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Economic and environmental effects of replacing bottom trawling with fishing with creels

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Bottom trawling is associated with negative external effects such as seafloor pressure and high fuel use. Replacing bottom trawls with passive gear, such as creels, is therefore interesting for policymakers. We investigate the response of the Norway lobster fishery in Sweden to an expanded creel area. Using an economic model (FishRent), we analyse fleet structure, net present value and two environmental indicators under five management scenarios. Our results show that expanding the creel area increases the number of creel fishers, while some trawlers leave the fishery. In total, the net present value and the environmental performance of the fishery improve.

Key words: bottom trawling, economic model, government policy, negative external effects, Norway lobster fisheries.

1. Introduction

Strategic choice of management measures can have large impacts on the environmental, social and economic sustainability of fisheries. The success of introducing measures aimed at reducing negative external effects from fishing depends on how fishers respond and adapt to measures. Bottom trawling has been debated for its negative effects on the environment and different measures to reduce these effects are of interest to policymakers. In Sweden, the majority of Nephrops (Norway lobster, *Nephrops norvegicus* L.) are fished using bottom trawls. However, fishing with creels has been found to environmentally outperform the trawl fishery, since creel fishing exerts lower seafloor pressure, uses less fuel per landed kilogram and has lower bycatch per landed kilogram (Ziegler and Valentinsson 2008; Hornborg *et al*. 2016). In contrast, demersal trawls, such as those used for Nephrops, are known to affect seafloor habitats, change species composition and reduce biodiversity (Ball *et al*. 2000; Bergmann *et al*. 2001; Bergmann *et al*. 2002; Sköld *et al*. 2018). Since trawl and creel fishing cannot take place simultaneously in the same geographical area, specific areas have been dedicated to each gear type.

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Expanding the creel area could be justified by the potential environmental benefits it brings, but the actual outcome depends on the response of fishers and in particular on the potential for fishers to make profits.

The purpose of this study is to analyse the response of fishers to an expansion of a creel fishing area. Social implications (indicated by changes in fleet structure), economic performance and indicators of environmental improvement (fuel use and sea floor impact) are compared in a set of different management scenarios. More specifically, we use a dynamic economic model (FishRent, see Frost *et al.* 2013) to model scenarios with and without an expansion of the creel area and look at the medium and long-term effects on profits, number of vessels, fuel use and area swept by trawling. We carefully adapt the model to the specifics of our case study by estimating elasticities of the production function and using changes in investment levels based on historical data. We also calculate potential increases in fuel costs due to longer distances to trawling areas, using data on a detailed geographical level.

Swedish Nephrops fisheries have previously been studied by Eggert and Ulmestrand (2000). Using a bioeconomic model, they compared the economic performance of trawl and creel fishing for Nephrops on the Swedish west coast and found that the creel fishery was run with a deficit during the time span of the study (1990s), making trawl fishing more competitive. More recently, Waldo and Paulrud (2013) used a model based on linear programming that optimised profits in the Swedish demersal fishery with data from 2007. They found that when economic profit is optimised, Nephrops are fished by creel fishers and small trawlers (0–12 m) to a greater extent. This suggests that creel fishing is profitable on average, contradicting the findings by Eggert and Ulmestrand (2000). However, the time periods examined in the two studies differ and many conditions for Nephrops fishing have changed substantially over the last 20 years, making useful comparisons difficult.

The economic viability of trawl and creel Nephrops fisheries has also been discussed in the context of other European countries. Morello *et al.* (2009) propose that the economic viability of creel fishing in the central Adriatic Sea (the Pomo pit) is likely to be low, due to high scavenger activity, high densities of small Nephrops (low priced) and long distances from ports. Leocádio *et al.* (2012) compare the financial viability of trawl and creel fisheries fishing off the Portuguese coast and conclude that the net present value of profits for a typical creel vessel is higher than for a typical trawler. The consequences of a trawl ban in an area off the west coast of Portugal are discussed by Eichert *et al.* (2018), who predict economic benefits since there will be no loss in catch value and operating costs will be lower when the fleet switches to creel fishing. In contrast to these previous studies, we use a model based on economic theory, where fleet dynamics play an important part in determining the development path of the fishery. We adapt an investment function, estimate effort elasticities and calculate changes in fuel costs to reflect the situation in the Swedish Nephrops fishery. We also elaborate on different management scenarios, including expanding the creel fishing area compared with not expanding it, with and without transferrable quotas, and with high or low investment rates. By evaluating reactions of fishers after an earlier expansion of the creel area, we believe that we are able to model reactions more accurately than has been the case in previous studies. More broadly, the study contributes to the literature on external effects in fisheries and the role of fisheries management. External effects in fisheries analysed in the literature include, for example congestion (Huang and Smith 2014), bycatches (Abbot and Wilen 2009) and CO_2 emissions (Parker and Tyedmers 2015; Waldo *et al.* 2016).

This paper is structured as follows. In section 2, management of Swedish Nephrops fisheries is described. Section 3 presents data, and in section 4, the FishRent model is presented and assumptions used in the model implementation are discussed. Section 5 describes different management scenarios, and section 6 presents the modelling results obtained for these scenarios. A discussion and some conclusions are presented in section 7.

2. Management of the Swedish Nephrops fishery

Under Swedish legislation, commercial fishing for Nephrops requires a fishing licence and a special permit, where every fishing licence gives the owner the right to use a particular vessel for fishing (SwAM 2014). To minimise by-catch, trawling for Nephrops requires the use of either a sorting grid for directed Nephrops fishing or a 90 mm cod-end with a large mesh window in the top panel (SELTRA-trawl) in the mixed (multi-species) fishery. Inside the trawl border (four nautical miles off the coastline in Skagerrak, three nautical miles in Kattegat), the use of a sorting grid is mandatory.

Before 2017, the Swedish Nephrops quota was allocated between grid trawling (50 per cent), mixed trawling (25 per cent) and creeling (25 per cent) (SwAM 2015), and vessel quotas were allocated as weekly rations to each vessel (SwAM, 2016). Quotas were not transferable between vessels. On 1 January 2017, yearly individual quotas were introduced in demersal fisheries in Sweden, including for vessels with permits to fish for Nephrops in Kattegat and Skagerrak. The possibility to lease quotas during the year was introduced but the system did not include full transferability. In addition to quota restrictions, fishing with creels is also limited to 800 creels when one person is taking part in the fishery or to 1400 creels when two or more persons are involved in a firm's fishery (SwAM 2014).

The focus of this study is on the geographical restrictions that divide the area for Nephrops fishing between trawls and creels. The general rule is that trawling is only allowed outside the Swedish trawl border, that is the area between the boundary and the coastline is allocated to creel fisheries. In 2004, the trawl border was moved from two to four (three in Kattegat) nautical miles off the shoreline, thereby increasing the area available for creel fishing by 55 per cent (Jonsson and Valentinsson 2016). However, certain designated areas were still left open for trawlers using a sorting grid.

Currently (2020), there is 760 km^2 of muddy or mixed habitat considered suitable for Nephrops fishing with creels and 829 km^2 available for trawlers inside the trawl boundary (Jonsson and Valentinsson 2016). If creel fishers were allowed to use the entire area within the boundary, the available area for creel fishing would approximately double (ibid, 2016). Figure 1 shows areas available for trawl and creel fishing on the Swedish west coast.

3. Data

Data on landings (kilograms of Nephrops) and number of days-at-sea per vessel and year are taken from the vessels' logbooks, while price data are based on information from landing declarations. Cost data for the fleet segments originate from the EU economic data collection framework (EU 2017). All values used as input in the model are the average of 2013 and 2014 except for calculations of investment rate limits and effort elasticities, where longer time periods are used (see below). The sampling of economic data does not make it possible to separate vessels using grid trawl from vessels using other types of trawls. However, the trawler segments used here, that is small trawlers (10–12 m) and large trawlers (12–18 m), mainly use grid trawls. Data from 2012 show that the grid trawl was used for 78 per cent of the landings of small trawlers and 80 per cent of landings of large trawlers in that year. In addition to these two trawler segments, we assess two creel fishing segments, small creel fishers (0–10 m) and large creel fishers (10–12 m). In all segments, only vessels where more than 50 per cent of the landings value consist of Nephrops are included. Our segments include 141 vessels with 79 creel fishers and 62 trawlers. In total, these segments land 72 per cent of the Nephrops taken by Swedish vessels. Other segments catching Nephrops are mainly trawlers longer than 18 metres that also catch many other species. The data that support the findings of this study are available from the corresponding author upon reasonable request.

4. Modelling the Nephrops fishery

We use the dynamic bioeconomic FishRent model for our analysis. The full mathematical model is not presented here but is outlined in Salz *et al.* (2011) and Frost *et al.* (2013). The model has been used in evaluating: management strategies for the cod fishery in the Baltic sea (Frost *et al.* (2013); descriptors of good environmental status used in the EU Marine Strategy Framework Directive (Lassen *et al.* (2013); and the economic effects of fisheries management targeting eutrophication (Nielsen *et al.* (2019)) as well as in three studies by Simons *et al.* (2014a), Simons *et al.* (2014b) and Simons *et al.* (2015) analysing different aspects of the North Sea saithe fishery. In this section, we describe the FishRent model and show how it is applied in our

Figure 1 Map of the west coast of Sweden with trawl border, areas where grid trawls are allowed and areas where creels are allowed. Source: SwaM (2018).

case study. It should be clarified that our application of the Fishrent model use one species and four segments and compared with previous applications this is a small model. The value of our contribution is that we use detailed knowledge and data that is specific to our case study.

4.1 The FishRent model

The FishRent model has two modes for analysis: A simulation mode and an optimisation mode. In the optimisation mode, fishing effort is the control variable whereas in the simulation mode, the fishery is projected into the future such that current fishing effort, catches and profits affect future stock development, quotas, investments in new vessels etc. This corresponds to the expected development under business as usual (BAU). In the optimisation mode, the model maximises the Net Present Value (NPV) of economic profits in the sector by re-allocating fishing effort among vessels. In this type of analysis, the model selects the fishing effort and fleet size that gives the largest profit to the industry over the study period.

For a one-species model, the NPV of economic profit is defined as:

$$NPV\pi = \sum_{y,f}[p_f \cdot L_{y,f}(X_y, E_{y,f}) + OR_f - C_{y,f}(E_{y,f}, Fleet_{fy,f})] \cdot (1+\rho)^{-y} \qquad (1)$$

where π is profit; p_f is the price of the species for segment f, which is assumed to be constant over time for different segments; $L_{y,f}$ is the landings of the species in year y for segment f (the production function which is discussed in depth below); X_y is the stock size in year y; $E_{y,f}$ is the effort in year y for segment f; OR_f are revenues generated from other species; ρ is the discount rate used for calculating NPV; and C is the cost of fishing, which is dependent on the effort (E) and fleet size (*Fleet*). C is specified as:

$$\begin{aligned} C_{y,f}(E_{y,f}, Fleet_{fy,f}) = \; & FuC_f * E_{y,f} + CrC_f * Revenue_{y,f} + VaC_f * Revenue_{y,f} \\ & + FxC_f * Fleet_{y,f} + CaC_f * Fleet_{y,f} \end{aligned} \qquad (2)$$

where FuC_f is the fuel cost per effort day; CrC_f is the share of revenue used for paying crew wages (the crew is assumed to be paid by a revenue sharing system which is common for Swedish vessels); VaC_f is the variable costs, which are assumed to be a fixed share of revenues; FxC_f is the fixed costs per vessel (other than capital costs); and CaC_f is the capital costs per vessel.
Further, the model restricts the fishery to keep within quota limits and not to use more effort in year y than is possible using the fleet available in year y. The model contains specific modules for setting the quotas (management module), investments (investment module) and stock development (biological module). These are not specified in detail here, but full descriptions can be found in Frost *et al.* (2013) and Salz *et al.* (2011), who provide detailed information on the model.

4.2 Implementing the FishRent model for the case of Swedish Nephrops

Before turning to scenarios, we describe how the FishRent model is applied to the Swedish Nephrops fishery. We believe that the FishRent model with its functions as described above is well suited to the case of Swedish Nephrops. However, all input parameters are estimated from data that are relevant for the studied case. Table 1 presents the parameters and their sources.

Some of the parameters need a more detailed presentation, which is provided below.

Table 1 Parameters used in the application of the FishRent model on Swedish Nephrops fisheries

Parameter	Estimated for the Nephrops fishery	Comment
Catch parameters		
Landing function (eq 3)	Yes	The parameters in the Cobb–Douglas landing function are estimated for the Swedish Nehprops fishery. This is beyond what most studies using FishRent do.
Biologial parameters		Not used in the Nephrops application
Fleet parameters		
Days at sea in start year	Yes	Logbook data for Swedish Nephrops
Maximum days at sea per year	Yes	From logbook data
Investment price	Yes	Based on insurance value in Swedish Neprhops fishery
Upper and lower investment limits per year	Yes	See section 4.2.3 in the paper
Investment speed (% of profits/losses)	No	12 % is used based on the Danish model. The results are not sensitive to this as was shown in the sensitivity analysis in the response to the previous review report. Note, that this parameter is only used in the simulation version of the model (i.e. not applicable to scenarios 3-5 in our study).
Fleet shares		
Segment's shares of national quota	Yes	Based on Swedish Nephrops landings
Economics		
Prices	Yes	Swedish Nephrops prices are used
Revenues from other species	Yes	Data from Swedish Nephrops fleet
Fuel costs	Yes	Data from Swedish Nephrops fleet, adjusted for increased steaming time for trawlers when creel area is expanded.
Crew costs	Yes	Data from Swedish Nephrops fleet
Other variable costs	Yes	Data from Swedish Nephrops fleet
Fixed costs	Yes	Data from Swedish Nephrops fleet
Capital costs	Yes	Data from Swedish Nephrops fleet
Discount factor	Yes	Based on Swedish standard (3, 5 %)

4.2.1 The production function

A feature of the model important for this analysis is the production function (L). This is the function determining the production level based on effort (E) and stock (X). Production is determined as:

$$L_{yf} = \alpha_f E_{y,f}^{\beta} X_y^{\gamma} \tag{3}$$

where α_f is the catch coefficient for segment f; $E_{\mathrm{y,f}}$ is effort of segment f in year y; X_{y} is the stock in year y; and β is the effort elasticity, that is how sensitive production is to changes in effort. Higher β implies that production change more when effort changes, while γ has a similar implication for the stock level. However, in the empirical application the stock is assumed to be constant and therefore normalised to one, which means that the production function reduces to:

$$L_{y,f} = \alpha_f E_{y,f}^{\beta} \tag{4}$$

The motivation for using a constant stock is provided in section 4.2.2.

We estimate effort elasticities (β) in equation 4 to be used in the Cobb–Douglas production function in our adaption of the FishRent model based on data from logbooks covering the period 2012–2016. Taking logarithms of (4) and using landings and effort data of different vessels (i), the function can be estimated as:

$$lnL_{y,i} = \alpha + \beta_1 lnE_{y,i} + \varepsilon_{y,i} \tag{5}$$

where $lnL_{y,i}$ is the log of the production (in kilograms) by vessel i in year y and $lnE_{y,i}$ is the log of effort in number of days-at-sea of vessel i in year y. As we want to estimate separate effort elasticities for each segment, we extend equation (5) and interact the effort variable with four segment dummy variables, $S_{y,i}$. We also add a vessel-specific time trend, t_i, to control for linear trends in the data and use vessel effects (μ_i) to control for characteristics of each vessel and its crew. The motivation for using a vessel-specific time trend is that vessels (with their captains and crew) are assumed to follow their own production pattern over time. In addition, quotas are based on previous catches during the time period that we study which is also suggesting that yearly landing patterns are vessel-specific. Our extended model is thus:

$$lnL_{y,i} = \alpha + \beta_1 lnE_{y,i} S_i + t_i + \mu_i + \varepsilon_{y,i} \tag{6}$$

The results of re-estimating (6) are presented in Table 2.

The results suggest that effort elasticities are rather high in all segments. As a rule of thumb, an elasticity of 0.6–0.9 for trawlers is commonly used in the FishRent Model (Salz *et al.* 2011). Our results are in line with this value. For

Table 2 Results of estimation of effort elasticities for four Nephrops segments

Variable	Coefficient	Robust standard error
Effort of…		
Small creel fishers	0.889***	0.077
Large creel fishers	0.887***	0.071
Small trawlers	0.881***	0.074
Large trawlers	0.853***	0.131
Vessel-specific time trend	−0.015*	0.007
Constant	4.560***	4.560
R-sq	0.25	

Note: Number of observations = 662. Vessel-specific effects and cluster robust standard errors are used. Significance stars are *for $P < 0.05$ and *** for $P < 0.001$.

fishing with passive gear, effort elasticities are normally assumed to be lower (in Salz *et al.* (2011) a value of 0.1–0.4 is suggested), but this is not what our results imply. Rather, effort elasticities are similar for trawlers and creel fishers. Statistically, coefficients are within the same confidence intervals and not separable from each other.

We are interested in the effects of a potential future expansion in creel area, and we use our statistical model to check whether effort elasticities changed with the expansion of the creel area in 2004. The idea is that an expanded area might increase the marginal product of the creel fishery, as an increasing number of days at sea will not result in lower catches at the same rate as before when a larger area becomes available. The intuitive explanation is that the creel fishery will have increased possibilities to fish in the most productive areas and thus catches will be higher at each given effort level. To investigate whether effort elasticities changed after the last creel expansion period, we adapt the model so that the period before and after the 2004 expansion is used, that is 1997–2008 and use an interaction for the period after the creel area expansion (i.e. 2004–2008). The results are presented in Table 3.

The results show that coefficients are significant and positive for all segments and that the magnitude of the coefficients is smaller before the creel area expansion (and also compared with the values in Table 2). The reason could be that, before the creel area expansion in 2004, it was difficult to expand for creel fishers, and other regulations might have similarly prevented the trawl fishery from expanding. We use the interaction coefficients of the creel fisher segments as proxies for increases in effort elasticities in the event of a future creel expansion, that is for the small creel segment the effort elasticity increases by 5.4 per cent and for the large creel segment the increase is 8 per cent. To calculate the catch coefficients, α_f, we use the estimated elasticities together with data on effort and production from 2013/2014.

4.2.2 Biology and quotas

The Nephrops stock size in Skagerrak and Kattegat is considered to be stable and has been harvested below maximum sustainable yield since 2012 (ICES

Table 3 Results of estimation of effort elasticities in four Nephrops segments in two periods: 1997–2003 and 2004–2008

Variable	Coefficient	Robust standard error
Effort of…	1997–2003	
Small creel fishers	0.362***	0.093
Large creel fishers	0.316***	0.091
Small trawlers	0.436***	0.090
Large trawlers	0.434***	0.117
Interaction…	2004–2008	
Small creel fishers	0.054***	0.012
Large creel fishers	0.080***	0.011
Small trawlers	0.048*	0.024
Large trawlers	0.028*	0.011
Vessel-specific time trend	0.001	0.001
Constant	6.269***	0.326
R-sq	0.27	

Note: Number of observations = 1572. Vessel-specific effects and cluster robust standard errors are used. Significance stars are *for $P < 0.05$ and *** for $P < 0.001$.

2018). The Nephrops stock size has only been estimated since 2011, making the period for estimating the input parameters for the biological module too short. In the model, we therefore assume that the Nephrops stock and the total allowable catch (TAC) for Skagerrak and Kattegat are constant over the years. This is justified by the fact that the TAC has been kept at a more or less constant level for many years and that the national TAC has not been fully used by the Swedish Nephrops fishery since 2011 (ICES 2018). From 2016 onwards, the TAC has been set for catches, rather than landings, and for a smaller minimum size, making comparisons with previous years difficult. After imposition of the catch quota (which thereby increased the quota), the reported catch has been much lower than the TAC. As an upper limit in our model, we use a landings quota of 5110 tons for the Nephrops fishery in Kattegat and Skagerrak, which is the average of the landings quotas applied in 2013 and 2014 (ICES 2018). The Swedish quota was 1344 tons and our studied segments caught 72 per cent of the total Swedish Nephrops catch in 2013/2014. Assuming that the availability of quota is based on catch shares, our segments had 967 tons of quota available.

If bycatch of other species is high, it is possible that the Nephrops quota cannot be fished because of limited quota availability for other species (choke species). Since our segments mainly use gear associated with low bycatch, we assume that the choke risk is small and we do not use quotas for other species in the model. However, revenues from other species are included as a fixed percentage of Nephrops revenues in the model.

4.2.3 Investments

Investment in the simulation version of the FishRent model is limited to a fixed percentage of profits (see Frost *et al.* (2013) for details). Investment in new vessels will occur if a segment has a positive profit and disinvestment (exit of vessels) will occur when a segment has negative profits. In both versions of the model, upper and lower investment rate limits, that is the maximum number of vessels that can appear or disappear each year, must be defined. These investment rate limits are important in determining the development path of the model, that is how fast the model moves to a new equilibrium. To find reasonable investment rate limits, we use historical data on changes in the number of vessels and calculate average investment rates for two five-year periods for each segment. The first period is the last five years of available data (2012–2016), and the second is the five years following the last creel area expansion (2004-2008). If a fleet segment with positive profits disinvested on average during the last five years, we set the investment rate limit to zero (even though the segment has a positive profit, we believe that there are indications that no newcomers will enter the segment). Likewise, if there are disinvestments in a segment, we set the investment rate limit to zero. This may seem somewhat restrictive, but it prevents the model from investing if profits are positive when the actual investment is negative, and vice versa. Table 4 shows the investment rate limits used in the adaptation of the FishRent model to the Swedish Nephrops fishery. Since we use a different dataset (logbook data), the segments in this data are not directly comparable to those used in the model analysis.

As Table 4 shows, investments have been slightly positive in three of our segments on average in 2012–2016 and negative in the large trawler segment. In 2004, when the trawl border was expanded, the creel fishery could expand and this resulted in an increase in the number of creel vessels. The average investment rate during this period was approximately 9 and 8 per cent per year for small and large creel fishers, respectively. We use these estimates in the model for the two creel segments to reflect an expected increase in the creel fishery if a larger area becomes available. We also use the investment rates of trawlers during this period to set disinvestment rate limits. As is evident from Table 4, trawlers disinvested during the period, at a rate of 3.7 per cent for small trawlers and 0.4 per cent for large trawlers. As before, we

Table 4 Investment rate limits used in the model, limits are from two periods: 2012–2016 and 2004–2008 and for our four segments

	Investments	Disinvestments
2012–2016 (Low investments)		
Small creel fishers	0.1%	0.0%
Large creel fishers	0.5%	0.0%
Small trawlers	0.5%	0.0%
Large trawlers	0.0%	- 1.4%
2004–2008 (High investments)		
Small creel fishers	8.9%	0.0%
Large creel fishers	7.5%	0.0%
Small trawlers	0.0%	-3.7%
Large trawlers	0.0%	-0.4%

Source: Own calculations based on logbook data.

use zero rates for upper and lower limits to prevent investments from moving in an unexpected direction.

During the last creel area expansion period, around 45 new creel fishers entered the fishery and the area that became available for creel fishing increased by 55 per cent. If the current creel area is expanded to cover the whole area within the trawl boundary, that would imply an extension of the creel area by 108 per cent. We set an upper limit to the expansion of the creel fisher fleet that takes into consideration the fact that eventually it will be difficult for the creel fishery to expand beyond a certain level. Assuming that the expansion in the number of vessels is proportional to the previous area expansion, we calculate the upper limits of the number of vessels based on the number of vessels added per km^2 after the last creel area expansion.

4.2.4 Fuel costs

We assume that fuel costs of trawlers increase when these are no longer allowed to fish inside the trawl boundary. The increase in fuel costs is based on calculations of steaming time per trip for small and large trawlers. Steaming time is time used for travelling to fishing grounds, as opposed to time when the trawl is towed along the sea bed. By comparing trawlers that fish outside and trawlers that fish inside the trawl boundary in 2013–2014, we calculate a fuel cost increase factor as:

$$1+\left(\frac{h_{outside\,i}-h_{inside\,i}}{h_{inside\,i}}\right)*sh\_inside_i \tag{7}$$

where $h_{outside\,i}$ is the average steaming time on trips when trawlers in segment i fishes outside the trawl boundary; $h_{inside\,i}$ is the average steaming time on trips when the trawler in segment i fish inside the trawl boundary; and sh_inside_i is the share of trips that are currently (2013–2014) made in the area inside the trawl boundary by segment i. The underlying assumption is that if trips currently conducted inside the trawl boundary take place outside the boundary, it will take longer for an average vessel to travel to its fishing grounds. For an average small trawler on an average trip, the increase in steaming time is 11 per cent and for a large trawler it is 31 per cent. Small trawlers are more common within the boundary (56 per cent of trips) than large trawlers (36 per cent of trips), meaning that a larger number of small trawlers will be affected by an increase in fuel costs. The factor is multiplied by the fuel costs of the trawler segments in the actual data to estimate fuel costs after a creel area extension. The factor is 1.06 for small trawlers and 1.11 for large trawlers.

4.2.5 Other assumptions

An implicit assumption when applying the Fishrent model is that the functional forms are relevant for the Swedish Nephrops fishery. The production function, as discussed thoroughly in section 4.2.1, is a Cobb-–Douglas production function and is commonly used in both fisheries economics and in economics more general. We believe that this is not a controversial choice. The functional forms for different cost items differ in the model. Fixed costs (e.g. harbour fees; FxC_f) and capital costs (CaC_f) are assumed to be proportional to fleet size. The model assumes that all vessels within a fleet segment are identical, and thus these costs change proportional to changes in the number of vessels in a segment. This is reasonable for the Swedish Nephrops fleet where vessels are analysed in narrowly defined segments (creel fishers 0–10m and 10–12 m; trawlers 10–12m, 12–18m). Fuel costs (FuC_f) are assumed to be proportional to effort (days at sea), that is the fuel consumption is the same for each day fishing (except when areas change, section 4.2.4). Other variable costs (e.g. landing fees; VaC_f) and wages (CrC_f) are assumed proportional to revenues. The latter is based on wages being set in a traditional sharing system where the remuneration to the crew depends on revenues.

Our data show large differences in crew costs as the crew cost share ranges from 5 per cent for small creel fishers to 17 per cent for large trawlers. Since many of the small vessels in our study are operated by single-owner firms where wages are not always taken out it is somewhat difficult to separate between crew costs and profits. To facilitate comparisons between segments, we adjust crew costs in three of our segments (small creel fishers, large creel fishers and small trawlers) by using the crew cost share of revenues of the large trawler segment. This means we assume that, for each segment, 17 per cent of revenues consist of labour costs. Another assumption in the application is that Nephrops prices are fixed. This is based on Sweden being a small fishing nation that does not affect the world market prices (see e.g. Hammarlund 2015). Finally, we use a discount rate of 3.5 per cent for future profits and calculate the NPV of future profits from the Nephrops fishery. The discount rate level is within the range of values used when evaluating social investments (Svensson and Hultkrantz 2015).

5. Scenarios

We analyse an expansion of the area for creel fishing under two different expectations about the future management of the Swedish Nephrops fishery. In the first type of scenarios (BAU and AREA), we assume that it will not be possible to sell or buy quotas within the system. This could be the case for example with a system with weekly quotas (as during our study period) or with a system with yearly quotas that are not tradable over years (as was introduced in 2017 in Swedish demersal fisheries). In this case, the fishery is restricted by quotas, permits and licences that are issued by the national authority. For modelling scenarios under this assumption, we use the simulation version of FishRent. Since the creel area is approximately doubled, we assume that the regulator doubles the quota that is available for creel fishers, meaning that the quota increases from 330 to 660 tons for creel fishers, while trawler segments will lose some of their current shares of the quota. This means that the total quota share for our four segments increases from 72 to 80 per cent of the national quota (the non-modelled trawlers lose some quota to the creel fishers). As there is approximately 148 tons of unutilised quota in the current situation, part of the quota allocated to the creel fishery in the expansion scenarios does not have to be taken from trawlers.

The BAU and AREA scenarios do not extract maximum profits from the fishery. Rather, the management system slowly moves towards a situation where the fishery makes zero profits in the long run. Restrictions on investments prevent the fishery from reaching zero profits. In a second type of scenarios (MAX1-MAX3), we assume that quota trade between segments is possible, as would be the case for example if a system with individual transferable quotas (ITQs) were introduced in the Nephrops fishery. Thus, these scenarios allow for quota tradability and expand the creel area. We use the maximisation version of FishRent whereby the fishery moves towards a state in which the NPV of fishery profits is maximised. As before, the quota share of our segments increases to 80 per cent of the national quota. In all, we identify five scenarios (two without maximisation and three with maximisation) that we believe are interesting and possible management scenarios for the Swedish Nephrops fishery.

In Table 5, the assumptions of the first two types of scenarios (The BAU and AREA scenarios) are described.

Scenario 1 is the business as usual (BAU) scenario. We use investment rate limits from the most recent time period (as described in Table 4) and assume that the creel area is not expanded. We call our second scenario AREA as it implies that the area for creel fishers is expanded. This has four effects on the fishery: investment rate limits increase (see Table 4), effort elasticities increase

Table 5 Scenarios using the simulation version of FishRent

Scenario 1 (business as usual, BAU) – Unchanged area for creel fishers
Simulation under the assumption that the area for the Nephrops fishery is geographically limited to the current area. The investment rate is low (see Table 3).
Scenario 2 (AREA) – Increased area for creel fishers
Simulation under the assumption that the creel fishery is expanded such that the area for this fishery increases by 108 per cent. We assume this has four effects on the fishery:

a The investment rate in the creel fishery increases and investment rates for trawlers decrease (see Table 4).
b The effort elasticity increases for creel fishers (see Table 3).
c Fuel costs increase for trawlers that are no longer allowed to fish inside the trawl boundary (see section 4.2.4).
d Expansion of the creel fishery will be stopped by the regulator if the fishery reaches a level where all the available area is used (as described in section 4.2.3).

(see Table 3), fuel costs increase for trawlers (se section 4.2.4) and the expansion of the fishery will be stopped if all available new area is used (as described in section 4.2.3).

Table 6 describes the assumptions of our three maximisation scenarios. The assumptions of scenario 3 (MAX1) are the same as for scenario 1 (BAU), and the assumptions of scenario 4 (MAX2) are the same as for scenario 2 (AREA). The only difference here is that we maximise the net present value of the fishery instead of simulating the development of the fishery.

Scenario 5 is the MAX3 scenario where the assumption about the effort elasticities and fuel costs is the same as in the MAX2 scenario but investments are unlimited. This scenario is very flexible, and the results should be interpreted as high estimates corresponding to the long-run equilibrium in a fishery with a fully functioning ITQ system and no area restrictions for creel fishers.

6. Results

Our results are presented and discussed below. We show the change in the number of vessels and the change in the NPV of profits of the fishery, when the creel area is expanded. An important aspect of the management of the

Table 6 Scenarios using the maximisation version of FishRent

Scenario 3 (MAX1) – Maximised profits and unchanged area for creel fishers

The net present value of the fishery is maximised under the assumption that that the area for the Nephrops fishery is geographically limited to the current area. The investment rate limit is low (see Table 4).

Scenario 4 (MAX2) – Maximised profits and increased area for creel fishers

Maximisation under the assumption that the creel fishery is expanded such that the area for this fishery increases by 108 per cent. We assume this has four effects on the fishery:

a The investment rate in the creel fishery increases and investment rates for trawlers decrease (see Table 4).

b The effort elasticity increases for creel fishers (see Table 3).

c Fuel costs increase for trawlers that are no longer allowed to fish inside the trawl boundary (see section 4.2.4).

d Expansion of the creel fishery will be stopped by the regulator if the fishery reaches a level where all the available area is used.†

Scenario 5 (MAX3) – Maximised profits, no investment limits or limits on area for creel fishers

Profits are maximised without any investment or disinvestment limits for the segments. The effort elasticity increases for creel fishers, and fuel costs increase for trawlers as in scenario 4.

†Effect d in the maximisation model allows for restructuring between segments, and the assumption used here is that the number of creel fishers will not exceed the number of small creel fisher equivalents. On average (2013/2014), a large creel fishing vessel catches 3.1 times as much as a small creel fishing vessel. We use this figure to calculate small creel fisher equivalents. When the maximum of the small creel fisher equivalents is reached, we assume that the regulator stops new vessels entering the creel fishery and that the number of vessels in all segments is unchanged for the remainder of the period.

Nephrops fishery is how different environmental factors are affected. Thus, we use our model results to estimate changes in fuel use and the amount of seafloor area swept in the different scenarios in our analysis. We present the situation in 'year 1', which is the observed situation in 2013–14 (Current), in year 10 and in year 25.

6.1 Vessels

We start by investigating the change in the number of vessels in our five scenarios (Table 7). The number of creel fishers increases slightly in the BAU scenario, since there are positive profits that can be invested. However, the rate of investment is very slow, since the number of new permits is restricted without the area expansion. For trawlers, there is no change in the number of vessels, reflecting a stable situation under existing regulations. The small increase in the number of vessels thus reflects a situation where entry of vessels is limited by regulations on licences and permits.

In the AREA scenario, the area for creel fishers is expanded and further investments in the creel fishery are possible. The number of creel fishers increases from a total of 79 in the current situation to a total of 165 by year 25. At some point in time, the expansion will be stopped by the regulator when the vessel limit is reached. In this scenario, the number of small trawlers decreases whereas the number of large trawlers is unchanged. Overall, the area expansion is beneficial for the creel fishery, as expected, primarily at the expense of small trawlers. Larger trawlers are better suited to fishing further from the coastline, that is outside the new creel areas, and all large trawlers continue their fishing activities in the AREA scenario.

In the MAX1 scenario, we maximise profits with an unchanged creel area. Comparing the MAX1-scenario with the BAU scenario shows that restructuring towards an economic optimum is associated with a decrease in the number of large trawlers (Table 7). In the MAX2 scenario, where the creel

Table 7 Change in the number of vessels in four Nephrops segments in five scenarios (for scenario descriptions, see Table 5 and 6)

Scenario		Small creel fishers	Large creel fishers	Small trawlers	Large trawlers	Total
Current	Year 1	58	21	32	30	141
BAU	Year 10	59	21	32	30	142
	Year 25	60	23	32	30	145
AREA	Year 10	115	37	24	30	205
	Year 25	121	44	16	30	211
MAX1	Year 10	59	22	32	26	139
	Year 25	60	23	32	21	137
MAX2	Year 10	119	39	23	29	210
	Year 25	119	44	20	29	212
MAX3	Year 10	123	105	1	2	232
	Year 25	123	105	1	2	232

fishing area is expanded, it becomes profitable to invest in the creel fishery. However, fuel costs of trawlers increase, making some trawlers leave the fishery since they are unprofitable. The disinvestment rate for large trawlers is lower than for small trawlers, making the drop in the number of large trawlers smaller than that of small trawlers. In the MAX3 scenario, investment is assumed to be free, that is there are no limitations on the number of vessels that can enter or exit each year. The results for this scenario suggest that the number of creel fishers increases by more than in any other scenario and that the disinvestments in the trawler fleet are also higher.

6.2 Net present value of profits

The NPV of profits earned in each segment over a 25-year period is presented in Table 8. The difference between the BAU scenario and the AREA scenario is around €5.3 million, indicating that expanding the creel area increases the total value of the Nephrops fishery. The value of the creel fishery will then increase, whereas disinvestments together with higher fuel costs will make the small trawler segment unprofitable. For large trawlers, the decrease in profits is an effect of increased fuel costs caused by the creel area expansion.

Increasing the creel area and simultaneously introducing a more flexible quota system gives an extra €5.5 million, that is the difference between the MAX1 and MAX2 scenarios. As expected, creel fishing becomes more profitable. For the trawler segments, the MAX2 scenario allows for a decrease in the number of trawlers, which makes small trawlers less unprofitable despite the increase in fuel costs. However, increasing fuel costs make large trawlers less profitable than in the MAX1 scenario. Allowing for full flexibility between segments (ITQ system with no area limitations, i.e. the MAX3-scenario) gives the highest revenue for the fishery and makes all segments profitable (although profits for small trawlers are close to zero).

6.3 Fuel use

To calculate fuel use, we use data on fuel costs and a constant fuel price of €0.51 per litre. The average fuel price in 2013/2014 is calculated using information about the price of diesel in 2007 (Swedish Board of Fisheries

Table 8 Net present value (NPV) (million €) of profits over 25 years in four Nephrops segments in five scenarios

	Small creel fishers	Large creel fishers	Small trawlers	Large trawlers	Total NPV
BAU	6.1	6.7	−1.9	4.5	15.3
AREA	9.2	10.3	−1.2	2.3	20.6
MAX1	6.1	6.7	−1.9	4.6	15.5
MAX2	9.3	10.5	−1.3	2.4	21.0
MAX3	10.6	25.4	0.0	1.7	37.7

2007) minus fuel taxes that year (Swedish Tax Authority 2018), together with a diesel price index from Statistics Sweden (SCB 2018).

Fuel use in our five scenarios is presented in Table 9. We analyse total fuel use and fuel use per kilogram of Nephrops landed by creel fishers and trawlers. An important driver of changes in fuel use is the vessel composition, since fuel use will increase when the number of vessels increases in a segment. To obtain a relative measure of fuel use, we divide fuel use by landings. If a certain policy results in higher fuel use to land the same amount of Nephrops, it might be considered less environmentally friendly.

Compared with the current situation, total fuel use increases slightly in the BAU scenario (Table 9). This is due to investments in the creel fishing segments, which means a few additional vessels and slightly larger landings. In the AREA scenario, fuel use increases compared with the current situation because new creel fishers enter the fishery and because large trawlers have to travel further to get their catches. The fishery also uses more fuel per kilogram catch, mainly because trawlers are more fuel intensive. The MAX scenarios give similar results, although fuel use is lower in MAX1 (compared with BAU) and in MAX2 (compared with AREA), due to restructuring of the fleet in the form of disinvestments in the fuel-intensive trawler segments. In the MAX3 scenario, which allows for full flexibility of the segments, fuel consumption is lower than in the MAX2 scenario. Fuel use per kilogram catches is also lower because a larger amount of Nephrops is caught by the less fuel-intensive creel fishing segments and the remaining trawlers are more fuel-efficient (interestingly, trawl fishers have become more fuel-efficient than creel fishers, a result that probably should be interpreted with caution).

Fuel use per kilogram for trawlers is in line with Ziegler and Hornborg (2014), who show that fuel use per kilogram landed was between 4 and 5 litres for grid trawlers during 2005–2010. However, fuel use per kilogram catch for creel fishers is higher than earlier estimates show, for example a survey by

Table 9 Total fuel use, fuel use per kilogram of catch and swept area in five scenarios

Scenario		Fuel use, million litres	Fuel use, litres per kg creel catches	Fuel use, litres per kg trawl catches	Swept area (km^2)
Current	Year 1	5.0	4.8	6.2	14,163
BAU	Year 10	5.0	4.8	6.2	14,170
	Year 25	5.1	4.9	6.2	14,174
AREA	Year 10	6.2	5.0	6.8	12,972
	Year 25	6.2	5.0	6.8	11,747
MAX1	Year 10	4.7	4.8	6.2	13,271
	Year 25	4.4	4.9	6.1	11,978
MAX2	Year 10	6.2	5.0	6.7	12,585
	Year 25	6.2	5.0	6.7	12,129
MAX3	Year 10	5.5	5.1	4.7	1,292
	Year 25	5.5	5.1	4.7	1,292

Ziegler and Valentinsson (2008) found that fuel use for creel fishers was 2.2 litres per kilogram landed. The difference could be due to fuel use by creel fishers in the present study being based on a different sample. The results in Table 9 on fuel use by creel fishers should thus be interpreted with caution.

6.4 Impact on the seafloor

Finally, we investigate how the impact of fishing gear on the seafloor is affected in our different scenarios. We use data on area swept, measured in km^2 per ton of Nephrops, for different gear types, as presented in Hornborg *et al.* (2016). We see that the swept area decreases or remains stable in the scenarios where the creel area is expanded (Table 9). Note that seafloor area swept represents the total fishing effort within an arbitrary spatial unit, and it is not a measure of the fishing footprint, that is the spatial extent of the fishery. If a trawler fishes the same trawl track a second time, the swept area is doubled but the footprint is not affected. Comparing the AREA scenario with the current situation, we find a decrease in total swept area, as more creel fishers enter the fishery, and also a decrease in the total trawling effort, as the number of small trawlers decreases. In the MAX2 scenario, the swept area decreases compared with the current situation but since there are many creel fishers entering without enough trawlers leaving the impact on the seabed is slightly larger than in the MAX1 scenario (in year 25). As the number of trawlers decreases in the MAX3 scenario, the swept area decreases to less than one-tenth of that in the current situation. In this scenario, we assume that the areas of the sea are divided between trawlers and creel fishers so as to maximise the economic value of the fishery.

6.5 Sensitivity

In order to check the robustness of results, we have conducted sensitivity analyses on the total quota for the Nephrops fishery, the parameters in the production function, the maximum number of days per year for vessels to fish and on the assumption of how much of profits are invested in the BAU and AREA scenarios. Results for the number of vessels and the net present value of the total fishery are presented in Table 10 and Table 11.

As a first sensitivity analysis, we raise the Nephrops quota by 20 per cent. This results in more vessels joining the fishery in the more flexible scenarios MAX2 and MAX3. Whether it is realistic with an increase of so many new vessels is perhaps dependent on whether the increase in quota is related to a growth of the Nephrops stock in all areas or if there is another reason for the increase in quota (a change in how much quota is allocated to each nation would perhaps not increase the amount of creel fishers as much as the amount of trawlers). The number of vessels as well as the net present value of profits is higher with more quota in the MAX2 and MAX3 scenarios but is unaffected in other scenarios. We have also conducted a sensitivity analysis where the

Table 10 Number of vessels in year 25 in the investigated Nephrops fishery in five scenarios under different parameter assumptions

	BAU	AREA	MAX1	MAX2	MAX3
Original model	145	211	137	212	232
Quota increase by 20 per cent	145	211	137	282	274
Quota decrease by 20 per cent	145	211	132	147	189
Upper bound of CI of estimate of change in effort elasticity	145	211	137	205	151
Lower bound of CI of estimate of change in effort elasticity	145	211	137	229	299
Maximum amount of DAS increase by 20 per cent	145	224	140	204	204
Higher share of profits invested in simulation model	145	210	NA	NA	NA

Note: DAS, Days at sea.

Table 11 Net present value (NPV) (million €) of profits over 25 years in the investigated Nephrops fishery in five scenarios under different parameter assumptions

	BAU	AREA	MAX1	MAX2	MAX3
Original model	15.3	20.6	15.5	21.0	37.7
Quota increase by 20 per cent	15.3	20.6	15.5	24.5	44.0
Quota decrease by 20 per cent	12.0	15.2	12.6	16.5	31.3
Upper bound of CI of estimate of change in effort elasticity	15.3	22.0	15.5	23.0	45.2
Lower bound of CI of estimate of change in effort elasticity	15.3	19.2	15.5	20.2	31.7
Maximum amount of DAS increase by 20 per cent	25.0	31.8	25.7	50.8	50.8
Higher share of profits invested in simulation model	15.3	22.1	NA	NA	NA

Note: DAS, Days at sea.

available quota decrease with 20 per cent. As expected, this reduces the net present value of the fishery in all scenarios.

To conduct a sensitivity analysis of the estimated change in effort elasticities in the production function, we use the upper and lower end of the 95 per cent confidence intervals of the statistical estimation. This will affect the AREA, MAX2 and MAX3 scenarios. Using higher or lower effort elasticities does not change the results in any important ways. Although the net present value changes somewhat, the relationship between the scenarios is the same as in the original model.

We also perform a sensitivity analysis where we assume that the maximum days at sea for an average vessel is 20 per cent higher than the current days at sea. As expected, a more efficient fleet will catch more per vessel and in all scenarios we see that the fishery would become more profitable. In fact, the net present value is exactly the same in the MAX2 and MAX3 scenarios implying that assuming this kind of efficiency would be enough to reach the long-run profit maximising situation already in the MAX2 scenario.

Finally, a parameter that is only used in the simulation version of the model is tested for its sensitivity. The parameter is the share of profits that is invested/disinvested whether the segments are profitable/unprofitable. The share is set to 12 per cent in the original model, and we conduct a sensitivity analysis where the share is set to 24 per cent. This does not affect the results in the BAU scenario since vessel investment is kept at a very restrictive level anyway (see Table 4). The results of the AREA scenario are affected somehow as assuming that a larger share of profits are invested/disinvested in new vessels will result in somewhat higher profits of the fishery in the long run.

7. Discussion

Similar to studies on Nephrops fisheries such as Waldo and Paulrud (2013), Leocádio *et al.* (2012), and Eichert *et al.* (2018), our data show that creel fishers are more profitable than trawl fishers. The profitability relative to trawlers does, however, fluctuate over time in Sweden (Waldo and Blomquist 2020), which might explain differences with Eggert and Ulmestrand (2000) who find trawling in Sweden more profitable than creeling. It is difficult to explain these differences in profit but possible explanations are that they are related to technological development, changes in regulations or changes in consumer preferences. With this in mind, we use both simulation and maximisation scenarios to show that allowing for an expansion of the creel fishery could improve the overall economic performance of the Nephrops fishery. Allowing for an expansion of the fishing grounds, and thereby increasing the number of licences for the creel fishing fleet increase profits for creel fishers. For trawlers currently fishing in the area, it will be necessary to fish in other areas and this could affect the possibilities to make profits. Our analysis suggests that a number of small trawlers will leave the fishery. Thus, expanding the creel area will not benefit all segments, that is economic benefits will be redistributed between segments.

The expansion of the creel fishery also has environmental effects. As expected, less trawl fishing reduces the impact on the sea bottom, which is an important environmental benefit. However, increasing catches for creel fishers means that the number of vessels used for creel fishing increases. For trawlers, fuel use increases as they have to travel further to reach fishing grounds. From a policy perspective, it is interesting that despite creel fishing requiring less fuel per kilogram of catch (Ziegler and Valentinsson 2008), we show that total fuel use might not decrease with an expansion of the creel area.

Overall, we show increased economic and environmental benefits in terms of reduced seafloor impact with an expansion of the creel area. It is thus very likely that there would be a positive net benefit to society from expanding the creel fishing area. If managers are simultaneously concerned about fuel use, the optimal policy would be to impose fuel taxes to reduce the negative external effect on climate from the Nephrops fishery (see e.g. Waldo *et al.* 2016).

We adapt the model using real data in order to find relevant parameters for the Swedish Nephrops fishery. First, we estimate effort elasticities for our four segments using vessel-specific data. Our estimates are similar for different segments, and thus, we do not find that vessels using active and passive gear differ notably in this respect. In particular, we find that the effort elasticity of creel fishers is higher than is usually assumed for vessels using passive gears in fishery models (see e.g. Salz *et al.* 2011). This means that the productivity of creel fishers will not decrease with effort as fast as would have been the case if we had used estimates from previous studies. Second, we use investment rate limits that are based on real data. Rather than just guessing the investment rate limits, we base the limits on how each segment invested after a previous extension of the creel area. This makes our projections on how the fishery moves to a new equilibrium more plausible. Finally, we use steaming time on fishing trips to estimate the increase in fuel costs of trawlers in the event of a creel area expansion. Thus, we acknowledge that the cost of trawlers might increase due to the reform and suggest how important this cost increase might be.

The results from the FishRent model are of course associated with some caveats. For example, the calculations of profits are dependent on the underlying data and, in particular, it is difficult to measure labour costs of small-scale fishers. Small-scale fishers are often privately owned firms, making it difficult to separate between wages and profits. We approach this issue by assuming that labour costs are an equal share of each segment's revenues, but other approaches are of course possible. Our approach has the advantage that it facilitates comparisons between segments but has the disadvantage that the level of overall profits might be underestimated or overestimated.

We assume that the creel area expansion affects the fuel costs of trawlers. It is also possible that trawl fishers which spend a longer time travelling to their fishing grounds have higher labour costs in addition to higher fuel costs. Furthermore, trawling outside the trawl boundary could mean more competition with trawlers not using the grid trawl and competition with Danish fishers. The latter are allowed to fish outside the boundary, but not inside it. Thus, we acknowledge that there could be further cost increases for trawlers, affecting their profitability and other outcomes of the model. However, estimating how these costs would increase is outside the scope of this study and is left to future research.

Modelling the future of the Nephrops fishery is challenging, as regulations are continually changing. Our analysis is based on data from 2013 to 2014, but in the short period since then several regulations have changed. The most important is perhaps the regulation that introduced the system of yearly quotas, but other examples are the introduction of the landing obligation with lowering of the minimum landing size in 2016, and the increase in the catch quota in recent years. However, the main purpose of the model is to compare the outcomes when expanding or not expanding the creel area, not to forecast the future development of the Nephrops fishery in all aspects.

In summary, the modelled results of increasing the creel area point to an overall increase in sector profits and a lower impact on the seafloor by trawling. On the other hand, changes in CO_2 emissions are uncertain and profits are redistributed between segments (and potentially local communities). Thus, the analysis identifies some interesting features of the policy that need to be further analysed and discussed with stakeholders before implementation.

Data availability statement

The data that support the findings of this study are available from the Swedish Agency of Marine and Water Management. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the authors with the permission of the Swedish Agency of Marine and Water Management.

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