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RESEARCH ARTICLE

Long-run management of Greenland's fishery on Greenland halibut (Reinhardtius hippoglossoides)

Frank Jensen,* Ayoe Hoff, Jette Bredahl Jacobsen, and Henrik Meilby

Department of Food and Resource Economics, University of Copenhagen, Copenhagen, Denmark
*Corresponding author: Frank Jensen; Email: fje@ifro.ku.dk

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Abstract

In this paper, we consider four scenarios for economic optimal management of a fisheries resource by a high sea and coastal fleet segment. These scenarios differ with respect to whether a common or two separate fish stocks are considered and whether the profit from land-based processing is included. The model is parametrized using the Greenland halibut fishery on the west coast of Greenland as an empirical case. For this fishery, we show that the relative ranking of the optimal high sea industry harvest and profit compared to the coastal industry harvest and profit depends on the chosen scenario. When comparing the scenarios for optimal management and the actual situation, we find that the fish stock tends to be overexploited.

Keywords: Greenland halibut; coastal vessels; high sea vessels; optimal management

JEL classification: Q22; R13; R52; O13

1. Introduction

Since Greenland obtained partial autonomy from Denmark in 2009,[1] an ongoing political issue has been securing increased economic independence, with fisheries being an important sector for the economy. For example, the primary fishing sector generated between 76 and 88 per cent of the total value of exports between 2013 and 2015 (Statistics Greenland, 2020).

Greenland halibut (hereafter Grl. halibut) has gained increasing importance for primary fisheries. In the period between 2013 and 2015, the Grl. halibut harvest constituted approximately 33 per cent of the total Greenlandic harvest of all fish species by weight and approximately 44 per cent by income, and the Grl. halibut price increased by approximately 47.5 per cent from 2010 to 2019 (Statistics Greenland, 2020). This

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[1] With the agreement of 2009, a local government was established in Greenland. However, Greenland still has representatives in the Danish parliament and it is still highly dependent on subsidies from Denmark. Therefore, we use the term 'partial autonomy' to characterize the relation between Greenland and Denmark.

has generated increased political pressure for larger Grl. halibut quotas, but concerns for overexploitation of the fish stock have been raised (Fiskerikommissionen, 2021). Thus, an important policy issue for Greenland is securing the long-run sustainable management of the Grl. halibut fish stock.

The largest amount of Grl. halibut is harvested on the west coast of Greenland. In this respect, at least three different fleet segments target Grl. halibut, namely, high sea vessels, coastal vessels above 6 m and coastal boats below 6 m.[2] A total allowable catch (TAC) is fixed each year based on biological recommendations, and this TAC is allocated to the high sea and coastal areas as total quotas (e.g., Ogmundsson and Bæk, 2021). The total high sea Grl. halibut quota is then divided between two fleet segments represented by vessels from Greenland and foreign vessels. The total coastal quota is also allocated to two fleet segments given by vessels above 6 m and boats below 6 m (e.g., Ogmundson and Haraldson, 2017[3]). Regarding the regulation of individual vessels, an individual transferrable quota system was introduced in 2012 for coastal vessels above 6 m targeting Grl. halibut in Disko Bay, Uummannaq and Upernavik, whereas time-limited licences without a maximum harvest are used for both high sea vessels from Greenland and coastal boats below 6 m (e.g., Ogmundsson, 2019).[4]

At least two issues are relevant for optimal management of Grl. halibut. First, Grl. halibut spawn and grow in the high sea area (e.g., Boje, 2002). However, according to Fiskerikommissionen (2021), the migration of young Grl. halibut from the high sea area constitute the main source of recruitment for the coastal stock size. Furthermore, Grl. halibut does not spawn in coastal areas (e.g., Boje, 2002). Thus, the natural growth of Grl. halibut on the west coast of Greenland appears to differ between the high sea and coastal area. This implies that we shall operate with separate high sea and coastal fish stocks, but in current biological assessments, a common fish stock is assumed (e.g., Treble and Nogueira, 2018). However, if this assumption can be questioned, it is relevant to investigate the implications for optimal management of Grl. halibut in terms of operating with two separate fish stocks rather than a common fish stock.

Second, from an economic perspective, it is not only primary fisheries but also secondary land-based processing industries that are important for Greenland (e.g., Ogmundson and Haraldson, 2017). For high sea vessels, the harvest of Grl. halibut is to a large extent processed on board, but to ensure land-based employment and profitability, a legal landing obligation is imposed. According to this obligation, high sea vessels shall deliver at least 25 per cent of the Grl. halibut for land-based processing (e.g., Ogmundson and Haraldson, 2017). In contrast, coastal vessels and boats normally deliver the entire harvest of Grl. halibut to land-based processing.[5] Thus, an important issue is the implications for optimal management of Grl. halibut in terms of considering the profit of land-based processing.

To our knowledge, only Fredenslund (2022) has used a modelling approach to study the optimal management of Grl. halibut. By using a static, steady-state equilibrium

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[2] The high sea area is located more than 3 nautical miles from the coast, while the coastal area lies within a 3 nautical mile limit.

[3] Ogmundson and Haraldson (2017) is available from the authors of this paper upon request.

[4] The total Grl. halibut quota is not transferable between vessels in different fleet segments (high sea vessels, coastal vessels above 6 m and coastal boats below 6 m). Thus, vessels cannot trade with individual quotas between fleet segments.

[5] A few coastal vessels have an exemption from this rule since 75 per cent of their landings can be processed on board.

model, Fredenslund (2022) showed that the coastal Grl. halibut fish stock in Disko Bay, Uummannaq and Upernavik is overexploited. In reaching this conclusion, Fredenslund (2022) used a model with two fleet segments (coastal vessels above 6 m and coastal boats below 6 m), but only one fish stock was considered, and land-based processing was not included. However, a modelling approach can also be used to investigate the effect of operating with separate high sea and coastal fish stocks and considering land-based processing. These topics constitutes important areas for future research.

The purpose of this paper is to address these research topics. We depart from a theoretical model at the industry level with a high sea and coastal fleet segment. The model is used to identify four scenarios for the optimal, long-run, steady-state equilibrium management of fishery resources that differ with respect to whether a common or two separate fish stocks exist and whether the land-based profit is considered. The model is parametrized using the high sea and coastal Grl. halibut fisheries on the west coast of Greenland as an empirical case. For Grl. halibut, we compare the outcome under four scenarios for optimal management. Furthermore, to investigate whether economic overexploitation of the Grl. halibut fish stock is occurring, the scenarios for optimal management are compared to the actual situation. Finally, when parameterizing the model for Grl. halibut, many estimated parameter values are highly uncertain, so to investigate the robustness of our results, we conduct sensitivity analyses by varying each parameter value separately with ±50 per cent.

With the analysis in this paper, we also contribute to at least two additional strands of related fishery economic literature. First, many empirical papers discuss long-run optimal management with several fleet segments and fish stocks. Examples of empirical papers operating with several fleet segments are Ulrich *et al.* (2002), Camber *et al.* (2012) and Quinones *et al.* (2021), while DuPont *et al.* (2005), Danielsson *et al.* (1997) and Pope *et al.* (2021) are examples of studies of actual fisheries that consider multiple fish stocks. However, the empirical literature on optimal management with multiple fleet segments and fish stocks does not consider the effect of land-based processing. By doing so, we make a novel contribution to the literature.

Second, several papers investigate the relationship between primary fisheries and land-based processing. A number of papers have shown that optimal management of primary fisheries will have a negative effect on the land-based profit (e.g., Casey *et al.*, 1995; Eythorsson, 2000; Norman-Lopez and Pascoe, 2011). More importantly, Grafton *et al.* (2012) argue that the optimal harvest and stock size will be reduced when the land-based profit is taken into account, but only one fish stock and fleet segment is considered. In this paper, we investigate the implications for optimal management of including the land-based industry profit, and we operate with several fleet segments and fish stocks. Thereby, we make a novel contribution to the abovementioned literature.

2. Grl. halibut fishery on the west coast of Greenland

In this section, we will describe the Grl. halibut fishery on the west coast of Greenland, and descriptive statistics for this fishery are provided in table 1.[6]

From table 1, we see that the total Grl. halibut quota allocated to high sea vessels from Greenland and coastal vessels above 6 m increased between 2014 and 2015, while the quota allocated to coastal boats below 6 m increased during the entire period. A part

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[6] A detailed description (including a definition of the indicators in table 1 and the actual harvest of all fish species) can be found in appendix A.

Table 1. Indicators for the high sea and coastal area on the west coast of Greenland, 2013–2015

Indicator	Fleet segment	2013	2014	2015
Grl. halibut quota (tons)	High sea vessels from Greenland	8,075	8,075	9,725
	High sea vessels from other nations	5,850	5,850	5,850
	Coastal vessels above 6 m	11,577	11,577	12,270
	Coastal boats below 6 m	13,123	14,817	15,930
Total revenue (million DKK) (all fish species)	High sea vessels from Greenland	435.4	543.7	614.4
	Coastal vessels above 6 m	117.3	124.7	64.2
	Coastal boats below 6 m	264.3	284.3	374.5
Total costs (million DKK) (all fish species)	High sea vessels from Greenland	254.1	307.2	350.8
	Coastal vessels above 6 m	63	75	27.9
	Coastal boats below 6 m	74.6	77.4	110.5
Number of active vessels	High sea vessels from Greenland	4	4	4
	Coastal vessels above 6 m	128	125	122
	Coastal boats below 6 m	759	762	780

Sources: Ogmundson and Haraldson (2017), Fiskerikommissionen (2021).

of the high sea Grl. halibut quota is allocated to foreign vessels according to international fishing agreements covering a reasonably long period.[7] This implies that the high sea Grl. halibut quota allocated to foreign vessels was constant between 2013 and 2015 (table 1).

From Fiskerikommissionen (2021), we have information about the number of used licences for harvesting Grl. halibut for the period between 2013 and 2015, and we use this as a measure of the number of vessels participating in the fishery. From table 1, we see that only 4 production trawlers from Greenland participated in the high sea Grl. halibut fishery between 2013 and 2015. Furthermore, the number of coastal vessels above 6 m and boats below 6 m is approximately constant over the entire period. Compared to vessels above 6 m, a large number of boats below 6 m participate in the coastal Grl. halibut fishery.

Ogmundson and Haraldson (2017) reported the total industry revenue and accounting costs for vessels targeting Grl. halibut in the high sea and coastal area, and this

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[7] Greenland has an agreement with the European Union (EU). According to this agreement, Greenland obtains free access for fish products to EU markets and receives economic compensation for providing vessels from the EU with access to the fishing territory of Greenland. Greenland also has bilateral agreements with several other fishing nations, according to which vessels from Greenland obtain access to the territory of other nations while other nations obtain access to fishing areas of Greenland.

Table 2. Four scenarios

	Common fish stock	Two separate fish stocks
Without land-based profit	1	2
With land-based profit	3	4

information can also be found in table 1.[8] The revenue and costs are identified for all vessels targeting Grl. halibut but covers the harvest of all fish species. From table 1, we see that the revenue and accounting costs for high sea vessels from Greenland and coastal boats below 6 m increased between 2013 and 2015. However, coastal vessels above 6 m experienced a considerable decrease in revenue and accounting costs between 2014 and 2015, although the Grl. halibut quota for this fleet segment has increased. The explanation for this fact is that the harvest of Grl. halibut by coastal vessels above 6 m decreased in 2015, indicating that the Grl. halibut quota was not fully utilized for this fleet segment (appendix A).

3. Theoretical model

In this paper, we use a theoretical model to construct four scenarios for optimal management of Grl. halibut on the west coast of Greenland. An overview of these scenarios is provided in table 2.

There are four important facts related to the theoretical model. First, we use a static model, which we solve for a long-run steady-state equilibrium.[9] Following Clark (1991), a static fisheries economic model implies that the undiscounted long-run economic yield for one period is maximized subject to the fish stocks being in a steady-state equilibrium.[10] Second, we operate with two fleet segments represented by high sea and coastal vessels. From table 1, the coastal fleet segment can be divided into vessels above 6 m and boats below 6 m. However, for simplicity, we have chosen only to operate with one coastal fleet segment. Third, we consider a model at the industry level, implying that we operate with revenue, costs and harvest for entire fleet segments. Fourth, we use a dual instead of primal formulation of the model. According to Neher (1990), a fishing technology is captured by a production function with a primal formulation, implying that fishing effort and stock size are control variables. With a dual approach, a cost function is introduced, and harvest and stock size are control variables. There is a close relation between a primal and dual formulation in the sense that a production function can be used to derive a cost function (e.g., Neher, 1990).

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[8] The revenue and accounting cost observations in Ogmundson and Haraldson (2017) have been obtained from tax authorities and the revenue is corrected for subsidies while the accounting cost is adjusted for taxes and depreciations.

[9] Dynamic models have been extensively used to investigate optimal management of a fisheries resource (e.g., Clark, 1991). However, in a model with two fleet segments and fish stocks where the land-based profit is considered, dynamic adjustment paths towards a steady-state equilibrium can be very sensitive to minor changes in parameter values. Thus, as a simplification we have used a static model in this paper.

[10] The empirical analysis is based on actual observations for the total high sea and costal industry costs, implying that the capacity and capacity utilization is assumed to be given, but introducing long-run optimal management will probably generate a reduction in the capacity and capacity utilization implying that the total industry costs will decrease (e.g., Greboval and Munro, 1999). However, we do not have data on the total high sea and coastal industry costs when changing the capacity and capacity utilization, Thus, as a simplification we have chosen to use the actual high sea and coastal industry costs.

3.1. Scenario 1

Scenario 1 in table 2 covers optimal management with a common fish stock without taking the land-based profit into account. Initially, we derive a resource restriction in a steady-state equilibrium (see, e.g., Clark (1991) for an introduction to resource restrictions). We let x be the common Grl. halibut stock size for the high sea and coastal area and the natural growth function is denoted $F(x)$. In line with the convention, we assume an inverse U-shaped growth function in the sense that $F'(x) > 0$ for $x < x^{MSY}$, $F'(x) < 0$ for $x > x^{MSY}$ and $F''(x) < 0$ for all x, where x^{MSY} is the Grl. halibut stock size at maximum sustainable yield (MSY). The coastal industry Grl. halibut harvest is denoted h_C (subscript C covers the coastal area), while h_H is the high sea industry Grl. halibut harvest by vessels from Greenland (subscript H covers the high sea area). Furthermore, β denotes a constant scaling factor for the harvest by vessels from other fishing nations in the high sea area. Formally, we have that $h_F = \beta h_H$, where h_F is the high sea industry Grl. halibut harvest by foreign vessels (subscript F covers foreign vessels). Now, the resource restriction in a steady-state equilibrium becomes:

$$F(x) - h_H - h_C - \beta h_H = 0. \tag{1}$$

From (1), the natural growth is equal to the aggregated Grl. halibut harvest in a steady-state equilibrium. The aggregated Grl. halibut harvest consists of the coastal harvest and the high sea harvest by vessels from Greenland and other fishing nations. Note that in the scenarios with a common Grl. halibut fish stock, interactions between high sea and coastal vessels arise due to the resource restriction (two fleet segments exploit a common fish stock).

Next, we derive an objective function and the coastal industry cost function for vessels targeting Grl. halibut is denoted $C_C(h_C, x)$. We assume that an increase in the Grl. halibut stock size generates a reduction in the costs since it is easier to harvest fish, implying that $(\partial C_C/\partial x) < 0$.[11] Furthermore, we assume that $(\partial C_C/\partial h_C) > 0$ and $(\partial^2 C_C/\partial {h_C}^2) > 0$, implying that the marginal coastal harvesting costs are positive and increasing (e.g., Clark, 1991). The high sea industry cost function for vessels from Greenland is denoted $C_H(h_H, x)$, and for the derivatives of the high sea cost function, we adopt the same assumptions as for the coastal cost function ($(\partial C_H/\partial x) < 0$, $(\partial C_H/\partial h_H) > 0$ and $(\partial^2 C_H/\partial {h_H}^2) > 0$). In addition, p_C and p_H denote constant coastal and high sea Grl. halibut prices, respectively.[12] Now $\pi_H(h_H, x) = p_H h_H - C_H(h_H, x)$ is the total high sea industry profit for vessels from Greenland defined as revenue minus costs, while $\pi_C(h_C, x) = p_C h_C - C_C(h_C, x)$ is the total coastal industry profit from harvesting Grl. halibut. Note that in the high sea profit function, we have excluded the gain of providing foreign vessels with the opportunity to harvest Grl. halibut in the high sea area.[13] We can now define the long-run economic yield, $\pi(h_H, h_C, x)$, as the sum of the total high

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[11] Following Neher (1990), this implies that harvesting Grl. halibut is assumed to be a search fishery.

[12] An assumption about constant prices for fish products is common in fisheries economic models (see, e.g., Asche *et al.* (2017) for a justification).

[13] It can be argued that the Grl. halibut harvest by vessels from other fishing nations should only be included in (1) if the monetary gain from international fishing agreements is considered in the objective function. However, we do not have data on the payoff for Greenland from agreements with other nations so, as a simplification, we disregard this gain in the objective function. Taking the gain of agreements with other nations into account would tend to make high sea fisheries more profitable.

sea and costal profit:

$$\pi(h_H, h_C, x) = \pi_H(h_H, x) + \pi_C(h_C, x) = p_H h_H - C_H(h_H, x) + p_C h_C - C_C(h_C, x). \tag{2}$$

Note that in (2), we have disregarded discounting because we are interested in maximizing the long-run economic yield.

Now, the problem is to maximize (2) subject to (1), and for solving this problem, we set up the following Lagrange function:

$$\begin{aligned} L = {} & p_H h_H - C_H(h_H, x) + p_C h_C - C_C(h_C, x) \\ & + \lambda(F(x) - h_H - h_C - \beta h_H), \end{aligned} \tag{3}$$

where $\lambda > 0$ is the shadow price, or the marginal user cost of the Grl. halibut fish stock (Anderson, 1977). By using h_H, h_C and x as control variables, we obtain the following first-order conditions:

$$\frac{\partial L}{\partial h_H} = p_H - \frac{\partial C_H}{\partial h_H} - \lambda(1+\beta) = 0 \tag{4}$$

$$\frac{\partial L}{\partial h_C} = p_C - \frac{\partial C_C}{\partial h_C} - \lambda = 0 \tag{5}$$

$$\frac{\partial L}{\partial x} = -\frac{\partial C_H}{\partial x} - \frac{\partial C_C}{\partial x} + \lambda F'(x) = 0 \tag{6}$$

$$\frac{\partial L}{\partial \lambda} = F(x) - h_H - h_C - \beta h_H = 0. \tag{7}$$

According to (4), the optimal high sea harvest occurs where the marginal high sea profit is equal to the marginal user cost of the Grl. halibut fish stock corrected with the scaling factor for the harvest by vessels from other fishing nations. Equation (5) indicates that the optimal coastal harvest arises where the marginal coastal profit is equal to the marginal user cost of the fish stock. According to (6), the optimal stock size occurs where the sum of the high sea and coastal cost savings associated with an increase in the stock size is equal to the value of the marginal growth. Finally, (7) is identical to the resource restriction from (1). Equations (4)–(7) represent four equations with four unknowns (h_H, h_C,x and λ), and solving this equation system provides optimal values of the unknowns, which we denote $h_H{}^*$, $h_C{}^*$, x^* and λ^*. By using these solutions, we can define the optimal high sea and coastal industry profit as $\pi_H(h_H{}^*, x^*) = p_H h_H{}^* - C_H(h_H{}^*, x^*)$ and $\pi_C(h_C{}^*, x^*) = p_C h_C{}^* - C_C(h_C{}^*, x^*)$, while the optimal long-run economic yield becomes $\pi(h_H{}^*, h_C{}^*, x^*) = \pi_H(h_H{}^*, x^*) + \pi_C(h_C{}^*, x^*)$. In this paper, we will identify the abovementioned indicators empirically for the Grl. halibut fishery on the west coast of Greenland.

3.2. Scenario 2

We now consider scenario 2, where we investigate optimal management with separate high sea and coastal fish stocks (table 2). Now, we must operate with two separate resource restrictions and we allow for migration from the high sea to the coastal area. To derive these restrictions, we let x_C and x_H be the coastal and high sea Grl. halibut stock size, respectively. The coastal and high sea natural growth functions of Grl. halibut are denoted $G_C(x_C)$ and $G_H(x_H)$, and as in section 3.1, we assume inverse U-shaped growth functions. Finally, the net migration of Grl. halibut is captured by $M(x_H, x_C)$, and three facts are important in relation to this function: (i) we assume that $M(x_H, x_C) > 0$, implying a net migration from the high sea to the coastal area; (ii) the net migration from the high sea area is assumed to be identical to the net migration into the coastal area; and (iii) following Chapman *et al.* (2012), we assume that $(\partial M/\partial x_C) < 0$ and $(\partial M/\partial x_H) > 0$, implying that the net migration decreases (increases) with an increase (decrease) in the coastal stock size and a decrease (increase) in the high sea stock size. Given this notation, the high sea and coastal resource restrictions become:

$$G_H(x_H) - h_H - \beta h_H - M(x_H, x_C) = 0 \tag{8}$$

$$G_C(x_C) - h_C + M(x_H, x_C) = 0. \tag{9}$$

Equation (8) indicates that in a steady-state equilibrium, the high sea natural growth must be equal to the high sea Grl. halibut harvest by vessels from Greenland and other fishing nations plus the net migration of Grl. halibut to the coastal area. Similarly, (9) indicates that the coastal natural growth plus the net migration of Grl. halibut from the high sea area must be equal to the coastal Grl. halibut harvest in a steady-state equilibrium. Since we have two resource restrictions, we must introduce two shadow prices, and the marginal user costs of the coastal and high sea fish are denoted ε_C and ε_H, respectively. Note that in the scenarios with two separate fish stocks, interactions between high sea and coastal vessels occur due to the net migration.

Regarding the objective function, the only difference compared to section 3.1 is that the separate stock sizes for the high sea and coastal areas must be considered in the cost functions. Thus, $C_C(h_C, x_C)$ and $C_H(h_H, x_H)$ are coastal and high sea industry cost functions for harvesting Grl. halibut and, for the derivatives of the cost functions, we adopt the same assumptions as in section 3.1. Now, the problem is to maximize the long-run economic yield from (2) (with the adjusted cost functions) subject to (8) and (9). To solve this problem, a Lagrange function is formulated (with $\varepsilon_H > 0$ and $\varepsilon_C > 0$ as Lagrange multipliers) and, since we have two separate fish stocks, the first-order conditions for x_H and x_C are:

$$\frac{\partial L}{\partial x_H} = -\frac{\partial C_H}{\partial x_H} + \varepsilon_H G'_H(x_H) - \varepsilon_H \frac{\partial M}{\partial x_H} + \varepsilon_C \frac{\partial M}{\partial x_H} = 0 \tag{10}$$

$$\frac{\partial L}{\partial x_C} = -\frac{\partial C_C}{\partial x_C} + \varepsilon_C G'_C(x_C) - \varepsilon_H \frac{\partial M}{\partial x_C} + \varepsilon_C \frac{\partial M}{\partial x_C} = 0. \tag{11}$$

According to (10), the optimal high sea Grl. halibut stock size occurs where the marginal high sea cost savings from an increase in the stock size are equal to the value of the high sea marginal growth corrected for the net cost of the marginal migration to the coastal area. The optimality condition for the coastal fish stock in (11) can be interpreted in a similar way. Regarding the first-order conditions for h_H and h_C, these are identical to (4) and (5) with two minor adjustments: (i) there are two distinct shadow prices, $\varepsilon_H > 0$ and $\varepsilon_C > 0$; and (ii) x_H and x_C are included in the cost functions. Now the adjusted versions of (4)–(5) and (8)–(11) represent six equations with six unknowns (h_H, h_C, x_H, x_C, ε_H and ε_C) and, as in section 3.1, the equation system can be solved for optimal values of the unknowns. As in section 3.1, we can also use the optimal values of the unknowns to find the optimal high sea and coastal industry profit and the optimal long-run economic yield.

3.3. Scenario 3

We now turn to scenario 3, where the land-based profit is considered in the case with a common fish stock (table 2). A legal landing obligation requires high sea vessels to deliver at least 25 per cent of their Grl. halibut harvest for land-based processing. However, we assume that high sea vessels have no incentive to deliver more than 25 per cent of their Grl. halibut harvest for land-based processing. This implies that 0.25 h_H enters into the revenue and the cost function for the land-based processing industry. We also assume that coastal vessels deliver all Grl. halibut harvest for land-based processing, implying that h_C enters into the relevant land-based functions. We let $C_L(h_C, 0.25\, h_H)$ be a land-based industry cost function (subscript L covers the land-based industry), and we assume that $(\partial C_L/\partial h_C) > 0$, $(\partial^2 C_L/\partial {h_C}^2) > 0$, $(\partial C_L/\partial h_H) > 0$ and $(\partial^2 C_L/\partial {h_H}^2) > 0$. Furthermore, p_L is a constant price for Grl. halibut delivered from land-based factories while α capture a constant land-based utilization rate. Specifically, α capture the share of the harvest that is utilized by the land-based industry.[14] Now we get that $\pi_L(h_C, h_H) = \alpha p_L(h_C + 0.25h_H) - C_L(h_C, 0.25h_H)$ is the land-based industry profit, defined as the revenue minus the costs.[15] Compared to the scenario in section 3.1, additional interactions between high sea and coastal vessels now arise due to the land-based profit function. Now, the problem is to maximize the objective function from (2) with the land-based profit included subject to (1), and this problem can be solved by setting up a Lagrange function. We now let $\theta > 0$ denote the marginal user cost of the fish stock, and the first-order conditions for h_C and h_H become:

$$\frac{\partial L}{\partial h_H} = p_H - \frac{\partial C_H}{\partial h_H} + 0.25 p_L \alpha - 0.25 \frac{\partial C_L}{\partial h_H} - \theta(1+\beta) = 0 \tag{12}$$

$$\frac{\partial L}{\partial h_C} = p_C - \frac{\partial C_C}{\partial h_C} + p_L \alpha - \frac{\partial C_L}{\partial h_C} - \theta = 0. \tag{13}$$

Compared to (4) and (5), the only difference is that the marginal land-based profit is considered when identifying the optimal high sea and coastal harvest in (12) and (13) while the first-order condition for the stock size is identical to (6) except that θ is included. Now the adjusted version of (6), (7) and (12)–(13) represent four equations with four unknowns (h_H, h_C, x and θ), and again, we can solve the equation system for the optimal values of the unknowns. The optimal values can also be used to find the optimal high sea and coastal industry profit, the optimal land-based profit and the optimal long-run economic yield.

3.4. Scenario 4

We now consider scenario 4, where we include the land-based profit function in the case described in section 3.2 (table 2). Now, interaction between high sea and coastal vessels

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[14] We include α in the model because we want to use the high sea and coastal Grl. halibut harvest as control variables.

[15] Note that the high sea vessels and land-based processing factories have the same owner in Greenland, implying that the land-based industry profit function should have been included as a part of the high sea profit function. More importantly, the land-based processing factories may have a monopsony in relation to coastal vessels, implying that they will try to decrease the price and increase the quantity of Grl. halibut that is received from coastal vessels. Taking this into account implies that we must estimate a negatively-sloped demand function for the amount of Grl. halibut that land-based processing factories obtain from coastal vessels. However, we do not have data to perform this task, so as a simplification we assume that high sea vessels and land-based processing factories have separate owners.

also arises due to the land-based profit, and γ_H and γ_C denote the marginal user cost of the high sea and coastal fish stocks, respectively. We must incorporate the land-based profit into the objective function in the same way as in section 3.3, and the problem is to maximize the long-run economic yield in (2), including the land-based profit subject to the resource restrictions in (8) and (9). This problem can be solved by using a Lagrange function, and the first-order conditions for h_H and h_C are identical to (12) and (13), apart from the fact that the shadow prices are γ_C and γ_H. Furthermore, the resource restrictions are given by (8) and (9), while the first-order conditions for x_H and x_C are identical to (10) and (11) with the adjustment that γ_C and γ_H is included. Now the adjusted versions of (8)–(13) represent six equations with six unknowns (h_H, h_C, x_H, x_C, γ_H and γ_C). The solution to this equation system represents optimal values of the unknowns, and these values can be used to find the optimal high sea and coastal industry profit, the optimal land-based profit and the optimal long-run economic yield.

4. Functional forms and parameter estimation

Now we briefly summarize the parametrization of our model for the Grl. halibut fishery; more details can be found in appendix A. We have obtained a benchmark value for each parameter, but due to uncertainty we have generated an upper and lower bound by varying each parameter value by ± 50 per cent. An overview of the parametrization is provided in table 3.

4.1. The resource restrictions

First, we discuss how a growth function has been estimated for the scenarios with a common stock size of Grl. halibut. From section 3.1, the natural growth function must be inverse U-shaped, and to fulfil this requirement, we use a logistic specification (see, e.g., Clark (1991) for an introduction):

$$F(x) = rx\left(1 - \frac{x}{K}\right), \tag{14}$$

where $r$is the intrinsic growth rate and K is the carrying capacity. To estimate (14), we use time series for the stock size and harvest by all fishing nations of Grl. halibut on the west coast of Greenland for the period between 1997 and 2017 (MA Treble, personal communication, 2019, based on Treble and Nogueira (2018)).[16] We inserted the logistic growth function in (14) into the resource restriction from (1), and then the restriction was estimated with ordinary least squares (OLS) using harvest as the dependent variable (e.g., Elofsson and Svensson, 2019).[17] Thus, we obtain estimated parameter values for the intrinsic growth rate and carrying capacity in the scenarios with a common fish stock.

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[16] The stock size of Grl. halibut is identified for NAFO subareas 0 and 1 which cover more than the west coast of Greenland. Furthermore, Vihtakari *et al.* (2022) have shown that considerable migration of Grl. halibut occurs between NAFO subareas 0 and 1 and other management areas. Thus, our definition of the stock size of Grl. halibut on the west coast for Greenland can be discussed. However, in this paper we must use current stock assessments to identify the stock size of Grl. Halibut, and therefore we have chosen to use the data for NAFO subareas 0 and 1.

[17] By using this approach, we assume that the Grl. halibut fish stock is in a steady-state equilibrium for each year covered by the data. As an alternative, we have used the data on the stock size and harvest to calculate a time series for the natural growth for Grl. halibut and then (14) has been estimated directly with OLS (appendix A). With this approach we obtain a U-shaped (and not an inverse U-shaped) natural growth function for Grl. halibut, which is inconsistent with the theoretical model; thus, we cannot use this method.

Table 3. Functional forms and parameter estimates, common fish stock and two separate fish stocks

Assumption	Function	Specification	Label	Unit	Name	Benchmark value	Lower bound	Upper bound
Common fish stock	Growth	$F(x) = rx\left(1 - \frac{x}{K}\right)$	r		Intrinsic growth rate	0.34850	0.17423	0.52275
			K	Tons	Carrying capacity	480,027	295,785	887,356
	High sea cost	$C_H(h_H, x) = c_H \frac{{h_H}^2}{x}$	c_H	Million DKK/tons	High sea cost parameter	0.03876	0.019384	0.058151
	Coastal cost	$C_C(h_C, x) = c_C \frac{{h_C}^2}{x}$	c_C	Million DKK/tons	Coastal cost parameter	0.00892	0.00446	0.01339
Two separate fish stocks	High sea growth	$G_H(x_H) = r_H x_H \left(1 - \frac{x_H}{K_H}\right)$	r_H		High sea intrinsic growth rate	0.483	0.2415	0.7242
			K_H	Tons	High sea carrying capacity	157,339	104,885	314,057
	Coastal growth	$G_C(x_C) = r_C x_C \left(1 - \frac{x_C}{K_C}\right)$	r_C		Coastal intrinsic growth rate	0.579	0.2895	0.8685
			K_C	Tons	Coastal carrying capacity	44,367	29,578	88,735
	Migration	$M(x_H, x_C) = m \frac{x_H}{x_C}$	m	Tons	Net migration	237.009	118.5045	355,513
	High sea costs	$C_H(h_H, x_H) = c_H \frac{{h_H}^2}{x_H}$	c_H	Million DKK/tons	High sea cost parameter	0.024036	0.012018	0.036054
	Coastal cost	$C_C(h_C, x_C) = c_C \frac{{h_C}^2}{x_C}$	c_C	Million DKK/tons	Coastal cost parameter	0.00339	0.0017	0.00509

Table 3. *Continued.*

Assumption	Function	Specification	Label	Unit	Name	Benchmark value	Lower bound	Upper bound
Common and two separate fish stocks	High sea price		p_H	Million DKK/tons	Constant high sea price	0.01097	0.00549	0.01646
	Coastal price		p_C	Million DKK/tons	Constant coastal price	0.00935	0.00468	0.01403
	Scaling factor, other nations		β		Scaling factor for harvest	0.677	0.3385	1.0155
	Land-based cost	$C_L(h_C, h_H) = c_L(h_C + 0.25\, h_H)^2$	c_L	Million DKK/tons^2	Land-based cost parameter	2.53*10^{-7}	1.26*10^{-7}	3.97*10^{-7}
	Land-based price		p_L	Million DKK/tons	Constant land-based price	0.00714	0.00357	0.01072
	Land-based utilization rate		α		Share of harvest	0.92	0.46	1

With two separate fish stocks, we chose to allocate the common Grl. halibut stock size to the high sea and coastal area. To do this, we use the relative distribution of one-year-old Grl. halibut in the high sea and coastal area in Disko Bay from 1997 and 2011 (OA Jørgensen, personal communication, 2019, based on Jørgensen (2013)).[18] The total Grl. halibut harvest is allocated to the high sea and coastal areas by using the high sea quota share for 2015, which was calculated using the quotas reported in table 1. For the coastal natural growth, we again assume a logistic growth function, and r_C is the coastal intrinsic growth rate, while K_C is the coastal carrying capacity. Concerning the net migration function, we follow Chapman *et al.* (2012) and assume that the net migration depends on the relative density of the high sea and coastal Grl. halibut fish stock such that:

$$M(x_H, x_C) = m\frac{x_H}{x_C}, \tag{15}$$

where m is a net migration parameter. To estimate the coastal growth and migration functions, we use the same procedure as in the case with a common fish stock. Thus, we insert the coastal logistic growth and migration functions into (9) and then use OLS to estimate the coastal resource restriction with the coastal Grl. halibut harvest as the dependent variable. Hence, we obtain estimated parameter values for r_C, K_C and m.

For the high sea natural growth function, we also assume a logistic growth function, with r_H denoting the high sea intrinsic growth rate, while K_H is the high sea carrying capacity. To estimate this growth function, we use the steady-state resource restriction for the high sea fish stock in (8), but we must consider that migration will be identical in the high sea and coastal areas. Thus, we use (15) to construct a time series for net migration using the observations for the high sea and coastal stock size and the estimated value of m (see Chapman *et al.* (2012) for a justification for this procedure). Now, the sum of the observations for the high sea harvest and net migration become the dependent variable when using (8) to estimate r_H and K_H with OLS.

In the resource restrictions in (1) and (8), β captures a constant scaling factor for high sea Grl. halibut harvest by vessels from other fishing nations. The amount of Grl. halibut harvest allocated to other fishing nations is determined by international fishing agreements. Thus, we can identify β as the high sea Grl. halibut quota share allocated to other fishing nations, and this can be calculated by using the information in table 1.[19] From table 3, four facts are important in relation to the estimated resource restrictions: (i) the carrying capacity with a common fish stock is higher than the coastal and high sea carrying capacity; (ii) the high sea carrying capacity is larger than the coastal carrying capacity because the stock size tends to be higher in the high sea area; (iii) the migration parameter is very low, implying that the interaction between the high sea and coastal area is low[20]; and (iv) the share of the high sea harvest allocated to other nations represents

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[18] For the period between 2012 and 2017, we have used the average distribution of one-year-old Grl. halibut in the Disko Bay for the period between 1992 and 2011.

[19] We have only used the quota observations for 2013 and 2015 to secure consistency with our costs and price estimates described below.

[20] A low migration is in line with the results in the literature in the sense that it has been shown that juvenile Grl. halibut with a low weight migrate into the coastal area, while almost no Grl. halibut migrate out of the coastal area (e.g., Boje, 2002). Given this fact, it can be argued that we should have assumed a constant net migration. However, a constant migration implies that there is no interaction between high sea and coastal vessels in scenario 2, so it seems reasonable to assume that the net migration depends on the high sea and coastal stock size.

an additional cost for high sea fisheries since Greenland does not obtain a payoff from international fishing agreements within our model.

4.2. High sea and coastal industry profit function

We assume the following high sea industry cost function, which fulfils the assumption about the derivatives from section 3:[21]

$$C_H(h_H, x) = c_H \frac{h_H^2}{x}, \tag{16}$$

where c_H is a high sea cost parameter and $C_H(h_H, x)$ is the total high sea industry cost of harvesting Grl. halibut. To estimate the cost parameter in (16) in the case of a common fish stock, we use data on the total high sea accounting cost of harvesting for all fish species on the west coast of Greenland for the period between 2013 and 2015 from table 1.[22] From this, we obtain the total high sea cost of harvesting Grl. halibut for the period between 2013 and 2015 by using Grl. halibut quota shares defined as the high sea Grl. halibut quota divided by the high sea quotas on all species. To reduce the effect of random variations affecting the fisheries-related conditions in a given year, we take a simple average of the total cost observations over the period. From Ogmundson and Haraldson (2017), we also have information about the high sea Grl. halibut harvest for 2013–2015, which is again averaged over the period. Furthermore, as described in section

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[21] The cost function in (16) can be justified in two ways, and to summarize these we disregard the subscript for the fleet segment. First, with (16) the total costs are proportional to the product of the harvest (h) and the harvest divided by the stock size (h/x). The fact that the harvest affects costs seems obvious and it is also reasonable to argue that a high harvest compared to the stock size implies higher costs than a low harvest compared to the stock size. Second, as mentioned in section 3, a production function can be used to derive a cost function and this issue is investigated in appendix B. Specifically, we consider a Cobb–Douglas production function given as $h = qE^{\gamma}x^{\mu}$,where q is the catchability coefficient, E is fishing effort and γ and μ are parameters in the production function. From this production function, it is clear that if $\gamma < 1$, the marginal product of the effort is positive but decreasing. Furthermore, given the Cobb–Douglas production function, the cost function becomes $C(h, x) = c(h^{(1/\gamma)}/x^{(\mu/\gamma)})$ (appendix B). Now if $\gamma < 1$, the marginal harvesting cost is positive and increasing. Thus, provided that the marginal product of effort is positive but decreasing in a Cobb–Douglas production function, the marginal harvesting cost is positive and increasing. Furthermore, if we assume that $\gamma = \mu = 0.5$, the cost function becomes $C(h, x) = c(h^2/x)$, which is identical to (16). By inserting $\gamma = \mu = 0.5$ in the Cobb–Douglas production function, we get that$h = qE^{0.5}x^{0.5}$. Thus, if we want to justify the cost function in (16), we must argue that a production function given as $h = qE^{0.5}x^{0.5}$ is reasonable and this can be done in two ways. First, with the production function we assume constant returns to scale ($0.5 + 0.5 = 1$) which has been shown to hold for fisheries in many classical studies (e.g., Bjørndal, 1987; Hannesson, 2007). Second, for many fisheries, a conventional result is that a Cobb–Douglas production function provides better statistical results than a Schaefer production function given as $h = qEx$ (e.g., Hannesson, 1983; Doll, 1988). Thus, the cost function in (16) seems reasonable.

[22] It is commonly argued that we should use opportunity costs (not accounting costs) to estimate a cost function because the resource rent (not profit) will be identified (e.g., Jensen *et al.*, 2019). As mentioned in section 2, the cost observations in Ogmundson and Haraldson (2017) are accounting costs (collected from tax authorities), but by following Flaaten *et al.* (2017), we may obtain a very rough approximation for the opportunity costs by correcting the accounting costs with the remuneration of the skipper. However, by using the data in Ogmundson and Haraldson (2017), it is not possible to calculate the remuneration of the skipper, so we have chosen to estimate our cost parameters by using accounting costs. The opportunity cost of the skipper is probably higher for high sea than for coastal vessels since a skipper on high sea vessels has better alternative employment opportunities than a skipper on coastal vessels. Thus, using opportunity costs instead of accounting costs tends to make coastal fishing become more profitable.

4.1, we have information about the stock size for the period between 2013 and 2015, and we take an average of these observations. Now we have all the necessary information to calculate the high sea cost parameter by using (16).

For the high sea cost parameter with two separate fish stocks, the only difference compared to a common fish stock is that we use the average high sea fish stock for the period between 2013 and 2015 (instead of the average common fish stock) to calculate the high sea cost parameter using (16). For the coastal industry cost function, we assume the same cost function as in (16), and c_C is a coastal cost parameter, while $C_C(h_C, x)$ is the total coastal industry cost of harvesting Grl. halibut. With both a common fish stock and two separate fish stocks, the only difference, compared with the high sea cost function, is that the data for the total coastal cost of harvesting all species and the coastal harvest of Grl. halibut are reported for vessels above 6 m and boats below 6 m (table 1). Thus, we must aggregate the costs and harvest for the two fleet segments to obtain the total coastal cost of harvesting all species and the total coastal Grl. halibut harvest.[23]

Concerning the output price, we assume a constant high sea and coastal price on the harvest of Grl. halibut (section 3.1).[24] Furthermore, we can use the same high sea and coastal Grl. halibut price in the scenarios with a common and two separate fish stocks. In identifying the high sea price, we follow the recommendation by Flaaten *et al.* (2017) and use the same data source and procedure to identify cost parameters and prices.[25] Thus, we depart from the total high sea industry revenue of harvesting all species in table 1, and we use the same high sea Grl. halibut quota share as for the high sea cost function to calculate the total high sea industry revenue of harvesting Grl. halibut for the period between 2013 and 2015. As previously described, we average the revenue observations to reduce the effect of random price variations. From the estimation of the high sea cost functions, we also have information about the average high sea harvest of Grl. halibut. As an estimate for the high sea Grl. halibut price, we now use the average high sea revenue divided by the average high sea harvest. For the coastal Grl. halibut price, the only difference compared with the high sea price is that the total coastal industry revenue of harvesting all species and the harvest of Grl. halibut is reported for vessels above 6 m and boats below 6 m. Thus, we aggregate the revenue and harvest observations for these two fleet segments. Otherwise, we use the same procedure as for the high sea price. Three facts are important in relation to the parameters in the high sea and coastal profit functions

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[23] As mentioned in the introduction, high sea vessels normally do processing on board the vessels apart from (at least) 25 per cent of the Grl. halibut harvest, which is delivered for land-based processing due to the landing obligation, while coastal vessels deliver all landings to land-based processing factories. Thus, our cost data for high sea vessels partly include the costs of processing, while our cost data for coastal vessels do not include these costs. However, since we are not able to adjust the observations for high sea vessels for the costs of doing on board processing, this problem implies that we will focus on scenarios 3 and 4 when interpreting our results. Furthermore, adjusting the costs for high sea vessels for on board processing would tend to make high sea fisheries more profitable.

[24] The assumption about a constant high sea price can be discussed. Specifically, high sea vessels must deliver at least 25 per cent of their Grl. halibut harvest of land-based processing while the rest of the harvest is processed on board. It is obvious that the high sea price may differ depending on the way the harvest is processed. However, we cannot identify high sea prices that depend on the processing method. Thus, as a simplification, we assume that the high sea price is constant and independent of the processing method but allowing high sea vessels to differentiate their prices based on the processing method would tend to make high sea fishing more profitable.

[25] As an alternative, we could have obtained the price on Grl. halibut directly from Statistics Greenland (2020).

(table 3). First, the high sea and coastal cost parameter is lower with two separate fish stocks than with a common fish stock.[26] Second, the high sea cost parameter is higher than the coastal cost parameter with both a common and two separate fish stocks.[27] Third, the coastal Grl. halibut price is lower than the high sea price.

4.3. Land-based industry profit function

A cost function that is consistent with the assumptions about the derivatives from section 3 is given by:[28]

$$C_L(h_C, h_H) = c_L(h_C + 0.25h_H)^2, \tag{17}$$

where c_L is a land-based cost parameter and $C_L(h_C, h_H)$ is the total land-based industry cost of processing Grl. halibut. Three facts are important in relation to the land-based cost function in (17): (i) the land-based cost function depends on the total Grl. halibut harvest delivered to land-based processing; (ii) the land-based cost parameter, c_L, is assumed to be identical for the high sea and coastal Grl. halibut harvest; and (iii) the land-based cost function is identical in the scenarios with a common and two separate fish stocks.

For calculation of the land-based cost parameter, we use two main indicators: (i) the total industry costs for the primary fisheries industry of harvesting all fish species on both the east and west coasts (H Ogmundsson, personal communication, 2019; based on Ogmundsson (2019)); and (ii) the total industry costs for the whole fishing industry on both the east and west coasts (Ogmundson and Haraldson, 2017). The difference between these two cost measures represents a rough approximation for the total land-based processing industry costs covering the east and west coasts and all species. Next, we use relevant quota shares to obtain the total land-based costs of processing Grl. halibut on the west coast. These total land-based costs cover the period between 2013 and 2015 and, to reduce the impact of random variation, we take an average of these cost observations over the period. By using the information described in section 4.2, we can also calculate an average value of $h_C + 0.25h_H$, and now c_L can be calculated by using (17).

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[26] This can be explained by the fact that the high sea and coastal stock size is lower than the common fish stock (appendix A). To understand this, consider (16) and disregard the subscript for the fleet segment. Now the total costs and harvest are identical with a common and two separate fish stocks. Thus, if the stock size is lower with two separate fish stocks, the cost parameters must also be lower if (16) shall hold.

[27] An important driver behind this result is that the model is constructed at the industry level, and to see the implications of that, we disregard the subscript for the fleet segment. In appendix B we show that the cost parameter in a vessel-level model become $c = \frac{C(h,x)x}{h^2}n$ where n is the number of vessels. From table 1, we observe that very few vessels from Greenland participate in the high sea Grl. halibut fishery, while many coastal vessels and boats target Grl. halibut. By using the definition of the cost parameter, this tends to imply that the high sea cost parameter is lower than the coastal cost parameter in a vessels-level model.

[28] With (17), we assume that the only difference between the high sea and coastal vessels is that the former only deliver at least 25 per cent of their Grl. halibut harvest for land-based processing. However, although high sea vessels will try to minimize their costs in relation to land-based processing by selection of fishing grounds, the total land-based industry costs would probably be higher for high sea vessels than for coastal vessels since the travel distance to land-based factories is longer. This argument implies that we will operate with a separate land-based industry cost function for high sea and coastal vessels but we do not have data for doing so. However, taking the travel distance to land-based processing factories into account tends to imply that coastal fishing will become relatively more profitable.

The constant land-based Grl. halibut price is also identical for the scenarios with a common and two separate fish stocks and, to calculate this price, we use a similar procedure as for the land-based cost function. Thus, we obtained information about the total industry revenue generated by the primary fishing sector (H Ogmundsson, personal communication, 2019; based on Ogmundsson (2019)). Furthermore, we have data on the revenue earned by the entire fishing industry (Ogmundson and Haraldson, 2017). The difference between these two revenue numbers approximates the land-based processing revenue covering the east and west coasts and all fish species, and now we use relevant quota shares to obtain the revenue of processing Grl. halibut on the west coast. Information about this revenue is available for the period between 2013 and 2015, and to reduce the impact of random variation, we take a simple average of these numbers. We also obtained a measure for the average amount of Grl. halibut delivered from land-based processing factories (H Ogmundsson, personal communication, 2019; based on Ogmundsson (2019)). Now, the land-based price is found by dividing the average land-based revenue by the average quantity. The land-based utilization rate of Grl. halibut can be found by using two indicators: (i) the amount of Grl. halibut that goes into land-based processing which captures the demand (Ogmundson and Haraldson, 2017); and (ii) the amount of Grl. halibut that goes out of land-based processing factories which captures the supply (H Ogmundsson, personal communication, 2019; based on Ogmundsson (2019)). We have this information for the period 2013–2015; thus, as above, we take a simple average of these observations, and based on this, we can easily find a measure for α. From the land-based cost parameter, price and utilization rate summarized in table 3, it is clear that the marginal land-based profit is higher for high sea harvest than for coastal harvest.

5. Empirical results

To obtain empirical results for the Grl. halibut fishery on the west coast of Greenland, we used GAMS to solve the first-order conditions from section 3 numerically using the functional forms and parameter values from table 3. When solving the first-order conditions, we imposed nonnegativity constraints on all control variables, implying that the system of equations was solved using Kuhn–Tucker conditions. We have also used several different starting values for the control variables, and if various starting values lead to different solutions, we have selected the solution that provides the highest long-run economic yield.

Below, we will compare the results in the benchmark case with the actual situation for the period between 2013 and 2015, where averages over this period are used. The actual high sea harvest for vessels from Greenland and the actual coastal Grl. halibut harvest is found from observations in Ogmundson and Haraldson (2017), while the high sea harvest allocated to vessels from other fishing nations is found by using β. To find the actual high sea and coastal profit, we use the difference between the revenue and costs from table 1, while the observations described in section 4.3 are used to find the actual land-based profit. In the scenarios with a common fish stock, we use the observations described in section 4.1 to obtain the actual Grl. halibut stock size, while the growth function is used to find the actual growth. With two separate fish stocks, we use the high sea and coastal Grl. halibut stock size described in section 4.1 as a measure for the actual stock sizes, while the high sea and coastal natural growth functions are used to find the actual high sea and coastal growth. The actual net migration is found using the migration function. Below, we will also summarize the results of our sensitivity analyses; details can be found in appendix C. In these analyses, we set each parameter value at the upper and lower bound, while the other parameters are fixed at the benchmark value. The results of sensitivity analyses are mainly used to investigate the robustness of our results.

5.1. Benchmark case

The results for the benchmark case are reported in table 4. To describe the results under each scenario, we focus on the distribution of the optimal industry harvest and profit between high sea and coastal vessels, and in the high sea harvest, we include the harvest by foreign vessels. As indicated in table 4, the optimal coastal harvest and profit are higher than the high sea harvest and profit in scenario 1 (a common fish stock without land-based profit). This result can be explained by the fact that the high sea cost parameter is higher than the coastal cost parameter (section 4.2). All other things equal, a higher cost parameter implies a lower harvest and profit.

Turning to scenario 2 (two separate fish stocks without land-based profit), table 4 indicates that the optimal high sea harvest and profit are higher than the coastal harvest and profit. The main driver behind this result is that the high sea carrying capacity is higher than the coastal carrying capacity (section 4.1). A higher carrying capacity, all other things equal, implies a higher harvest and profit. The optimal high sea harvest is also higher than the coastal harvest in scenario 3 (a common fish stock with land-based profit), which can be explained by the fact that the marginal land-based profit is higher for high sea harvest than for coastal harvest (section 4.3). All other things equal, a higher marginal land-based profit implies a higher harvest. However, the optimal coastal profit is higher than the high sea profit in scenario 3, and the main explanation of this result is that the payoff from international fishing agreements with other nations is excluded in our model. The harvest by vessels from foreign nations represents an additional cost of high sea fishing (section 4.1). An additional cost, all other things equal, implies a lower harvest and profit. In scenario 4 (two separate fish stocks with land-based profit), the optimal high sea and coastal harvest and profit are approximately the same as those in scenario 2 (table 4), which is due to the low migration (section 4.1). All other things equal, a low net migration implies identical results in the scenarios with two separate fish stocks since the interaction between fleet segments is low. Turning to the land-based industry profit, table 4 indicates that the optimal land-based profit is lower than both the optimal high sea and coastal profit in both scenarios 3 and 4.[29]

Next, we compare the scenarios for optimal management with the actual situation. As indicated in table 4, the optimal high sea harvest and profit are lower than the actual harvest and profit in scenario 1, while the optimal coastal harvest and profit are higher than in the actual case. However, in scenarios 2 and 4, the optimal high sea harvest is close to the actual high sea harvest, while the optimal high sea profit is lower than the actual profit. Furthermore, the optimal coastal harvest and profit are lower than the actual coastal harvest and profit in scenarios 2 and 4. From table 4, we also observe

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[29] From table 4 we see that the results are highly dependent on the chosen scenario and this may raise concerns about the robustness of our results. Specifically, as mentioned in section 4, many of the parameter values are uncertain and this can provide an explanation for the sensitivity of our results with respect to the choice of scenario. However, table 3 indicates that the parameter values are highly dependent on whether a common or two separate fish stocks is assumed while the marginal land-based profit is reasonably high. Thus, it can be argued that the sensitivity of our results with respect to the choice of scenario reflects the actual characteristics of the Grl. halibut fishery.

Table 4. Results for the Grl. halibut fishery on the west coast of Greenland

	A common fish stock				Two separate fish stocks		
	Scenario 1	Scenario 3	Actual situation		Scenario 2	Scenario 4	Actual situation
Indicator	Without land-based profit	With land-based profit		Indicator	Without land-based profit	With land-based profit	
High sea harvest (tons)	240	22,774	18,558	High sea harvest (tons)	17,382	17,393	18,558
Greenland (tons)	143	13,580	11,066	Greenland (tons)	10,365	10,371	11,066
Other nations (tons)	97	9,194	7,492	Other nations (tons)	7,017	7,021	7,492
Coastal harvest (tons)	41,200	18,632	24,946	Coastal harvest (tons)	7,375	7,395	24,946
High sea profit (million DKK)	1.57	122.28	227.13	High sea profit (million DKK)	86.34	86.30	227.13
Coastal profit (million DKK)	327.66	162.58	266.97	Coastal profit (million DKK)	61.00	61.02	266.7

Table 4. *Continued.*

	A common fish stock			Two separate fish stocks			
	Scenario 1	Scenario 3			Scenario 2	Scenario 4	
Indicator	Without land-based profit	With land-based profit	Actual situation	Indicator	Without land-based profit	With land-based profit	Actual situation
Land-based profit (million DKK)		24.93	40.00	Land-based profit (million DKK)		39.52	40.00
Stock size (tons)	263,010	267,817	67,927	High sea stock size (tons)	95,365	94,114	42,115
Shadow price (million DKK)	0.0066	0.0035		High sea shadow price (million DKK)	0.0034	0.0036	
Natural growth (tons)	41,438	41,261	20,323	High sea natural growth (tons)	10,365	10,371	14,897
				Coastal stock size (Tons)	23,174	22,805	25,812
				Coastal shadow price (Million DKK)	0.007208	0.0087	
				Coastal natural growth (Tons)	7,375	7,395	6,819
				Migration (Tons)	975	978	387

that the optimal high sea harvest is higher than in the actual situation in scenario 3, while the optimal high sea profit, coastal harvest and coastal profit are lower than in the actual values. The optimal land-based profit is also lower than the actual land-based profit in scenario 3, while the optimal and actual land-based profits are almost identical in scenario 4 (table 4).

Finally, we discuss overexploitation of the Grl. halibut fish stock. In scenarios 1 and 3 (a common fish stock), table 4 indicates that the optimal stock size is higher than the actual stock size so, currently, the Grl. halibut fish stock is economically overexploited. Furthermore, in the actual situation, the total Grl. harvest is higher than the natural growth, so the Grl. halibut fish stock will decrease over time. With two separate fish stocks (scenarios 2 and 4), table 4 indicates that the optimal high sea stock size is higher than the actual stock size, implying that economic overexploitation of the high sea fish stock occurs. From table 4, we also see that the optimal coastal fish stock in scenarios 2 and 4 is close to the actual coastal fish stock. However, the actual coastal harvest is higher than the actual coastal natural growth, so the coastal fish stock will decrease over time.

5.2. *Sensitivity analysis*

When investigating the robustness of our results, we focus on the relative ranking of the optimal high sea and coastal harvest and profit.[30] Our results are reasonably robust when excluding land-based processing (scenarios 1 and 2). Specifically, from section 5.1, we have that the optimal coastal harvest and profit are higher than the high sea harvest and profit in scenario 1. This result holds for all parameter variations apart from the lower bound of the coastal price. In scenario 2, the optimal high sea harvest and profit are higher than the coastal harvest and profit in the benchmark case (section 5.1). This ranking of the optimal harvest and profit only changes for the lower bound of the high sea price and the upper bound of the coastal price. However, in scenario 1, the optimal high sea harvest to vessels from Greenland and foreign vessels is zero for (i) the lower bound of the intrinsic growth rate; (ii) the upper bound for the scaling factor to other nations; (iii) the lower bound of the high sea price; (iv) the lower bound of the coastal cost parameter; and (v) the upper bound of the coastal price. An implication of this result is that it could be optimal to exclude high sea vessels from Greenland and other nations from the Grl. halibut fishery.[31]

When taking land-based processing into account (scenarios 3 and 4), our results are reasonably sensitive to parameter variations. In scenario 3, we know from section 5.1 that the optimal high sea harvest is higher than the coastal harvest, while the optimal coastal profit is higher than the high sea profit. These results do not hold for (i) the lower bound for the carrying capacity; (ii) the lower bound for the intrinsic growth

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[30] Following Lehuta *et al.* (2010), we can interpret the results of the sensitivity analyses as numerical comparative static results. Here we focus on the sign of the effect of changing an exogenous variable on an endogenous variable. A summary of the numerical comparative static results is available in appendix C and, from a theoretical point of view, these results correspond to the expectations.

[31] The policy relevance of this recommendation can be questioned. It is probably desirable to allow high sea vessels from Greenland to participate in the Grl. halibut fishery, implying that long-run economic yield will not be maximized. Furthermore, it is probably profitable to provide foreign vessels with rights to harvest Grl. halibut in the high sea area since this generates a payoff to Greenland due to the international fishing agreements. However, allowing high sea vessels from Greenland and foreign vessels to harvest Grl. halibut when the long-run economic yield is negative may involve subsidies to high sea fishing.

rate; (iii) the lower bound for the high sea cost parameter; (iv) the upper bound for the coastal price; (v) the upper bound for the land-based cost parameter; (vi) the lower bound for the land-based price; and (vii) the upper bound for the land-based utilization rate. In scenario 4, the optimal high sea harvest and profit are higher than the coastal harvest and profit in the benchmark case (section 5.1). This result changes for the lower bound for the high sea carrying capacity, the upper bound for the coastal carrying capacity, the lower bound for the high sea price and the upper bound for the coastal price.

6. Brief summary and main policy implications

In this paper, we consider four scenarios for optimal management of high sea and coastal vessels targeting the Grl. halibut fishery on the west coast of Greenland:

Scenario 1: common fish stock in the high sea and coastal area while disregarding the profit from land-based processing;

Scenario 2: separate fish stocks in the high sea and coastal area while disregarding the profit from land-based processing;

Scenario 3: common fish stock in the high sea and coastal area while including the profit from land-based processing; and

Scenario 4: separate fish stocks in the high sea and coastal area while including the profit from land-based processing.

In scenario 1, the optimal coastal harvest and profit are higher than the high sea harvest and profit, while the optimal high sea harvest and profit are higher than the coastal harvest and profit in scenario 2. For scenario 3, the optimal high sea harvest is higher than the coastal harvest, while the optimal coastal profit is higher than the high sea profit, and in scenario 4, we obtain approximately the same results as in scenario 2.

Thus, our empirical results are highly dependent on the chosen scenario. Provided that we believe in our results, a main policy implication is that a regulator (or manager) needs to be very explicit about the assumptions behind the policy decisions. Specifically, the regulator must explicitly consider: (1) whether common or separate fish stocks for various fleet segments exist; and (2) whether the profit of secondary fisheries-related activities will be considered. Since our results differ significantly depending on the choice of scenario, it will generate large mistakes in the harvest and profit allocated to various fleet segments if the policy decision is based on incorrect assumptions. This can be an argument for introducing a precautionary principle when making public decisions, since this principle minimizes the probability that wrong decisions will lead to catastrophic events.

For Grl. halibut, this issue is highly important because this fish species is important for the development of the economy in Greenland. Greenland is working towards full independence from Denmark, but a factor that limits the possibility of independence is the ability to generate income. Here Grl. halibut plays an important role since there has been a huge increase in the price of this species. However, an increase in the harvest of Grl. halibut puts pressure on the fish stock. Hence, the issue of long-run sustainable management of the Grl. halibut fish stocks, which we consider in this paper, is crucial to ensure economic and political independence.

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