# Assessing the effect of management measures in the Southern Bothnian Sea

## An exploration of fuzzy cognitive mapping

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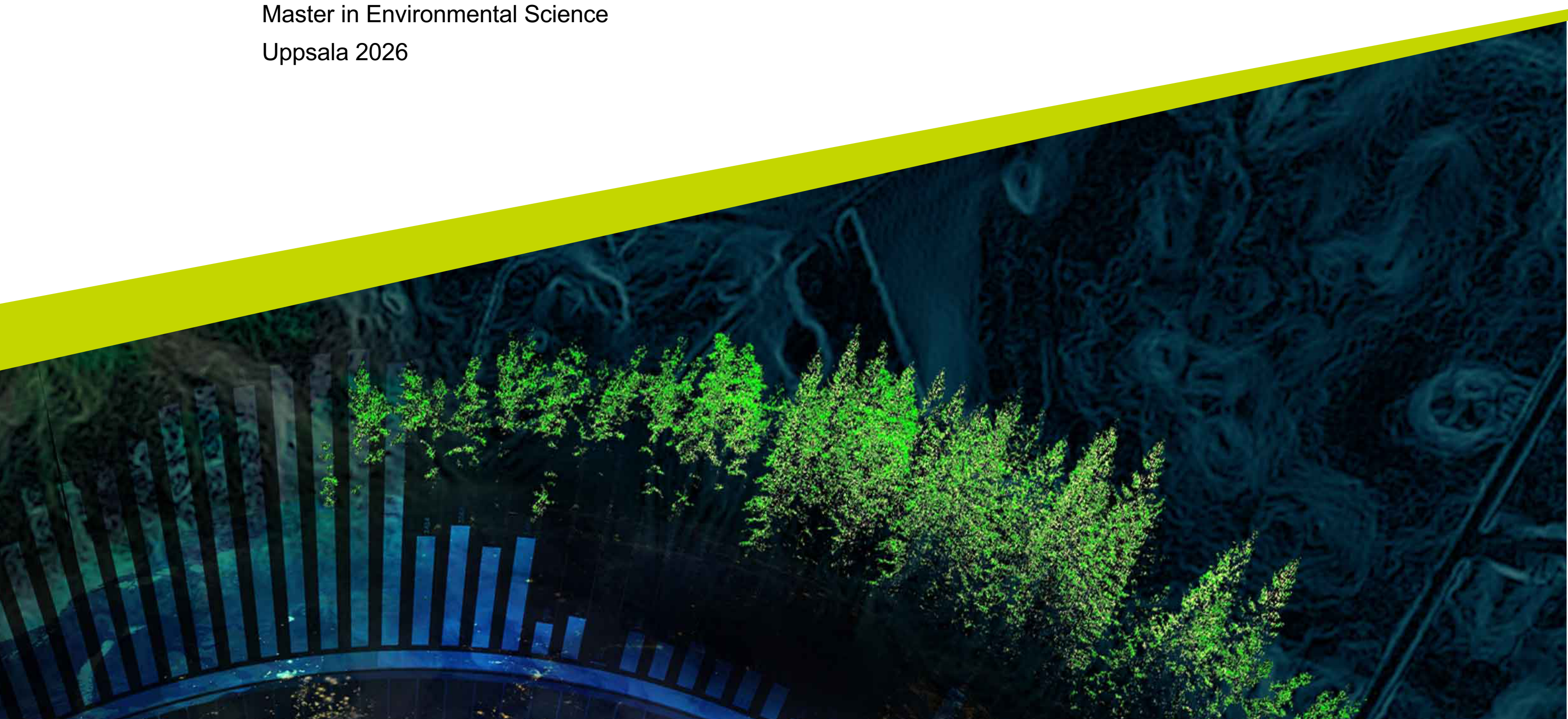

# Assessing the effect of management measures in the Southern Bothnian Sea: An exploration of fuzzy cognitive mapping

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# Abstract

In the face of current deterioration of marine ecosystems management aimed at restoring and conserving marine habitats is important. In Sweden there is a national call for increased ecosystem-based management (EBM) in the Baltic Sea, where overfishing and eutrophication are of growing concern, to preserve biodiversity and secure the provision of ecosystem services. Simulating the outcomes of management frameworks can be especially relevant for marine systems, due to the high uncertainty related to assessment of marine habitats, and modelling of different scenarios may also be useful to optimise the effect of management. Fuzzy cognitive mapping (FCM) is a modelling approach that can be used for such evaluations. In the southern Bothnian Sea a regional management framework, as well as a fuzzy cognitive map of the socio-ecosystem, have been developed by local stakeholders and scientists from the Swedish University for Agricultural Sciences (SLU). The aim of this thesis was to investigate how FCM modelling could be used to support EBM, by assessing potential effects of the management measures of the Southern Bothnian Sea, considering emerging trade-offs and synergies, and by developing scenarios for herring management.

One of the central findings includes the importance of submerged aquatic vegetation (SAV) in the system. Measures that benefitted vegetation generally had positive effects on the rest of the system, while measures that were negative for aquatic vegetation generally negatively affected other ecological components and ecosystem services. This contrasting effect on vegetation is one example of a trade-off between measures identified in the analysis, while synergies found included measures related to herring management. The results also suggested that management focused on herring would benefit from the use of long-term management measures and marine protected areas (MPAs), instead of, for example, setting annual fish quotas. Depending on the preferred outcome of stakeholders these results could be used to discuss how measures can be adjusted to increase their positive effect on the socio-ecosystem, and how to avoid potential conflicts. FCM modelling could therefore provide managers and stakeholders with a deeper understanding of system interactions, while highlighting current perceptions of the system. In the context of EBM, where analysis of whole social-ecological systems is of use, such insights may be especially relevant.

*Keywords:* Fuzzy cognitive mapping, ecosystem-based management, Bothnian Sea

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# Abbreviations

| Abbreviation | Description |
|---|---|
| ASS | Alternative Stable State |
| EBM | Ecosystem-based management |
| FCM | Fuzzy cognitive mapping / Fuzzy cognitive map |
| MC | Monte Carlo |
| MPA | Marine protected area |
| MSFD | Marine Strategy Framework Directive |
| PSU | Practical salinity unit |
| SAV | Submerged aquatic vegetation |
| SLU | Swedish University of Agricultural Sciences |
| SU | Stockholm University |
| SwAM | Swedish Agency for Marine and Water Management |

# 1. Introduction

Due to biodiversity loss and climate change, management of marine ecosystems has become more important and is of global concern (Andersen et al. 2015). The worsening state of marine ecosystems is linked to several different human pressures, including overfishing, eutrophication and climate change (HELCOM 2023). Efforts aimed at mitigating the deterioration of marine habitats are as such necessary, and are part of several international and national, sustainability goals and strategies (Blenckner et al. 2015). For example, policy initiatives such as the European Union (EU) Marine Strategy Framework Directive (MSFD) and habitats directive, as well as the Swedish environmental quality objectives both call for better marine health and safeguarding of the marine ecosystem and the ecosystem services they provide (Directive 2008/56/EC; Naturvårdsverket n.d.). Integrated management approaches, such as ecosystem-based management (EBM), where the complexity of pressures and marine ecosystems is recognised, and the role of humans is included in the analysis, are therefore needed (Riisager-Simonsen et al. 2020). The goal of EBM is to create a sustainable management approach by integrating environmental, social and economic aspects, and in Europe there are policy recommendations for the implementation of such management (Scotti et al. 2022).

The Baltic Sea is a brackish sea, where the pronounced gradient in salinity and temperature across sub-basins has shaped the biodiversity. The system is influenced both by natural variables such as freshwater input, annual ice coverage and winds, as well as anthropogenic pressures including climate change, eutrophication and fishing (Österblom et al. 2007). The brackish water, as well as the relatively young age of the sea, has made the Baltic Sea species-poor. Key fish species include cod (*Gadus morhua*), herring (*Clupea harengus*) and sprat (*Sprattus sprattus*). The fish community is, however, changing, with increasing domination of three-spined stickleback (*Gasterosteus aculeatus*), and declining herring stocks, as well as a reduced number of predator fish, such as cod (Olsson et al. 2019; Svedäng et al. 2023, Österblom et al. 2007). Coastal fishers have also experienced the depletion of herring, especially at spawning grounds near the coast (Svedäng et al. 2023). Since fish quotas are adjusted annually based on stock assessments, higher abundance of fish can lead to increased fishing efforts, which is a potential reason for the limited recovery of depleted fish populations (Trijoulet et al. 2026). Furthermore, fish communities are closely tied to submerged aquatic vegetation (SAV) as it provides feeding, spawning and nursing habitats (Wikström et al. 2025). SAV can also act as sinks for both carbon and nutrients, and aquatic vegetation has been determined to be a key indicator of the ecological status of coastal ecosystems in the Baltic Sea (Huber et al. 2022;

Wikström et al. 2025). SAV is, however, also impacted by stressors such as eutrophication, coastal development and sediment runoff, and globally there is a loss of seagrass ecosystems (Cole & Moksnes 2016).

A century ago, the Baltic was an oligotrophic sea with oxygenated deep waters (Österblom et al. 2007). Despite efforts to reduce nutrient loading, eutrophication remains a major issue (HELCOM 2023), as increased nutrient loads have led to higher primary production and oxygen consumption, causing phytoplankton blooms and anoxic bottom waters (Andersson et al. 2015, Blenckner et al. 2015). The changes in species communities and reduced fish stocks can be related to environmental degradation and overfishing. The steep depletion of cod, specifically, as well as rising temperatures and increased nutrient loading, have altered food web dynamics and decreased the fish productivity of the Baltic, and the sea has undergone a regime shift from a cod-dominated system to a sprat-dominated one (Österblom et al. 2010, Tomczak et al. 2022). Coastal fish stocks, such as salmon (*Salmo salar*) and sea trout (*Salmo trutta*), have also decreased, due to, for example, coastal eutrophication and blocked migration routes which negatively affect reproduction (Blenckner et al. 2015; Pekcan-Hekim et al. 2016). Climate change also poses a threat to the ecological status of the Baltic Sea through changes in temperature, nutrient loading and salinity. These changes may favour species that are non-indigenous to the area (Viitasalo & Bonsdorff 2022), while being detrimental to other species, such as the Baltic ringed seal (*Pusa hispida botnica*) which is negatively affected by poor ice conditions in winter (Kauhala et al. 2019). Some pressures will also be exacerbated with climate change. Nutrient loading may, for example, increase with increased runoff, which when coupled with higher temperatures could lead to larger anoxic areas. The food-web dynamics of the Baltic Sea is as such projected to be altered even further, with socio-ecological consequences (Viitasalo & Bonsdorff 2022).

The Baltic Sea can be divided into six sub-basins. In this thesis the focus is on the Bothnian Sea, which is separated from the Bothnian Bay in the north and the Central Baltic in the south by shallower sills that partially restrict the exchange of deepwater layers between these sub-basins. In the Bothnian Sea the species composition is influenced by the low salinity range (~6 PSU), and the coastal fish species community includes freshwater-tolerant species such as pike (*Esox lucius*) and perch (*Perca fluviatilis*) (Faithfull & Bergström 2025), while cod is not as common, as it cannot reproduce in the area (Bergström et al. 2025). Instead, herring is a central part of the food web, functioning as a food source for birds, marine mammals and other fish, while driving top-down effects on the food-web through zooplankton predation (Faithfull & Bergström 2025). Predators of the Bothnian Sea that feed on herring include great cormorant (*Phalacrocarax carbo*), grey seal (*Halichoerus gryphys*) and ringed seal, but the mortality of herring stocks mainly comes from herring fisheries (Kuosa et al. 2017). As in the rest of the Baltic Sea, fishing pressure is an important driver of ecosystem degradation in the Bothnian Sea, and the herring biomass has declined in the area. The changes in the Bothnian Sea food web can also be linked to eutrophication, as well as climate-related pressures of changing salinity and temperature (Faithfull & Bergström 2025; Kankaanpää et al. 2023). Management measures aimed at reducing nutrient loads and herring fishing quotas could therefore be important for mitigating the deterioration of the Bothnian Sea ecosystem (Bauer et al. 2019; Faithfull & Bergström 2025). Without such efforts the ecosystem could shift towards an alternative stable state (ASS), a self-reinforcing state from which recovery may require greater management effort (Blindow et al. 2025).

In the Bothnian Sea, as in the rest of the Baltic Sea, the shifting states of the ecosystem as well as multiple pressures at several scales create difficulties for management. Holistic management approaches, such as EBM, where ecosystem dynamics and collaboration between different sectors of society are in focus, are therefore essential (Andersen et al. 2015; Österblom et al. 2010). EBM is based on the response of ecosystems to cumulative and interacting stressors, and the role of stakeholders is important for aligning environmental, social and economic goals (Clark et al. 2022; Riisager-Simonsen et al. 2020). There is a national call for increased EBM in the Baltic Sea, and the biodiversity of the region must be protected in order to secure its productive capacity and ecosystem services (HaV 2025).

Marine ecosystems provide several cultural, provisional, recreational and regulatory ecosystem services to humans, which are all important to safeguard. Understanding and accounting for the benefits provided by the marine ecosystem is important for ensuring decision-making that maintains the well-being of both the ecosystem and people (Cordero-Penín et al. 2023). For marine management it can also be important to balance recreational and commercial objectives (Damiano et al. 2024), and local engagement can be relevant to improve how management decisions are received (Borja et al. 2016). The ability to obtain a wide range of stakeholder perspectives is a key strength of EBM, and these perspectives could be used to identify both potential trade-offs and synergies regarding how management measures interact to affect the environment (Le et al. 2023). By considering interactions between management measures, conflicts and synergies can be used to promote ecological benefits while minimising negative consequences and unnecessary management costs. Interactions between management measures can be defined as synergistic if the two measures taken together generate positive effects on outcomes, and as a trade-off if the measures have conflicting outcomes or objectives (Calado et al. 2025; Mansfield et al. 2024).

The interactions of management measures can, for example, be modelled using qualitative modelling approaches, such as fuzzy cognitive mapping (FCM), where societal, economic and ecological components can be included (Alomia-Hinojosa et al. 2022). FCMs can be especially useful for EBM and decision-making processes due to their ability to simulate potential impacts of management (Reum et al. 2021), as well as the possibility to include human pressures in the model (Aminpour et al. 2020; Olsen et al. 2022). Furthermore, FCM allows for modelling of systems that are data-poor and provides an accessible way of synthesising information from several different sources (Grey et al. 2015, Reum et al. 2021). For example, it can be used to combine local and expert knowledge as FCMs can be developed in participatory settings with managers, stakeholders, scientists, and other experts. FCMs are therefore useful for documenting and harnessing collective knowledge and can include relationships that are uncertain and difficult to quantify (Devisscher et al. 2016; Jetter & Yoon 2016), which can be especially relevant when considering management of data-deficient issues at local scales (Aminpour et al. 2020). Including local people in the process can also increase public acceptance regarding the management plans and create stakeholder engagement (Cleveland et al. 2024; Özesmi & Özesmi 2004), as the strategies developed can reflect both priorities of stakeholders while still including a credible understanding of the functioning of the system (Olsen et al. 2022).

Conflicts and synergies between management strategies can also be addressed by using FCM. For marine management, evaluating and simulating the outcomes of management frameworks can be especially relevant due to the high uncertainty related to assessment of marine systems, and modelling of different scenarios may be useful to optimise the outcomes of measures (Damiano et al. 2024; Metzger et al. 2017). In FCMs feedback loops between components can also be included, which can create oscillating dynamics in the system (Jetter & Kok 2014). By allowing for comparison of measures and evaluation of the advantages and disadvantages of different actions, FCM could therefore be used to assist the decision-making process (Alomia-Hinojosa et al. 2022; Cleveland et al. 2024; Solana-Gutiérrez et al. 2017). However, the qualitative nature of FCM makes uncertainty important to account for during the modelling (Baker et al. 2018), and the results of the model reflect perceived system dynamics rather than empirically validated predictions (Gray et al. 2015).

## 1.1 Problem statement

Local efforts and initiatives are of importance for successful EBM, and in the Southern Bothnian Sea a regional management framework has been developed by local stakeholders and scientists (HaV 2025). To support this management framework stakeholders have developed a fuzzy cognitive map to visualise how the management measures could affect the targeted pressures and associated ecosystem components. Assessing the potential impact of management measures, and the trade-offs and synergies between them, by further analysis of the FCM developed could be useful to improve the understanding of how management measures may affect the social-ecological system. With the intention of investigating how FCM modelling approaches can be used to support EBM and decision-making, the aim of this thesis is to apply modelling to the Southern Bothnian Sea FCM in order to:

1. Assess the effects of the management measures on ecological components and ecosystem services;

2. Identify trade-offs and synergies between management measures and;

3. Test different scenarios related to management of herring and compare outcomes on the social-ecological system.

# 2. Method and materials

## 2.1 The Southern Bothnian Sea EBM pilot area

### 2.1.1 Regional programme of measures

Due to the failure of reaching the environmental goals of the Baltic Sea, and to increase community engagement, an attempt to promote management and regional cooperation has been done by the use of EBM. In 2021 the Swedish Agency for Marine and Water Management (SwAM) initiated a pilot project for EBM of Swedish waters in three areas: the Stockholm archipelago, 8+fjordar on the west coast and the Southern Bothnian Sea (HaV 2025). In the Southern Bothnian Sea, local stakeholders, in collaboration with managers, have developed a regional management framework, with 23 management measures (Table 1). The overarching goal of the project is to work towards the Swedish environmental goals for marine management, and some prioritised aspects include the management of seals and great cormorants, establishing sustainable tourism, conserving small-scale costal fishing and improving the management of herring. The project involved five coastal municipalities of the region: Söderhamn, Gävle, Älvkarleby, Tierp and Östhammar, and stakeholders included, for example, representatives from the county administration boards of Gävleborg and Uppland, bird watching organisations and a sportfishing association (Sportfiskarna) (HaV 2025).

*Table 1. Management measures of the southern Bothnian Sea. Adapted and translated from the regional programme of measures (Delåtgärdsprogram Södra Bottenhavet 2025).*

| 1. Seals & Cormorants | 2. Salmon & Trout | 3. Herring | 4. Nature & Tourism | 5. Maritime Spatial Planning | 6. Measures & Coordination | 7. Sustainable Energy Extraction |
|---|---|---|---|---|---|---|
| 1.1 Reduced cormorant predation on fish stocks (Testeboån + Dalälven) | 2.1 Regional management of migratory species (salmon + trout) | 3.1 Reduced herring quotas in the Bothnian Bay. | 4.1 Mapping of nature values / basic survey of some areas | 5.1 Local and regional action coordination | 6.1 Restoration of salmon habitat (downstream Älvkarleby) | 7.1 Increased fossil-free energy extraction (offshore wind farms) |
|  | 2.2 Relocation of disease-control boundary for salmon. (Re-establishments) | 3.2 Fishing ban during winter months for up to 5 years (Oct–Mar) | 4.2 Mapping of visitor levels + marine tourism | 5.2 Platform for inter-municipal cooperation on land and water use | 6.2 Eutrophication is a growing problem — Action plan for each municipality needed | 7.2 State regulation of energy extraction. (e.g. auction procedures for offshore wind farms) |
|  | 2.3 Continued compensation stocking. (primarily trout) | 3.3 Strict protection; Finngrunden East + West/North. Free from human impact | 4.31 Protect areas to reduce impact on nature values | 5.3 Cross-border efforts around infrastructure, tourism, regional development | 6.3 Eutrophication – Post-dredging Analysis + training | 7.3 A broader perspective on energy extraction issues in the marine environment |
|  | 2.4 National plan for review of water environments and hydropower | 3.4 Protect sustainable coastal fishing: Reallocate approved quotas to coastal fishing | 4.32 Increase awareness of nature values |  | 6.4 Local water quality improvement projects, funding and the link to eutrophication |  |

### 2.1.2 Development of a fuzzy cognitive map for the Southern Bothnian Sea

In 2025 the stakeholders of the Southern Bothnian Sea were also involved in creating conceptual models. By the use of FCM stakeholders identified if the measures developed (Table 1) were affecting the pressures and in turn ecosystem components as they intended (HaV 2024). During participatory workshops the stakeholders were divided into interest groups based on the seven topics outlined in Table 1. Each group had a lead scientist assigned who worked in MentalModeler (www.mentalmoder.com) to clarify the links in the socio-ecological model as specified by the stakeholders. The first step in developing the models was to link each measure with the pressure it was intended to influence, then link the pressures with ecosystem components, and subsequently the ecosystem components with ecosystem services they provide. This was first done with the stakeholders and later, in a separate workshop, a group of scientists from the Swedish University of Agricultural Sciences (SLU) and Stockholm University (SU) adapted the ecosystem components into a simplified food web. The strength of connections between pressures, ecological components and ecosystem services was then adjusted based on scientific knowledge. This was followed by two rounds of feedback during which the stakeholders adjusted the strength of connections between the measures and the pressures and gave comments on the modified model of the researchers, based on their experiences. The researchers then checked the food web connections and made changes where appropriate according to stakeholder feedback and scientific knowledge. The model can continue to be updated as needed and the current version is visualised in Figure 1.

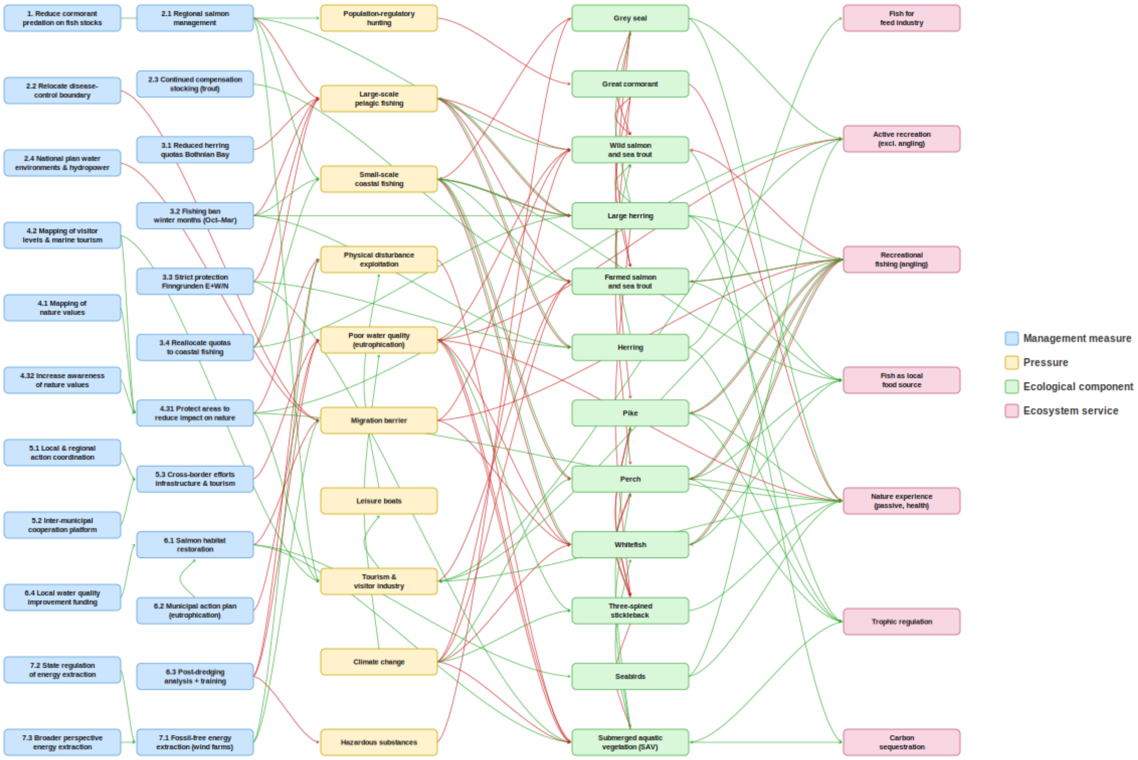


*Figure 1. Visualisation of the southern Bothnian Sea socio-ecological system. Adapted from [the current FCM](#).*

### 2.1.3 Stakeholder meeting in Tierp

The FCM of the Southern Bothnian Sea was built prior to the start of this thesis work, but connections and the uncertainties of some relationships between model components were adjusted during both a meeting with scientists from SLU, where links between pressures, ecological components and ecosystem services were in focus, as well as during a stakeholder meeting in Tierp in March 2026. During the meeting the stakeholders were divided into four groups of different focus: one for fish, one for seals and cormorants, one for nature and tourism and one for coordination of measures. The groups were then asked to assess the impact of the specific measures (Table 1), related to their groups topic, on pressures. Input from the stakeholders was also gathered by asking the stakeholders to discuss which ecological components and ecosystem services they thought were the most important. Each group picked one or two ecosystem services and ecological components, and their answers were then collected and used to prioritize scenario building. The most common species mentioned as being central were herring as well as wild salmon and sea trout, and the most important ecosystem service was determined to be fish as a local food source.

## 2.2 FCM model structure

FCM modelling was used as the analytical framework of this study. All analyses and visualisations were conducted using R (version 4.3.2), and the packages ggplot2 (Wickham 2016), dplyr (Wickham et al. 2023a) and tidyr (Wickham et al. 2023b). In the model, the system is represented as a weighted, directional graph, where concepts, or nodes, interact with each other through edges that represent perceived causal relationships (Aminpour et al. 2020; Özesmi & Özesmi 2004). An edge is a link between two nodes, often represented as an arrow, and the weight is a value assigned to each edge, indicating both the strength and direction of the causal relationship (Özesmi & Özesmi 2004). Fuzzy causal algebra can then be used to test the effect of perturbation of the system through the propagation of the causal relationships (Reum et al. 2021).

The cognitive map developed by scientists and stakeholders was transformed into an adjacency matrix with source nodes as columns and target nodes as rows. A source node can be defined as a node from which an edge originates and is the influencing variable, while a target node is the node to which the edge reaches, and is the variable being influenced. An increase or decrease in the source node propagates along the edge and affects the target node, and the activation of the target node is determined by the weighted sum of all incoming edges from source nodes (Özesmi & Özesmi 2004). The diagonal in the matrix was set to zero to prevent concepts from influencing themselves. The adjacency matrix included 133 edges and 54 nodes of four different categories: management measures, pressures, ecological components and ecosystem services. The edges are contained in the elements of the matrix and can be both negative and positive (Reum et al. 2021; Özesmi & Özesmi 2004). The values of the edges were drawn from the mapping done by stakeholders and experts, where the values were assigned on a scale from -1 to 1, in 0.25 increments. However, some changes were made to the original model to better reflect reality. One of the edges was manually added to the model to simulate the effect of measure 2.1 (Regional salmon management) on large-scale pelagic fishing, by the way of salmon bycatch. The edge from 7.1 (Expansion of fossil-free energy production) to climate change was removed, as local efforts are not likely to affect global climate change in a meaningful way. In Figure 1, nodes are represented as boxes of management measures, pressures, ecological components and ecosystem services, and edges are visualised as arrows.

After creating the adjacency matrix, the neutral, baseline values of the system were recorded by running the system without any influence from management measures. The new values of the system were then calculated using the standard synchronous update rule and the new state vector, which contains updated values of all concepts, was computed at each iteration step and stored, to be used at the next iteration. Using the update rule, at each iteration t, the activation value of node i was updated as:

$$A_i(t) = f(\Sigma_j w_{ji} \cdot A_j(t-1))$$

where $w_{ji}$ is the weight of the edge from node j (column, source node) to node i (row, target node), and f is an activation function that maps the weighted sum onto the interval $(-1, 1)$. The equation was applied at each iteration step until the system reached equilibrium, or stable oscillating cycles. A bipolar sigmoid activation function was used to keep the concept values in a correct range, and to stop the values from growing toward infinity (Grey 2015; Kok 2009). To keep the output values between -1 and 1 the activation function used was:

$$f(x) = 2 / (1 + e^{-x}) - 1$$

where x is the weighted sum of all incoming influences to a node. At each iteration, the new value of a concept is calculated as the sum of all incoming influences from connected concepts, and transformed through the sigmoid function. The network is updated simultaneously for all concepts at each step (Nápoles et al. 2026; Stylios & Groumpos 2004).

Each management measure was tested by fixing it at full implementation, 1.0, while every other concept was set to 0. The management signal then propagates through the network of causal relationships until the system reaches a new equilibrium, and the effect on the outcomes was recorded. After activation of a measure the simulations were run for up to 300 iterations for each of the 10 000 runs. The iterations continue until stable cycles are reached, defined as change of minimum and maximum values of less than 0.001, or to a stable equilibrium point. Each iteration therefore represents a single simultaneous update of all concept values across the network, while a run consists of up to 300 such iterations. Most outcomes did not reach a stable point but instead settled in oscillating cycles, due to feedback loops in the system (Jetter & Kok 2014; Stylios & Groumpos 2004). For example, there is a feedback loop between large-scale pelagic fishing and herring abundance, as fishing effort negatively affects the abundance of herring, and lower abundance of herring negatively affects fishing until the fishing pressure reaches a level where herring are abundant again and then fishing increases again, in a cycle. This loop caused herring to never settle at a single fixed point, and instead it oscillated in a stable cycle.

The effect of each measure on the outcome was measured on a normalised scale of (-1, 1), and the effects were calculated as the change in node value relative to the no-management baseline. The results were recorded for each simulation run and, for the oscillating nodes, the results included minimum and maximum values, as well as calculated midpoint values using:

$$(\text{maximum} + \text{minimum}) / 2$$

which represents the overall effect of a measure on an outcome. The minimum, maximum and midpoint results of each simulation run were stored to compute the distributional values and oscillation ranges. While the magnitude of the results is qualitative, positive outputs of the function indicate that a concept has increased above baseline and negative outputs indicate that the concept has decreased below baseline (Baker et al. 2018, Reum et al. 2021).

### 2.2.1 Monte Carlo analysis

Uncertainty is an important part of FCM since the interaction strengths of a system can be difficult to accurately assess. To account for uncertainty Monte Carlo (MC) analysis was used in the model, which is a method where repeated random sampling is used (Baker et al. 2018). 10 000 simulations were run for each management activation, and edge noise was added to the edge weights. For each MC simulation the edge weights were multiplied with a random noise factor, or edge noise, drawn from a normal distribution with mean 1 and standard deviation 0.15 (15%). The noise factor was made proportional to the edge weight by the function:

$$w^* = w \cdot (1 + N(0, 0.15))$$

where $w^*$ is the new weight, $w$ is the original edge weight, and $N(0, 0.15)$ draws a random value for each edge with a normal distribution of 0.15 and a mean of 0.

The results therefore show not just the average effect of management measures but a distribution of possible effects.

After discussions with scientists, four edges in the model were assigned elevated uncertainty levels of twice as much edge noise, 30%. These edges included the effect of measure 2.1 (Regional salmon management) on the pressure large-scale pelagic fishing, the effect between the policy measures 7.2, 7.3 and 7.1 (all related to fossil-free energy extraction), as well as effect of measure 7.1 on the pressure migration barrier. Five other edges received the same treatment due to uncertainty from the stakeholders. These edges were mainly related to the effect of measures regarding herring and included the effect of measure 3.1 (Reduced herring quotas) on large-scale pelagic fishing, the effect of measure 3.2 (Fishing ban winter) on large herring, the effect of measure 3.3 (Protection of Finngrundet) on herring, the effect of measure 3.4 (Reallocated fish quotas) on large-scale pelagic fishing, and the effect of measure 4.31 (Protect areas) on tourism. These uncertainties were mainly due to that the level of impact from measures will be dependent on the level and type of implementation.

### 2.2.2 Scenario testing

The main analysis focused on implementing all 23 management measures individually and evaluating the result of these separate scenarios. Each measure was activated by fixing it at full implementation of 1.0, while all other measures nodes were set to 0. The results were calculated based on effect changes from baseline values to the values after measure implementation, using the mean midpoint for the oscillating ranges. The mean midpoint effect, as well as the 5th and 95th percentiles of MC simulation distribution (representing 90% confidence interval), of each measure on ecological components and ecosystem services was then summarised.

Using the results from the management analysis a trade-off analysis was conducted by comparing which measures had the most contrasting effects on ecological components and ecosystem services. The biggest trade-offs of the system, with conflicts of values larger than 0.5, were summarised and visualised. The two measures with the biggest conflict value were also activated at the same time, by fixing both at 1.0 and running the model, to assess their joint effect on the system. Synergies between measures were identified by considering which measures had the biggest positive effect on an outcome node. For each outcome the two measures with the highest positive effect were evaluated to ensure that only measures that worked through different node pathways were selected. The win-win measure pairs were ranked according to their per simulation average midpoint effect on the outcome, and the top five pairs were selected and visualised, showing full distribution of the synergistic effects. The two measures with highest synergistic effect were then jointly activated to evaluate how the measures affected the system together.

A scenario analysis focused on measure 3.1 (Reduced herring quotas) and 3.3 (Protection of Finngrundet), was also carried out to assess how sensitive the outcomes were to fishing effort. These measures were directed towards management of herring, which was concluded to be one of the most important ecological components by the stakeholders. In the analysis the results of different levels of implementation were compared for each of the two measures by activating the outgoing edge from the measure at four levels of intensity (0.25, 0.5, 0.75 and 1). As in the main analysis, 10 000 MC simulations were made at each level, and the recorded results were based on mean midpoint effect sizes of the outcomes of every simulation run. In the system there is a feedback loop between the number of herring available and the level of large-scale pelagic fishing conducted. By removing that feedback loop and keeping the level of fishing constant regardless of the fish abundance, a different type of fisheries management approach was also simulated. As such, the two scenarios, keeping the fishing level constant and allowing free feedback between the level of fishing and the abundance of fish, were compared across the different levels of implementation of the measures.

# 3. Results

## 3.1 Effect of measures on ecological components and ecosystem services

Overall, the effect of the 23 measures on the ecological components of the system was variable, with midpoints ranging from -0.23 to 0.64 (Fig. 2). Many measures, such as measure 1 and 2.1, which were reduced cormorant predation and regional salmon management, respectively, had an effect on one or two species, while some measures had a larger impact, such as measure 3.3 and 3.4 (Protection of Finngrundet and Reallocated fish quotas). These measures had a positive effect on most ecological components, apart from three-spined stickleback and farmed salmon and sea trout. Measures focused on sustainable energy production (7.1-7.3) had negative effects on all ecological components except for three-spined stickleback.

While some ecological components were only affected by one or two measures, such as great cormorant and seabirds, wild salmon and sea trout and SAV responded positively to most measures. SAV had the overall most positive outcome (0.64 ± 0.11) from measure 3.3 (Protection of Finngrundet), and the largest negative response (-0.23 ± 0.08) from measure 7.1 (Fossil-free energy expansion). Wild salmon and sea trout benefitted most (0.49 ± 0.10) from measure 2.1 (Regional salmon management) and were most negatively affected (-0.13 ± 0.06) by measure 7.1 (Fossil-free energy expansion). Three-spined stickleback was negatively affected by most measures and had the larest negative response (-0.19 ± 0.06) to measure 3.3 (Protection of Finngrundet). The second most negatively affected species group were farmed salmon and sea trout, which was, however, positively affected (0.35 ± 0.10) by measure 2.1 (Regional salmon management).

|  | 1. Reduce cormorant pre... | 2.1 Regional salmon man... | 2.2 Relocate disease-co... | 2.3 Compensation stocking | 2.4 National plan water | 3.1 Reduced herring quotas | 3.2 Fishing ban winter | 3.3 Protection Finngrundet | 3.4 Reallocate quotas to | 4.1 Mapping of nature | 4.2 Mapping of visitor | 4.31 Protect areas to | 4.32 Increase awareness of | 5.1 Local & regional | 5.2 Inter-municipal coo... | 5.3 Cross-border effort... | 6.1 Salmon habitat rest... | 6.2 Municipal action plan | 6.3 Dredging analysis | 6.4 Local water quality | 7.1 Fossil-free energy ... | 7.2 State regulation of | 7.3 Broader perspective... |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Farmed salmon and sea trout** | 0.05 | -0.05 | -0.02 | 0.35 | -0.02 | 0.02 | -0.07 | -0.10 | -0.01 | -0.08 | -0.09 | -0.16 | -0.08 | -0.02 | -0.03 | -0.05 | -0.05 | -0.06 | -0.07 | -0.01 | 0.05 | 0.02 | 0.02 |
| **Great cormorant** | -0.17 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Grey seal** | 0.00 | 0.00 | 0.00 | -0.01 | 0.00 | 0.03 | 0.16 | 0.00 | 0.21 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Herring** | 0.00 | 0.09 | 0.00 | 0.00 | 0.00 | 0.09 | 0.43 | 0.46 | 0.13 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Large herring** | -0.01 | 0.01 | 0.00 | -0.02 | 0.00 | 0.07 | 0.32 | -0.01 | 0.43 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Perch** | 0.05 | -0.06 | -0.02 | -0.06 | -0.02 | 0.01 | 0.01 | 0.22 | -0.04 | 0.06 | 0.02 | 0.12 | 0.06 | 0.03 | 0.03 | 0.07 | 0.04 | 0.07 | 0.12 | 0.01 | -0.07 | -0.03 | -0.03 |
| **Pike** | 0.00 | 0.00 | -0.03 | -0.05 | -0.03 | 0.01 | 0.09 | 0.27 | 0.07 | 0.07 | 0.02 | 0.15 | 0.07 | 0.04 | 0.05 | 0.09 | 0.06 | 0.10 | 0.15 | 0.01 | -0.10 | -0.05 | -0.05 |
| **Seabirds** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.12 | 0.02 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 |
| **Submerged aquatic vegetation** | 0.01 | -0.02 | -0.01 | -0.04 | -0.01 | 0.03 | 0.18 | 0.64 | 0.15 | 0.15 | 0.03 | 0.29 | 0.15 | 0.07 | 0.09 | 0.18 | 0.16 | 0.20 | 0.32 | 0.04 | -0.23 | -0.11 | -0.11 |
| **Three-spined stickleback** | -0.01 | 0.01 | 0.02 | 0.04 | 0.02 | -0.02 | -0.12 | -0.19 | -0.13 | -0.05 | -0.02 | -0.10 | -0.05 | -0.04 | -0.05 | -0.11 | -0.04 | -0.11 | -0.13 | -0.01 | 0.07 | 0.03 | 0.03 |
| **Whitefish** | -0.01 | -0.06 | 0.05 | -0.05 | 0.05 | 0.00 | -0.05 | 0.11 | -0.11 | 0.03 | 0.01 | 0.06 | 0.03 | 0.03 | 0.04 | 0.07 | 0.07 | 0.08 | 0.08 | 0.02 | -0.06 | -0.03 | -0.03 |
| **Wild salmon and sea trout** | 0.04 | 0.49 | 0.20 | -0.02 | 0.19 | 0.08 | 0.30 | 0.27 | 0.24 | 0.02 | 0.01 | 0.04 | 0.02 | 0.04 | 0.05 | 0.10 | 0.17 | 0.12 | 0.07 | 0.04 | -0.13 | -0.06 | -0.06 |

*Figure 2. The midpoint effect sizes of management measures on ecological components of the FCM.*

The range of effects was smaller for ecosystem services than ecological components, with fewer negative effects on the outcomes (Fig. 3). The midpoint effect size ranged from -0.13 to 0.52. Some measures, such as 1 (Reduce cormorant predation), 2.2 (Relocate disease-control borders) and 2.4 (National plan water) had almost no effect on any ecosystem services. In contrast, measures 3.2-3.4, which were related to herring management, consistently had a positive effect across all ecosystem services and measures 3.3 (Protection of Finngrundet) and 4.31 (Protect areas) had the overall largest positive effects on ecosystem services. Measures 7.1-7.3 (Fossil free energy expansion) had no positive effect on any of the seven ecosystem services in the model.

The largest negative effect observed (-0.13 ± 0.05) was the response of carbon sequestration to measure 7.1 (Fossil-free energy expansion). Nature experience was the ecosystem service with the most positive results, with the biggest impact (0.52 ± 0.10) coming from measure 4.31 (Protect areas). Active recreation also responded strongly to measure 4.31 (Protect areas) and had the second most positive effect (0.50 ± 0.10). Trophic regulation responded positively to measure 3.3 (Protection of Finngrundet), as well as measures 3.2 and 3.4 (Fishing ban winter and reallocate quotas respectively). Fish as a local food source and recreational fishing both had small responses to most measures, except for to measures 3.4 (Reallocate quotas) (0.14 ± 0.09) and 3.3 (Protection of Finngrundet) (0.12 ± 0.06), respectively.

| | 1. Reduce cormorant pre... | 2.1 Regional salmon man... | 2.2 Relocate disease-co... | 2.3 Compensation stocking | 2.4 National plan water | 3.1 Reduced herring quotas | 3.2 Fishing ban winter | 3.3 Protection Finngrundet | 3.4 Reallocate quotas to | 4.1 Mapping of nature | 4.2 Mapping of visitor | 4.31 Protect areas to | 4.32 Increase awareness of | 5.1 Local & regional | 5.2 Inter-municipal coo... | 5.3 Cross-border effort... | 6.1 Salmon habitat rest... | 6.2 Municipal action plan | 6.3 Dredging analysis | 6.4 Local water quality | 7.1 Fossil-free energy ... | 7.2 State regulation of | 7.3 Broader perspective... |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Active recreation** | 0.00 | 0.00 | 0.00 | -0.01 | 0.00 | 0.01 | 0.07 | 0.12 | 0.08 | 0.25 | 0.07 | 0.50 | 0.25 | 0.06 | 0.07 | 0.15 | 0.09 | 0.16 | 0.13 | 0.02 | -0.04 | -0.02 | -0.02 |
| **Carbon sequestration** | 0.01 | 0.05 | 0.02 | -0.02 | 0.02 | 0.03 | 0.13 | 0.34 | 0.11 | 0.07 | 0.01 | 0.15 | 0.07 | 0.04 | 0.05 | 0.10 | 0.10 | 0.11 | 0.17 | 0.02 | -0.13 | -0.06 | -0.06 |
| **Fish as local food source** | 0.02 | 0.01 | 0.00 | 0.06 | 0.00 | 0.01 | 0.08 | 0.05 | 0.14 | 0.00 | -0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 | 0.02 | 0.00 | -0.02 | -0.01 | -0.01 |
| **Fish for feed industry** | 0.00 | 0.05 | 0.00 | 0.00 | 0.00 | 0.04 | 0.21 | 0.23 | 0.06 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Nature experience** | 0.06 | -0.02 | -0.01 | -0.04 | -0.01 | 0.02 | 0.11 | 0.20 | 0.11 | 0.26 | 0.07 | 0.52 | 0.26 | 0.06 | 0.08 | 0.16 | 0.10 | 0.18 | 0.18 | 0.03 | -0.07 | -0.03 | -0.03 |
| **Recreational fishing** | 0.02 | -0.04 | 0.04 | 0.05 | 0.04 | 0.01 | 0.03 | 0.12 | 0.03 | 0.01 | -0.01 | 0.03 | 0.01 | 0.01 | 0.02 | 0.03 | 0.05 | 0.04 | 0.05 | 0.01 | -0.06 | -0.03 | -0.03 |
| **Trophic regulation** | 0.02 | 0.01 | -0.02 | -0.04 | -0.02 | 0.05 | 0.27 | 0.30 | 0.22 | 0.04 | 0.02 | 0.09 | 0.04 | 0.02 | 0.02 | 0.05 | 0.03 | 0.06 | 0.09 | 0.01 | -0.05 | -0.03 | -0.03 |

*Figure 3. The midpoint effect sizes of management measures on ecosystem services of the FCM.*

## 3.2 Top oscillating outcomes

Due to the feedback loops of the system several outcomes oscillated continuously between an upper and lower state, with similar cycle ranges regardless of the measure activated. Six ecological components and ecosystem services had a mean stable oscillation range > 1 (Fig. 4). Fish as a local food source was the outcome node with the largest mean range (1.62), followed by recreational fishing (1.53) and whitefish (*Coregonus maraena*) (1.33). Recreational fishing, perch and farmed salmon and sea trout oscillated around 0, while fish as a local food source and trophic regulation had positive oscillation midpoints, and whitefish had a slightly negatively shifted cycle.

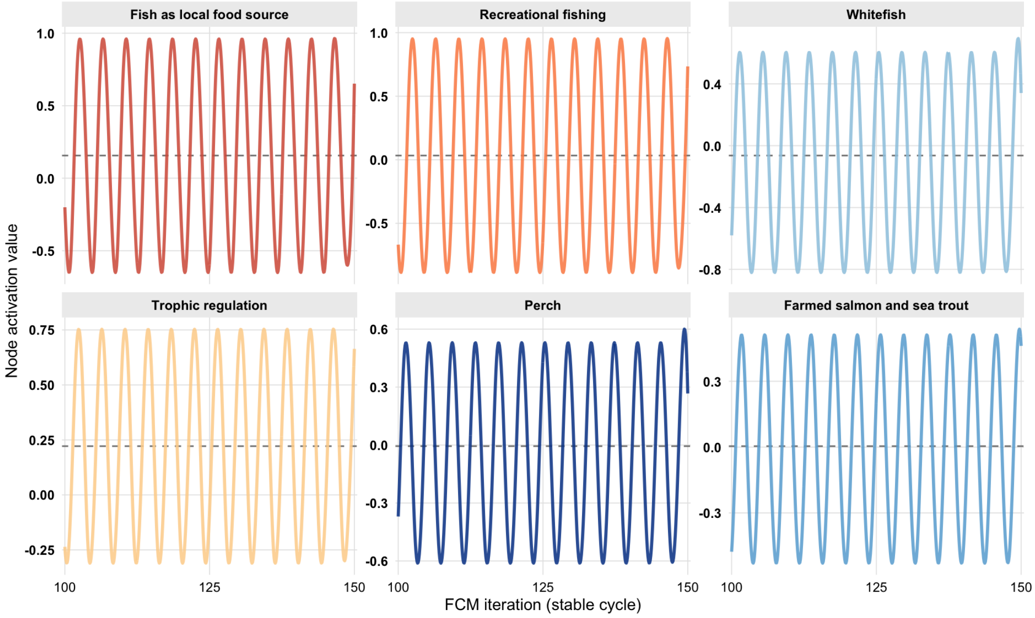


*Figure 4. Ecological components and ecosystem services with a mean oscillation range > 1. The dashed line represents the midpoint value of the cycles.*

## 3.3 Trade-offs and synergies

Several trade-offs between measures were found (Fig. 5). The largest conflict in the system was the effect of measures 3.3 (Protection of Finngrundet, and 7.1 (Fossil-free energy expansion) on SAV. The difference in mean effect for the two measures was 0.87 ± 0.14. The distribution of the values for SAV was also the widest among all top conflicts, which reflects high variability in the strength of the trade-off across the MC simulations. Measure 7.1 (Fossil-free energy expansion) appeared in four out of the top five conflicts analysed, due to its negative effects on SAV, wild salmon and sea trout, nature experience and active recreation. At the same time, measure 4.31 (Protect areas) was part of three trade-offs, due to its positive effect on nature experience and active recreation, as well as its negative effect on farmed salmon and sea trout. Both wild salmon and sea trout as well as farmed salmon and sea trout were parts of conflicts, with mean conflict values of 0.62 ± 0.11 and 0.51 ± 0.12, respectively.

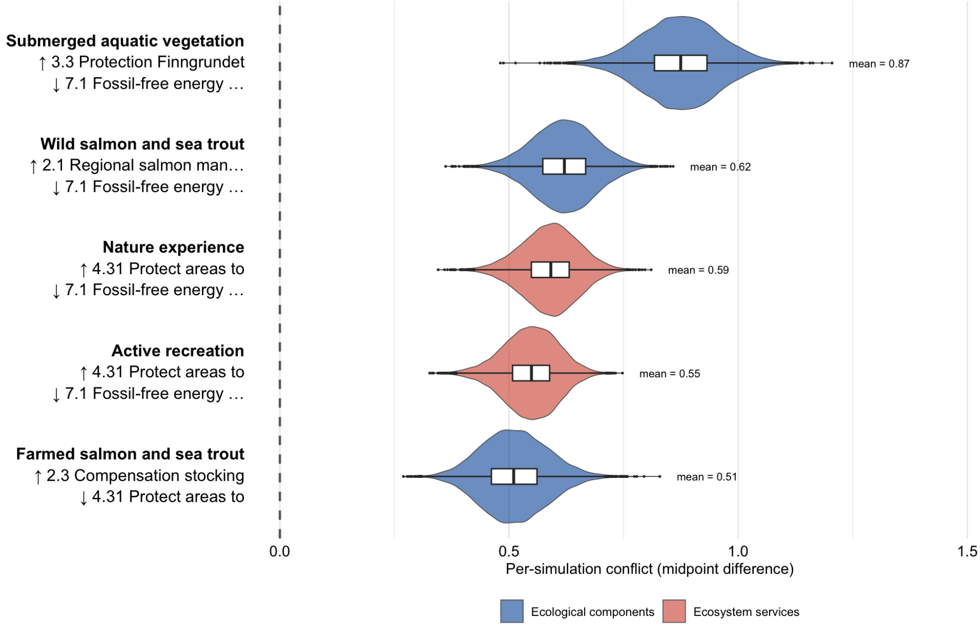
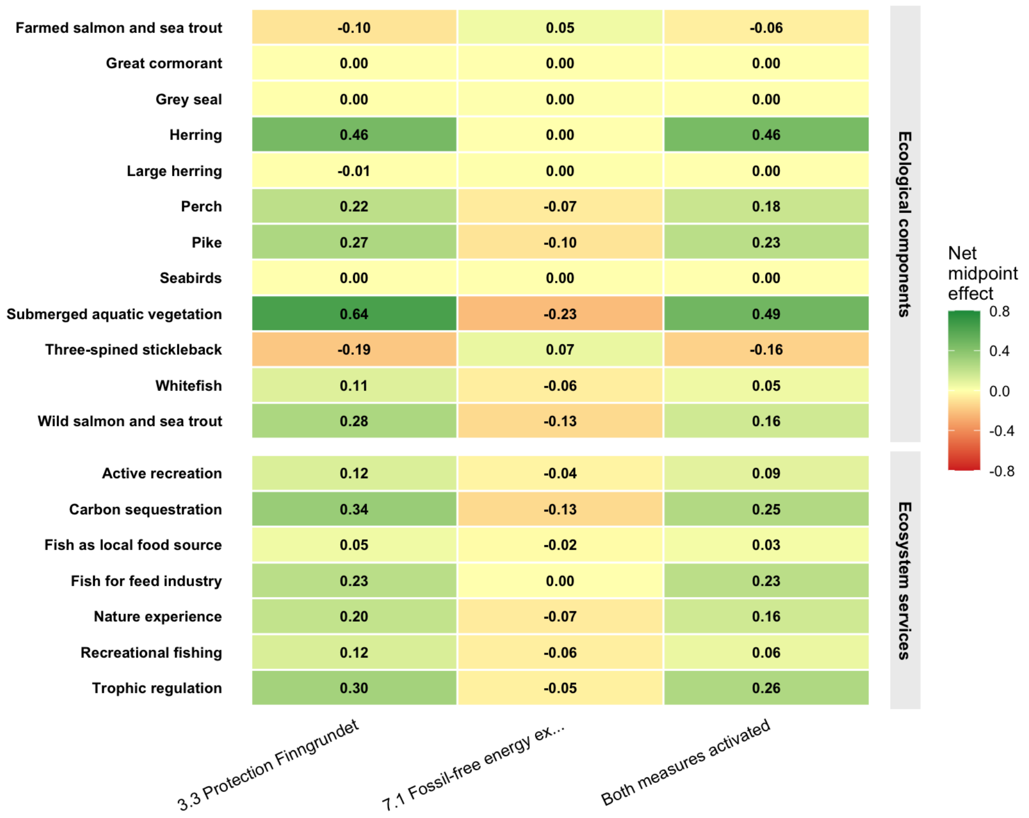


*Figure 5. The five largest trade-offs between measures, showing the mean difference in effect of the measures and the distribution of values across all Monte Carlo simulations.*

When the measures that were part of the largest trade-off, measure 3.3 (Protection Finngrundet) and 7.1 (Fossil-free energy expansion), were activated at the same time the positive effect of measure 3.3 (Protection of Finngrundet) generally outweighed the negative results of measure 7.1 (Fossil-free energy expansion) (Fig. 6). The focal conflict ecosystem component, SAV, still had a positive response (0.49 ± 0.16) when both measures were activated at the same time, while both farmed salmon and sea trout and stickleback had negative responses of -0.06 ± 0.04 and -0.16 ± 0.06 respectively.



| | 3.3 Protection Finngrundet | 7.1 Fossil-free energy ex... | Both measures activated | |
|---|---|---|---|---|
| Farmed salmon and sea trout | -0.10 | 0.05 | -0.06 | Ecological components |
| Great cormorant | 0.00 | 0.00 | 0.00 | |
| Grey seal | 0.00 | 0.00 | 0.00 | |
| Herring | 0.46 | 0.00 | 0.46 | |
| Large herring | -0.01 | 0.00 | 0.00 | |
| Perch | 0.22 | -0.07 | 0.18 | |
| Pike | 0.27 | -0.10 | 0.23 | |
| Seabirds | 0.00 | 0.00 | 0.00 | |
| Submerged aquatic vegetation | 0.64 | -0.23 | 0.49 | |
| Three-spined stickleback | -0.19 | 0.07 | -0.16 | |
| Whitefish | 0.11 | -0.06 | 0.05 | |
| Wild salmon and sea trout | 0.28 | -0.13 | 0.16 | |
| Active recreation | 0.12 | -0.04 | 0.09 | Ecosystem services |
| Carbon sequestration | 0.34 | -0.13 | 0.25 | |
| Fish as local food source | 0.05 | -0.02 | 0.03 | |
| Fish for feed industry | 0.23 | 0.00 | 0.23 | |
| Nature experience | 0.20 | -0.07 | 0.16 | |
| Recreational fishing | 0.12 | -0.06 | 0.06 | |
| Trophic regulation | 0.30 | -0.05 | 0.26 | |

*Figure 6. The midpoint effect sizes of measure 3.3 (Protection of Finngrundet), measure 7.1 (Fossil-free energy expansion) and both measures implemented at the same time through joint activation of 1.0.*

Synergies were found across the management measures (Fig. 7). Both measure 3.2 (Fishing ban winter) and 3.3 (Protection of Finngrundet) appeared in three of the five win-win pairs, and measures that focused on herring had the biggest synergistic results overall. The mean synergistic effect of measures 3.2 Fishing ban winter) and 3.3 (Protection of Finngrundet) was 0.44 ± 0.13. However, the effect on herring had a large distribution, due to the feedback loops, and the effect of the measures could therefore be variable. The ecosystem service nature experience was the second largest synergy, with an average mean value of 0.31 ± 0.08 when both measures 4.31 (Protect areas) and 6.1 (Restoration of salmon habitat) were activated.

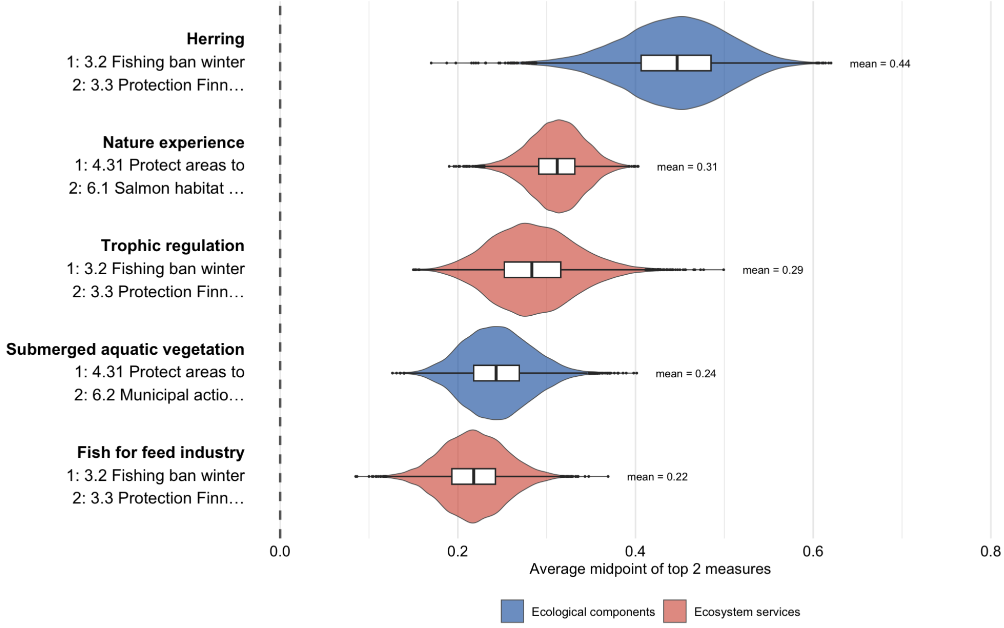


*Figure 7. The five largest synergies between measures, showing the most positive measure (1) and the second most positive measure (2) for each outcome. The distribution shows the average combined midpoint value of both measures' effect per Monte Carlo simulation.*

When the top synergistic measures 3.2 and 3.3 (Fishing ban winter and protection of Finngrundet, respectively) were activated at the same time both herring and SAV responded positively (0.75 ± 0.15 and 0.73 ± 0.12 respectively) (Fig. 8). Whitefish and large herring had different responses to measures 3.2 and 3.3, as whitefish benefitted more from measure 3.3 (Protection of Finngrundet) (0.11 ± 0.04), and large herring more from measure 3.2 (Fishing ban winter) (0.32 ± 0.18). The joint activation was however still favourable for large herring (0.34 ± 0.12), but less so for whitefish (0.03 ± 0.06). Trophic regulation was the ecosystem service that benefitted the most from the joint activation (0.54 ± 0.13).

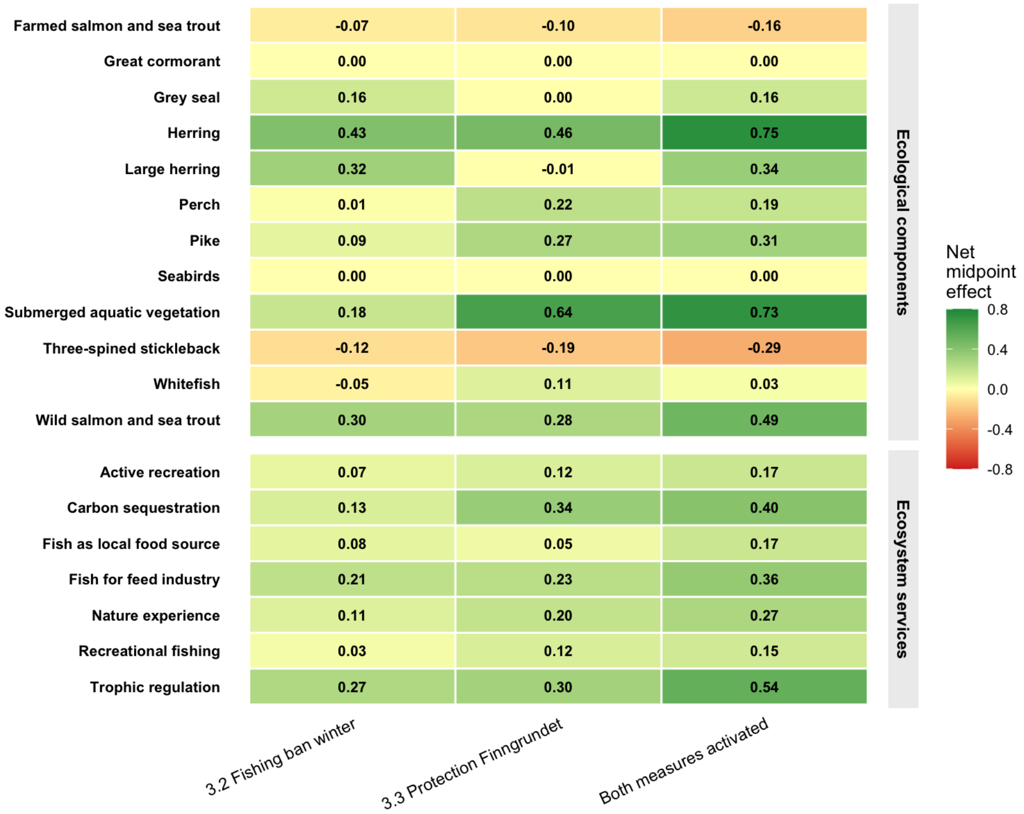


*Figure 8. The midpoint effect sizes of measure 3.2, measure 3.3, and both measures implemented at the same time through joint activation of 1.0.*

## 3.4 Scenario testing of measures 3.1 and 3.3

The results of different scenarios were tested by adjusting the level of edge weight from measures 3.1 (Reduced herring quotas) and 3.3 (Protection of Finngrundet) to the pressure large-scale pelagic fishing (Fig. 9). A comparison was also made by considering the difference in results between keeping the fishing level constant by removing the feedback from fish to large-scale pelagic fishing (fishing level fixed) and allowing the fishing level to respond to the abundance of fish (free feedback). When the fishing level was fixed at a constant level, corresponding to the level of implementation from measure 3.1 (Reduced herring quotas), the effect on ecological components and ecosystem services was consistently larger compared to the free feedback scenario. For both fixed-fishing pressure and free feedback scenarios large herring and wild salmon and sea trout were the species with the largest positive effect, while three-spined stickleback was the only species negatively affected. The transition from free feedback to fixed fishing pressure increased the effect on herring from 0.17 to 0.46 under full implementation (1.0) of the measure.

| | Free feedback | | | | Fishing level fixed | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0.25 | 0.50 | 0.75 | 1.00 | 0.25 | 0.50 | 0.75 | 1.00 | |
| Farmed salmon | 0.01 | 0.02 | 0.02 | 0.03 | 0.02 | 0.05 | 0.07 | 0.10 | Ecological components |
| Great cormorant | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| Grey seal | 0.02 | 0.03 | 0.05 | 0.07 | 0.05 | 0.10 | 0.15 | 0.20 | |
| Herring | 0.04 | 0.09 | 0.13 | 0.17 | 0.12 | 0.24 | 0.36 | 0.46 | |
| Large herring | 0.04 | 0.07 | 0.10 | 0.14 | 0.10 | 0.21 | 0.31 | 0.40 | |
| Perch | 0.00 | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 | 0.03 | 0.04 | |
| Pike | 0.01 | 0.01 | 0.02 | 0.03 | 0.02 | 0.04 | 0.06 | 0.07 | |
| Seabirds | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| SAV | 0.02 | 0.03 | 0.05 | 0.07 | 0.06 | 0.11 | 0.17 | 0.22 | |
| Stickleback | -0.01 | -0.02 | -0.04 | -0.05 | -0.04 | -0.08 | -0.11 | -0.14 | |
| Whitefish | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -0.01 | -0.01 | -0.02 | |
| Wild salmon | 0.04 | 0.08 | 0.12 | 0.16 | 0.13 | 0.25 | 0.35 | 0.45 | |
| Active recreation | 0.01 | 0.01 | 0.02 | 0.03 | 0.02 | 0.05 | 0.07 | 0.09 | Ecosystem services |
| Carbon sequestration | 0.01 | 0.03 | 0.04 | 0.05 | 0.04 | 0.09 | 0.13 | 0.16 | |
| Fish as food | 0.01 | 0.01 | 0.02 | 0.03 | 0.03 | 0.05 | 0.08 | 0.12 | |
| Fish for feed | 0.02 | 0.04 | 0.06 | 0.08 | 0.06 | 0.12 | 0.18 | 0.23 | |
| Nature experience | 0.01 | 0.02 | 0.04 | 0.05 | 0.04 | 0.07 | 0.11 | 0.14 | |
| Recreational fishing | 0.01 | 0.01 | 0.02 | 0.03 | 0.02 | 0.05 | 0.07 | 0.10 | |
| Trophic regulation | 0.02 | 0.05 | 0.08 | 0.10 | 0.08 | 0.17 | 0.25 | 0.32 | |
| Coastal fishing | 0.01 | 0.02 | 0.03 | 0.04 | 0.03 | 0.07 | 0.11 | 0.14 | Press. |
| Large-scale fishing | -0.09 | -0.17 | -0.26 | -0.34 | -0.25 | -0.50 | -0.75 | -1.00 | |

*Figure 9. Dynamic and fixed-pressure midpoint effect sizes of measure 3.1 (Reduced herring quotas) on ecological components, ecosystem services and pressures across four levels of implementation.*

Measure 3.3 (Protection of Finngrundet) had a positive effect on all ecological components except for farmed salmon and sea trout and three-spined stickleback (Fig. 10). The largest positive effects for both dynamic and fixed pressure were on herring and SAV, at all levels of implementation. Similarly to the results of the scenarios for measure 3.1 (Reduced herring quotas), increasing the implementation level of measure 3.3 (Protection Finngrundet) had larger effects, both positive and negative, across all outcomes. However, measure 3.3 (Protection Finngrundet) showed a smaller difference between free feedback and fixed fishing pressure conditions than measure 3.1 (Reduced herring quotas) across most outcomes. Still, fixing the pressure resulted in larger positive effects on outcome nodes such as, for example, trophic regulation, SAV and wild salmon.

| | | Free feedback | | | | Fishing level fixed | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 0.25 | 0.5 | 0.75 | 1 | 0.25 | 0.5 | 0.75 | 1 |
| Ecological components | Farmed salmon | -0.02 | -0.05 | -0.06 | -0.08 | -0.01 | -0.01 | -0.01 | 0.00 |
| | Great cormorant | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Grey seal | 0.01 | 0.01 | 0.02 | 0.03 | 0.05 | 0.10 | 0.15 | 0.19 |
| | Herring | 0.15 | 0.29 | 0.42 | 0.53 | 0.24 | 0.46 | 0.63 | 0.75 |
| | Large herring | 0.01 | 0.03 | 0.05 | 0.07 | 0.10 | 0.20 | 0.30 | 0.39 |
| | Perch | 0.07 | 0.13 | 0.18 | 0.22 | 0.08 | 0.15 | 0.19 | 0.21 |
| | Pike | 0.09 | 0.17 | 0.23 | 0.28 | 0.11 | 0.19 | 0.24 | 0.28 |
| | Seabirds | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | SAV | 0.20 | 0.38 | 0.54 | 0.66 | 0.26 | 0.48 | 0.64 | 0.74 |
| | Stickleback | -0.07 | -0.12 | -0.17 | -0.21 | -0.10 | -0.18 | -0.25 | -0.30 |
| | Whitefish | 0.03 | 0.06 | 0.08 | 0.10 | 0.03 | 0.05 | 0.06 | 0.06 |
| | Wild salmon | 0.10 | 0.19 | 0.27 | 0.34 | 0.20 | 0.37 | 0.50 | 0.59 |
| Ecosystem services | Active recreation | 0.04 | 0.08 | 0.11 | 0.13 | 0.06 | 0.11 | 0.15 | 0.18 |
| | Carbon sequestration | 0.11 | 0.21 | 0.29 | 0.36 | 0.15 | 0.28 | 0.36 | 0.42 |
| | Fish as food | 0.02 | 0.03 | 0.05 | 0.07 | 0.04 | 0.09 | 0.14 | 0.20 |
| | Fish for feed | 0.07 | 0.14 | 0.20 | 0.26 | 0.12 | 0.23 | 0.30 | 0.36 |
| | Nature experience | 0.07 | 0.13 | 0.18 | 0.22 | 0.10 | 0.18 | 0.25 | 0.29 |
| | Recreational fishing | 0.03 | 0.07 | 0.10 | 0.14 | 0.06 | 0.12 | 0.18 | 0.22 |
| | Trophic regulation | 0.09 | 0.18 | 0.27 | 0.35 | 0.17 | 0.34 | 0.47 | 0.56 |
| Press. | Coastal fishing | 0.02 | 0.04 | 0.05 | 0.07 | 0.05 | 0.10 | 0.14 | 0.19 |
| | Large-scale fishing | -0.05 | -0.09 | -0.15 | -0.20 | -0.25 | -0.50 | -0.75 | -1.00 |

*Figure 10. Dynamic and fixed-pressure midpoint effect sizes of measure 3.3 (Protection Finngrundet) on ecological components, ecosystem services and pressures across four levels of implementation.*

# 4. Discussion

## 4.1 Positive and negative effects of management measures

The effects of the 23 management measures were variable. The most effective management measures were generally related to herring management (3.1-3.4). These measures had the biggest positive impacts on for example herring, SAV and trophic regulation, and were mechanistically mainly driven by the effects on SAV. Aquatic vegetation was revealed to be a central node in the system, providing important functions such as improved water quality and habitats for fish. Due to the centrality of SAV in the food web, positive effects of for example measure 3.3 (Protection Finngrundet) cascade through the system and positively affect most ecological components and ecosystem services. At the same time, the measures related to fossil-free energy extraction and offshore windfarms (7.1-7.3) had the overall most negative effect on the system components due to an assumed increase in physical disturbance and exploitation of the seabed. Increased physical disturbance negatively affects SAV, and these impacts cascade through the system, through both a direct negative response from fish, as well as indirectly through feedback loops between water quality and SAV. Management of the Southern Bothnian Sea may therefore benefit from mitigating the effect of disturbances and promoting SAV. Certain key habitat-forming aquatic vegetation in the Baltic Sea, such as the large macroalgae *Furcellaria lumbricalis*, have also been predicted to be severely impacted by climate change, which further indicates the need for management which considers SAV both when planning measures as well as during monitoring (Torn et al. 2020).

Many ecological components and ecosystem services had small responses to management measures, and the results indicate that some measures affect only a few outcomes, while others have more widespread effects across the system. For example, measure 1 specifically targeted great cormorants and did not greatly impact the rest of the system. The findings therefore suggest that if the goal is to increase fish stocks it will be better achieved by measures focused on, for example, reduced industrial fishing and marine protected areas, such as measures 3.1 (Reduced herring quotas) and 3.3 (Protection Finngrundet), rather than targeting cormorants. Measures related to the management of salmon and sea trout (2.1-2.4) also had limited effects on the system as a whole, as they were specifically aimed at just one species. However, while for example measure 2.1 (Regional salmon management) seemed to be relevant for wild salmon conservation, measure 2.3 (Compensation stocking) instead had a slightly negative effect on wild salmon and sea trout. Compensation stocking of farmed salmon may therefore conflict with management goals concerning wild salmon, and it has been shown that stocking could lead to genetic homogenization of wild populations and compromise fitness (Bernaś et al. 2020; Östergren et al. 2021). However, such a direct negative link between farmed salmon and wild salmon is missing in the model. For management to have a widespread positive effect on the system some measures may therefore benefit from being implemented together with other measures or being redesigned to have a larger effect on pressures.

While these results cannot be used to assess how the system would react to management implementation in reality, due to the qualitative nature of the model, they are potentially useful for furthering understanding of the system and highlighting topics for discussion, which is relevant for EBM. For example, measures that were not very effective could potentially be re-evaluated, while measures that created unwanted side effects could be re-designed to mitigate some of the negative impacts. The results also highlight measures that could be beneficial for multiple objectives, as well as measures that are the less likely to contribute to a desired outcome state. FCM modelling could therefore be relevant to address the potential effectiveness of interventions (Cleveland et al. 2024; Grey et al. 2015).

## 4.2 Feedback loops and oscillations

There are several feedback loops in the system. For example, when herring increases, due to a reduced amount of large-scale pelagic fishing, the fishing effort will increase again due to the yearly setting of quotas, which suppresses the herring, and in turn the fishing is reduced until the level of herring biomass increases again, which makes the quotas higher again. Similar loops can also be seen between fish species and coastal fishing as well as recreational fishing, which limits the effect of measures focused on reducing fishing efforts. Another loop in the system includes the negative feedback between poor water quality (eutrophication) and SAV. Degradation of SAV leads to a reduced nutrient uptake, which increases the poor water quality and, in turn, affects SAV negatively in an amplifying loop. Furthermore, three-spined stickleback negatively affects SAV through predation pressure on zooplankton and has a positive connection to poor water quality in the model. Three-spined stickleback benefits from eutrophic conditions and has increased in several aquatic systems, including the Baltic Sea. Such an increase may be negative for the ecosystem as stickleback could impair the recruitment of other fish species, as well as increase the effect of eutrophication through zooplankton predation (Olin et al. 2022). The negative effects of three-spined stickleback could be hindered by predator recovery, as for example pike and perch prey on stickleback. Measures aimed at predator fish recovery and reducing nutrient loads are as such efficiently positive for the modelled system through the positive effects on both SAV and the food web by regulation of stickleback. It could also be relevant to consider implementing measures that are specifically aimed at stickleback, such as targeted removals, to prevent stickleback domination in the system (Olin et al. 2022; Olsson et al. 2019). Many parts of the system are therefore interconnected in different loops, which could be challenging for management.

As a consequence of the feedback loops most ecosystem services and ecological components oscillate between different states. While the size of the midpoint effects can be used to draw general conclusions regarding the impact of measures on the system, it can also be relevant to consider the full range of possible outcomes. Recreational fishing, perch and farmed salmon and sea trout all had mean cycles that oscillated around 0. Some measures may therefore have more substantial impacts on these ecosystem components and services than the midpoint effect size suggests, and the full ranges could also be important. These results could potentially be relevant when deciding on indicators for monitoring. Monitoring programmes and indicator frameworks are important for assessing the state of the ecosystem and for evaluating how the system is responding to management (Borja et al. 2016; Möllman et al. 2014). Monitoring of indicators should be able to detect change among the inherent variability of the system (Borja et al. 2016) and the oscillations between upper and lower states identified in this thesis suggests that assessing the impact of a measure could be difficult. For variable outcomes it could therefore be relevant to not only use single value indicators as a threshold to determine ecosystem status, and instead also consider indicators that account for a range of system states. A food-web indicator could be relevant in this context as such indicators can, for example, represent trophic level biomass, which, in turn, could be used to represent ecosystem services (Tam et al. 2017).

Fish as a local food source had the largest oscillation range of all outcomes and was the ecosystem service stakeholders considered to be most important. The outcome of this node is largely dependent on the status of the fish in the system, which, in turn, are affected by feedback loops. Management aimed at securing the use of fish as a local food source should therefore consider how to prevent shifts of fish stocks towards negative states. Depending on the objective of management it could also be desirable to minimise the oscillations and prioritise stable states, for example through more long-term management, such as setting fish quotas at longer time-intervals. The oscillations could also indicate that there is a risk for the system to fall into an alternative, undesirable stable state, which could be difficult to recover from. Further investigation into alternative stable states of marine ecosystems affected by feedback mechanisms and the use of multiple indicators may therefore be relevant (Blindow et al. 2025; Tam et al. 2017).

## 4.3 Trade-offs and synergies between measures

Identifying trade-offs between measures could be helpful for decision-making by evaluating where conflicts may be found (Gray et al. 2015) and could therefore be relevant for EBM. The largest trade-off found in the system was between measure 3.3 (Protection Finngrundet) and 7.1 (Fossil-free energy extraction), and their effect on SAV. The wish for increased fossil-free fuel and reduced $CO_2$ emissions makes the measures regarding clean energy extraction relevant, and electricity production from offshore wind farms has grown exponentially in the last decade. However, offshore windfarms can negatively impact coastal areas through both environmental degradation and effects on fishing (Galparsoro et al. 2022). As earlier mentioned, in the model fossil-free energy extraction through offshore wind power is assumed to have a negative effect on aquatic vegetation through increased pressure from physical disturbance, while the positive effect of measure 3.3 (Protection of Finngrundet) mainly stems from a direct positive connection to SAV through increased protection of marine areas. However, trade-offs are often context dependent (Calado et al. 2025). The conflict found between the measures could be mitigated by consideration of where the windfarms are built, since the effect of offshore wind farms is spatially variable and largely depend on the characteristics of the area (Galparsoro et al. 2022). The most negative impacts of windfarm construction are often related to construction, due to both increased underwater noise and habitat loss. Avoiding piling during windfarm construction could potentially reduce some of the negative effects on species, and choosing floating windfarms may instead be preferable in some cases (Rezaei et al. 2023; Teilmann & Carstensen 2012). The negative effects shown in the model could therefore be reduced by both type and location of the constructed windfarms.

While the findings suggest that there are stronger trade-offs than synergies, win-wins were also found. Most synergies included measures 3.3 (Protection of Finngrundet) and 3.2 (Fishing ban winter), due to their positive effect on outcomes that are important for the whole system, such as herring, SAV and trophic regulation. However, though measures 3.3 (Protection of Finngrundet) and 3.2 (Fishing ban winter) act through partly different pathways mechanistically, they are relatively similar, as they both include spatial closures and are targeted towards supporting herring. Measures that are instead aimed at different objectives, such as the second biggest win-win pair, measures 4.31 (Protect areas) and 6.1 (Restoration of salmon habitat) could instead be more interesting to promote since they may be financed differently, or be relevant for more stakeholders. Still, synergies may also be context-dependent, and the interactions between measures could therefore look different in reality (Calado et al. 2025; Mansfield et al. 2024).

Depending on the preferred outcome of stakeholders the results of this analysis could be used to discuss how potential conflicts can be avoided, and how the outcome of certain measures can be optimised by considering synergies. For example, the trade-offs found could be used to inform marine spatial planning, to mitigate the negative effects found on for example SAV (Lester et al. 2013), while potential synergies of measures could be promoted through co-development and integration of the visions of different stakeholders (Mansfield et al. 2024). At the same time, the lack of representation of space and time in the model create uncertainties regarding the true extent of the interactions between measures.

## 4.4 Scenario analysis: Reduced herring quotas and marine protected areas

Scenario development and planning can be relevant for natural resource management (Metzger et al. 2017). Measures 3.1 (Reduced herring quotas) and 3.3 (Protection of Finngrundet) represent two different approaches to herring management, fish quotas and protection of marine areas and the two scenarios, free feedback and fixed fishing pressure, illustrate the challenges of fish management. Currently fish quotas are adjusted yearly based on stock assessment, and recovery of fish stocks will therefore attract increased fishing effort (Trijoulet et al. 2026). When the pressure of industrial fishing was fixed at a constant level, a more long-term approach to management was simulated by removing the feedback loop between herring biomass and the herring fishing quota. Such long-term management had a greater positive effect on the system, as it allows for a longer recovery period for herring. Even though the recovery of depleted stocks through quota reductions is an important part of fisheries management (Blöcker et al. 2023), fishing quotas alone can be inefficient, and marine protected areas (MPAs) are also important. MPAs can both limit fishing efforts as well as reduce exploitation and disturbances, but the effect of MPAs depend on location, as they could be more or less conflicting with fishing efforts, as well as include more or less important habitat for fish (Binch et al. 2025). Spatial consideration is therefore once again important for assessing the impact of the management measures.

Furthermore, MPAs could also lead to fishing displacement, with increased fishing pressure in areas adjacent to the MPA, and without proper quota reductions the positive effects may therefore be limited (Bastardie et al. 2015; Binch et al. 2025). Still, the results suggest that measure 3.3 (Protection of Finngrundet) is the more robustly positive management measure, as it is less sensitive to a rebound of fishing efforts and has the most positive effects on outcomes. It could therefore be beneficial for management to focus on measures related to MPAs, as fishing closures may be a more reliable approach (Trijoulet et al. 2026). In aligment with the an EBM approach multi-species assessments may also be relevant as a strategy to create more sustainable fisheries practices (Möllmann et al. 2014). However, while measure 3.3 (Protection of Finngrundet) could have a positive effect on herring, there are limitations to how widespread the impact of local actions can be, as management often differs across countries and regions (Trijoulet et al. 2026).

Overall, the results of these scenarios indicate that short-term suppression of industrial fishing without any other implementation of measures may not be optimal to support herring, or other ecological components and ecosystem services of the system. Instead, creating more long-term management plans where MPAs are prioritised could be more beneficial.

## 4.5 Future research

There are several potential avenues for future research related to the modelling conducted in this thesis work. For example, improved herring management, which is one of the major challenges of the Baltic Sea, was largely in focus during this modelling. However, eutrophication is another important pressure (HELCOM 2023), and further analysis of measures aimed at reducing nutrient loading, and their effect on the system, could therefore be relevant. Currently, only three measures (6.2, 6.3 and 5.3) suppress eutrophication directly, even though this is a growing problem in the Bothnian Sea (Faithfull & Bergström 2025).

Including the effect of climate change in the model could also be relevant. At first, climate change was included as a background pressure in the model. However, this made it difficult to discern if the effect of certain measures were actually negative, or if the pressure of climate change was stronger than the impact of the measures, thus creating misleading results. To make the results more clear as to the objective of this project, which was to analyse the potential effect of the different measures, climate change as a pressure was therefore removed from the model. However, the early results where climate change was included imply that certain measures will not have the desired effects in face of climate change. Creating a model where climate change aspects are included may as such be both relevant and important in order to assess potential future states of the system (Viitasalo & Bonsdorff 2022).

Another challenge regarding FCM modelling is the representation of space and time (Gray et al. 2015; Kok 2009). As discussed, the effect of measures on outcomes may decrease, or increase, depending on the location and timing of certain measures, which is a limitation of the results. The importance of space and time was also discussed by stakeholders during the meeting in Tierp, and further investigation of the inclusion of spatial and temporal aspects, by the use of another model, could therefore be relevant. Other additions when considering the effectiveness of measures could be to include cost and feasibility (Cleveland et al. 2024). Furthermore, randomness is difficult to include in the model. Since every new state is derived from the previous one the possibility of analysing ecological systems with stochasticity as a driver is limited (Gray et al. 2015). However, such analysis could be interesting when considering a system such as the Baltic Sea, where processes can be driven by climatic fluctuations and variable fish recruitment (Viitasalo & Bonsdorff 2022; Österblom et al. 2007).

# 5. Conclusion

FCM is a relatively straightforward method that can provide managers and stakeholders with a way to analyse potential effects of management measures, and gain deeper understanding of system interactions, while highlighting current perceptions of the system. In the context of EBM, where analysis of whole social-ecological systems is useful, such insights may be especially relevant. The findings of this thesis indicate that some measures could have a greater positive effect on the system than others. Overall, measures that reduce exploitation and promote aquatic vegetation could be especially worth prioritising due to their system-wide positive impacts. At the same time, the results also suggest that some measures would benefit from adjustments in order to mitigate negative impacts and increase their effect on the system. For example, considering how and where offshore windfarms are constructed could reduce potential negative effects and help avoid trade-offs between management measures. Use of FCM for modelling of trade-offs, as well as synergies, may as such be relevant for EBM, by facilitating discussions regarding how unwanted negative effects could be avoided, and by highlighting the potential for collaboration between stakeholders.

It could also be relevant for managers and stakeholders to simulate different scenarios to improve the effectiveness of measures. The scenarios developed in this study, for example, highlight the potentially limited effect of only reducing fish quotas for management of herring, due to the feedback loops. Instead, the results sugest that more long-term management plans, combined with MPAs, could be more beneficial for both ecological components, by for example promoting herring biomass, and increase the delivery of ecosystem services, such as trophic regulation and nature experience. FCM modelling could therefore be a useful tool for evaluating management strategies and for developing measures that benefit both the ecosystem and stakeholders. In the context of EBM of the Southern Bothnian Sea, FCM modelling may assist managers in designing successful management strategies while facilitating stakeholder engagement and could as such contribute towards reaching environmental quality objectives and policy initiatives, such as the Marine Strategy Framework Directive.

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# Popular science summary

To improve the status of marine ecosystems management is important. In the Baltic Sea current human-induced pressures include, for example, overfishing and eutrophication, and these stressors are threatening both the biodiversity and the provisioning of ecosystem services in the region. In Sweden there is a call for increased implementation of ecosystem-based management (EBM) in the Baltic Sea. EBM is a holistic approach to management where different sectors of society are considered together in the analysis of the ecosystem. As it is relevant for EBM to consider both societal and ecological dimensions, modelling approaches that can include both are useful. One example of such a modelling approach is fuzzy cognitive mapping (FCM), where perceptions of both stakeholders and managers can be integrated. In the Southern Bothnian Sea, which is a sub-basin of the Baltic Sea, a regional management framework, as well as a fuzzy cognitive map has been developed. By the use of FCM modelling the focus of this report was on how qualitative modelling approaches can be used in the context of EBM, by assessing the effects of the management measures of the Southern Bothnian Sea on the social-ecological system.

While the findings of this report cannot be used as a guide for how the system would react to management measures in reality, they can be used to facilitate discussions and development of the measures. Overall, the results indicate that some measures are better for the system than others. For example, aquatic vegetation is an important for many other ecosystem components and measures that improve vegetation had positive effects across the system. At the same time, measures that impacted aquatic vegetation negatively generally had a wide negative effect on the rest of the system, and such measures could therefore benefit from being re-evaluated and adjusted, to prevent negative outcomes. These contrasting effects revealed trade-offs between certain measures, which could be especially relevant for managers to consider. The results also suggest that herring management would benefit from more long-term management, where fish quotas are not set yearly, but instead for longer periods of time, to allow for greater recovery of the system. FCM modelling could therefore be a useful tool for evaluating management strategies, while facilitating stakeholder engagement, and could as such contribute towards mitigating the deterioration of the Southern Bothnian Sea ecosystem.

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