019) - 59) Stagličić et al (2020) - 60) Bergström et al. (2021)

Appendix 13 Light logger data from clearing activities around Tjärnö, December 2023

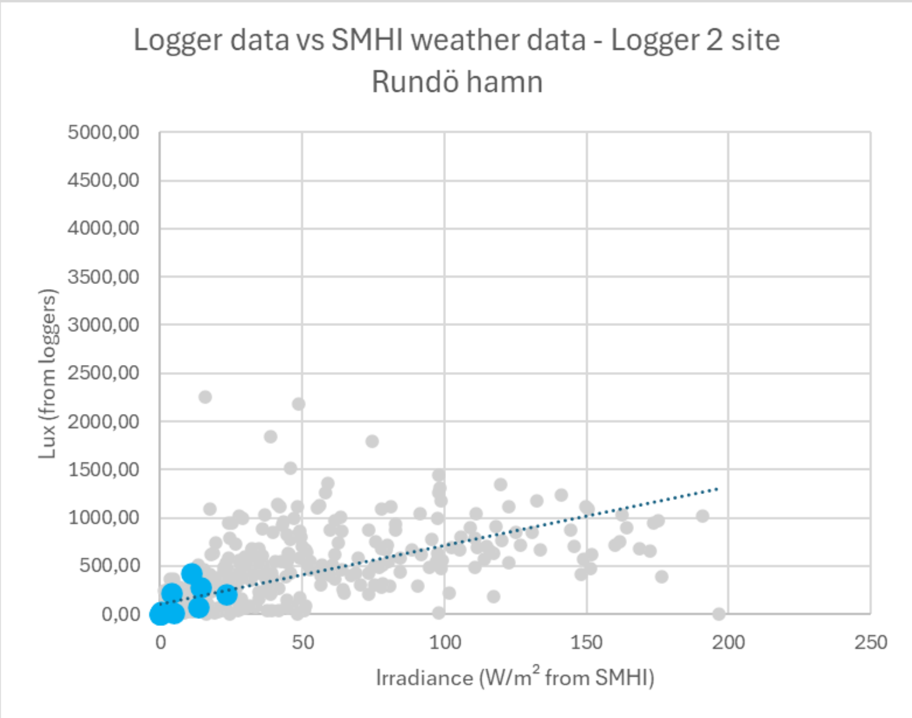
Site Rundö östra

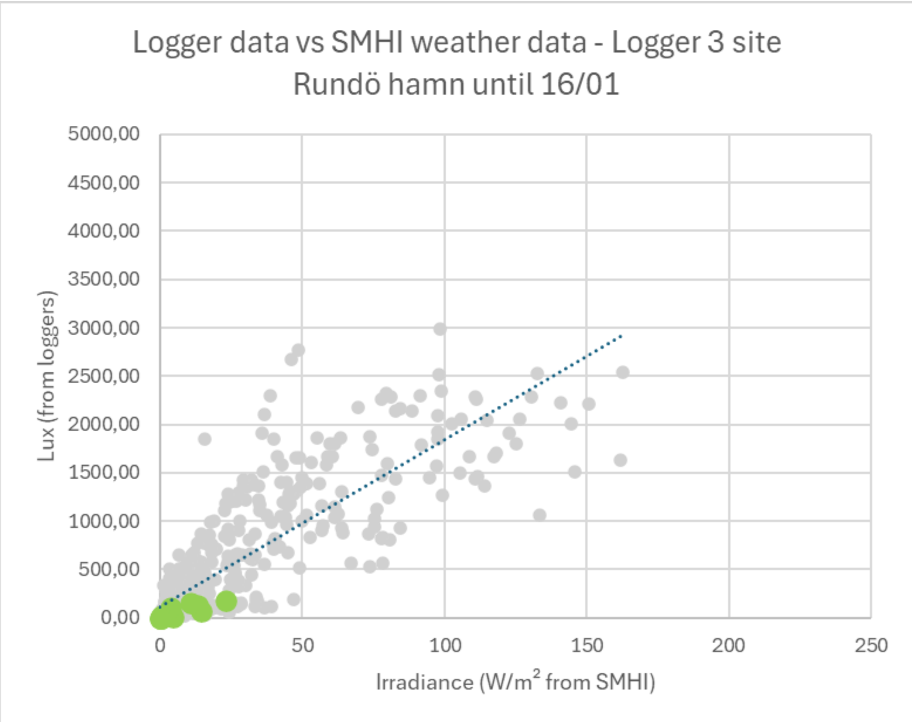
Clearing activity 21/12/2023. Logger 3 could not be retrieved.



Site Rundö Hamn

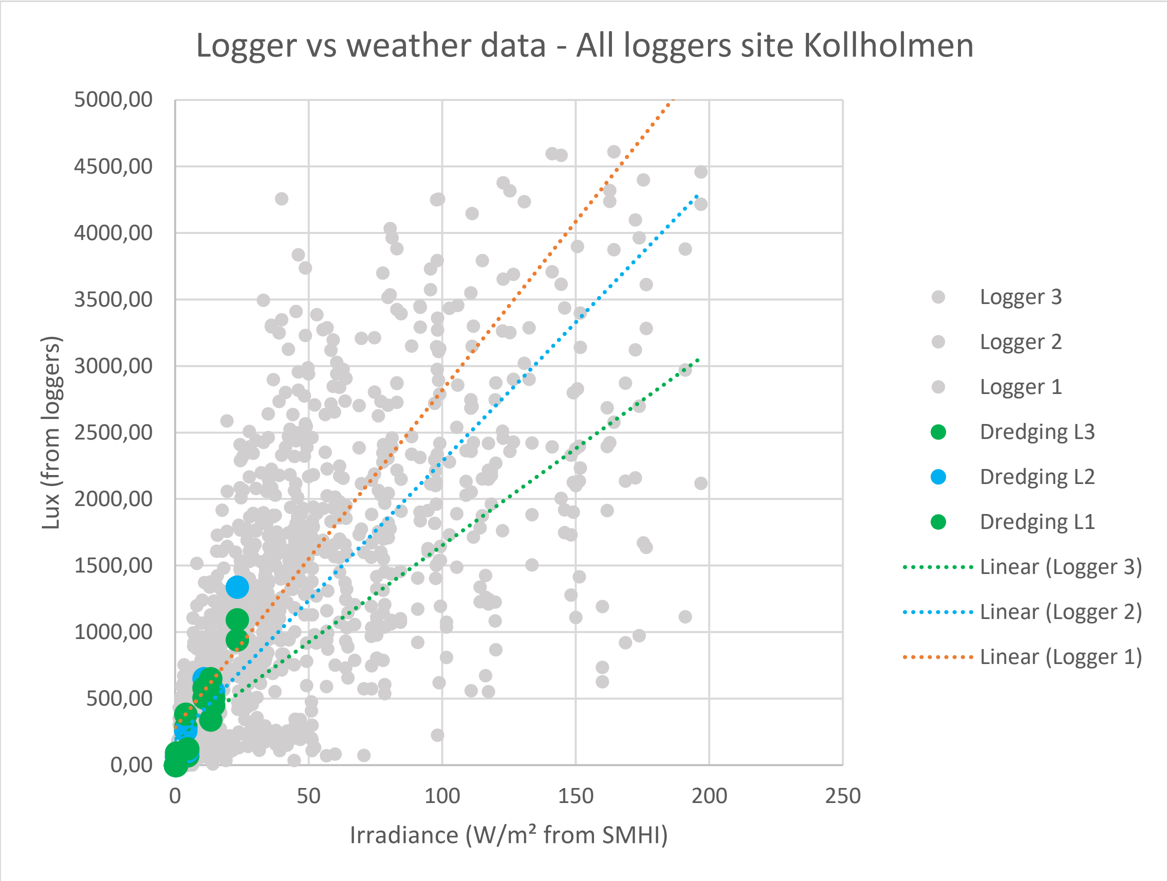
Clearing activity 21/12/2023. Logger 1 was taken out during start clearing activity (around 10:15 21/12/2023) and placed back at 11:45, 21/12/2023. Logging error at logger 3 from 16/01/2024.





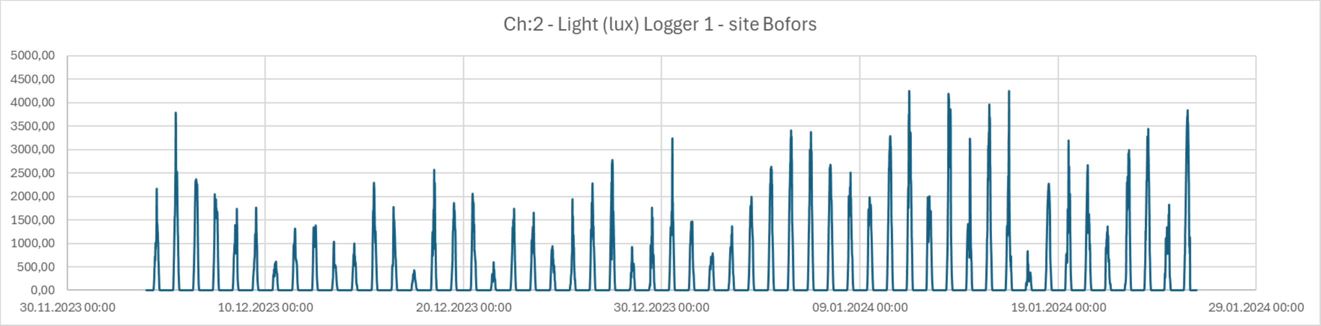
Site Kollholmen

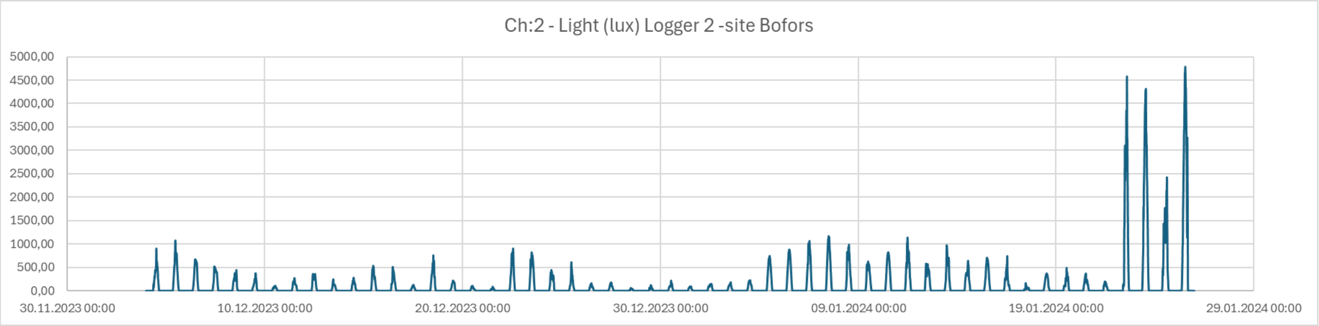
Clearing activity 13/12/2023

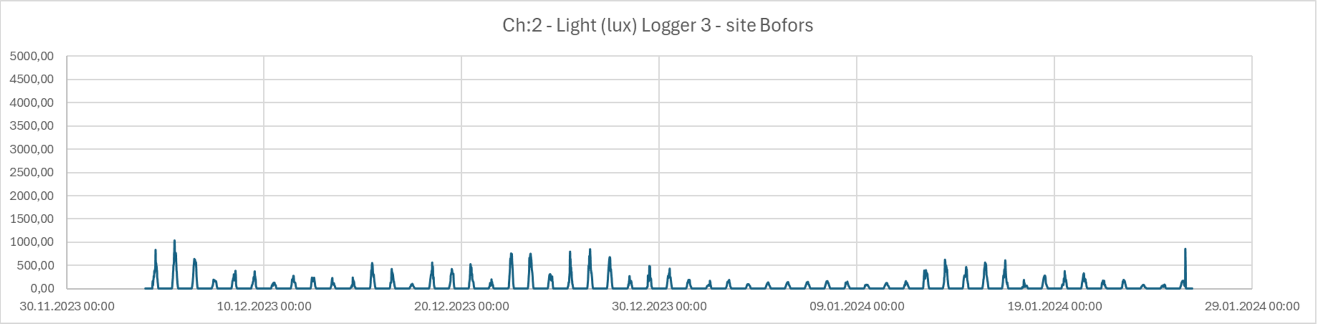


Site Bofors

Clearing activity 18/12/2023 – no decrease exceeding natural variation over the entire logging period visible.







Appendix 14 Additional graphs from the cost-efficiency analysis

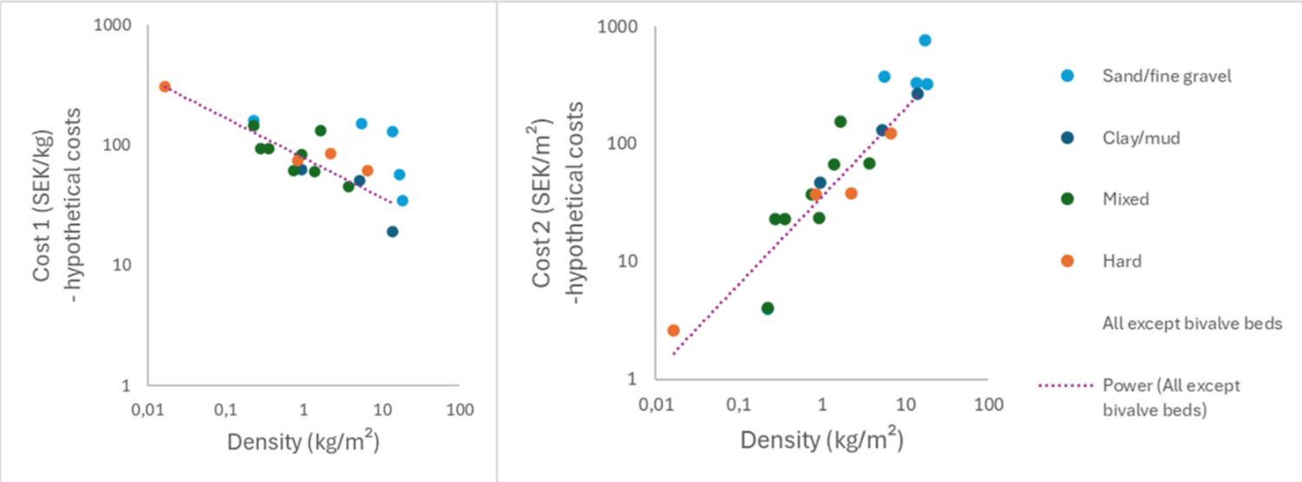


Figure 14.1 Relation between cost-efficiency indicators 1 (SEK/kg) and 2 (SEK/m²) and density (kg/m²) for handpicking by substrate for scenario 2 (hypothetical costs), presented on a logarithmic scale.

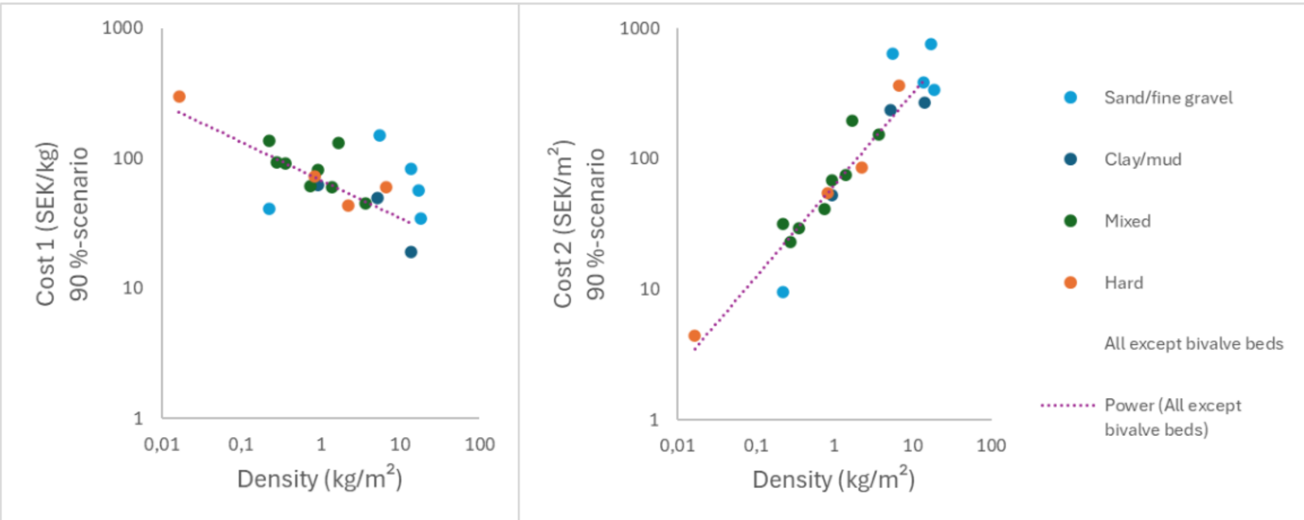


Figure 14.2 Relation between cost-efficiency indicators 1 (SEK/kg) and 2 (SEK/m²) and density (kg/m²) for handpicking by substrate for scenario 3 (hypothetical costs, 90%-clearance proportion), presented on a logarithmic scale.