Fishing motives and economic effects of climate change: an application on Arctic char in northern Sweden

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Abstract

Motives for fishing differ among fishers, which may imply different effects of climate change on the net values of fishing. Climate change has impacts on fish population dynamics and on other factors in the fishers' harvest decision, such as alternative sources of food or income. Here we present a bio-economic model that includes impacts of climate change on fish population and on net values of harvest by fishers with recreational or subsistence fishing motives. The conceptual analysis shows that the economic effects of climate change with simultaneous impacts on fish population growth and harvest values are inconclusive with common fishing access for both fisher types and when there are opposite simultaneous climate effects with exclusive access for one of the fisher types. Numerical results from our model of Arctic char (*Salvelinus alpinus*) in northern Sweden indicate that climate change, measured as temperature increases, reduces fish population growth but increases net values of fishing for both fisher types. The combined net effect of these counteracting forces is that annual net values can almost cease for the subsistence fisher in the future but increase considerably for the recreational fisher.

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1 Introduction

Fishing provides an important source of food and income since early days of mankind. Indeed, fish and aquatic invertebrates are regarded a major contributor to the rapid increase in brain volume during human evolution (Crawford et al., 1999). Nowadays, fishing for recreational purposes has gained in interest worldwide and the number of anglers at the global scale can be twice as large as the number of fishers in commercial fishery (FAO, 2021). However, the motives and associated benefits and costs of fishing are likely to be determined by different factors depending on type of fisher. Fishers are generally classified into three main categories, i.e. subsistence, commercial and recreational (e.g. Hind, 2015). Subsistence fishing is defined as fishing mainly for providing food or income for a small group, such as a household, commercial fishing for the purpose of generating net incomes from sales of fish, and recreational fishery mainly for social, enjoyment, and aesthetic appeal at the fishing locations. Since climate change is likely to affect not only the conditions for the fish populations but also the costs and benefits of fishing, fishers' harvest responses to climate change and associated economic effects will differ between the fisher types.

There is a large body of literature on the impacts of climate change on fish populations which considers only physical and biological factors (e.g. Jeppesen et al., 2010, 2012; Huang et al., 2021). Huang et al. (2021) showed in a meta-analysis of 1187 studies that climate change, measured mainly as warmer temperature, will reduce fish growth in both marine and freshwater ecosystems. At the fish population level, Jeppesen et al. (2012) demonstrated that warmer temperature during the last decades has changed the age structure and dynamics of fish populations in European lakes, and that the abundances of cold-water species have declined. There are, however, relatively few studies that analyse the economic effects of such changes, and a typical approach has been to estimate economic impacts of predicted climate change effects on the abundance of different fish species at the global or national scale. At the global scale, Lam et al (2016) showed that potential maximum revenues from fishery decrease for most countries. Suh and Pomeroy (2020) accounted for the dispersal effects in an economy with a relatively large fishery sector, the Philippines, and found that the gross domestic product could decrease by approximately 0.4% in a long-term perspective. A different approach was applied by Gren and Marbuah (2022), who showed in a meta-analysis of 208 studies on willingness-to-pay (WTP) for recreational fishing that an increase in temperature could raise the value of fishing.

The rather complex interactions between climate change, fish population and fishers' behaviour have been analysed only by a few studies (Haynie & Pfeiffer, 2012; Kourantidou et al., 2022). Haynie and Pfeiffer (2012) presented a conceptual framework for analysing effects of climate change on fishers' net values and on fish populations. It includes the interaction between environmental conditions in the sea, characteristics of the target fish species, and fishers' harvest decisions. The decisions include where and when to fish in order to maximize utility or profit, which, in turn, is

affected by the environmental conditions at the potential fishing locations. Kouranti-dou et al. (2022) considered commercial fishers' response to climate change impacts on the population of Arctic char in Canada and calculate associated economic effects. They found that the population growth rate increased as a result of climate change, and that net benefits for the commercial fishery sector increased.

Common to the empirical economic studies is the focus of climate impacts on fish populations, but climate change can have impacts also on other factors determining fishers' decision on catches. For example, the value of recreational fishing might be affected by e.g. more pleasant or unpleasant weather for fishing. Subsistence fishing can be affected by simultaneous impacts on possibilities to obtain food or income from complementary sources, such as reindeer herding in northern Sweden (Furberg et al., 2011; Rosqvist et al., 2022). Fishers will respond to these climate change impacts in addition to the effects on fish populations. The net economic effect then depends on the direction and magnitude of change in these different types of impacts, which has not been analysed in any study.

In the economics literature, the interaction between fishers and fish population has been approached by bio-economic tools, which has a long tradition in fisheries management (Knowler, 2002; Prellezo et al., 2012). The basic principle is that the abundance of one or several fish species depends on the fish population dynamics and on the fishers' values and costs of fishing. Integrated numerical models are then constructed which link the dynamics of fish populations with fishers' harvest decision rules. The models are used for assessing responses in fishers' effort and harvest and associated impact on fish population to changes in e.g. regulations, values and costs of fishing, and environmental pollution.

Bio-economic models have been used to assess economic effects of climate change on commercial fishery (Kourantidou et al., 2022), and to evaluate efficient allocation of harvest between different fisher types (Bishop & Sample, 1980; Xuan & Armstrong, 2016). Both Bishop and Sample (1980) and Xuan and Armstrong (2016) made theoretical contributions on the optimal allocation of harvest between different fisher types. Bishop and Sample (1980) examined commercial and recreational fishers, and Xuan and Armstrong (2016) focused on commercial wild fishery and capture based aquaculture. Other studies examined the existence of conflicts or synergies in a non-optimal framework by analysing preferences and practices mainly by commercial and recreational fishers (e.g. Voyer et al., 2016).

The purpose of this study is to model and calculate effects of multiple climate change impacts on fish populations and on factors that determine harvest decisions for the non-commercial fisher types; i.e. recreational and subsistence fishers. To this end, a numerical bio-economic model is constructed, where the determinants of the net value of fishing differ between the recreational and subsistence fisher. Utility and costs of fishing enter the objective function for the recreational fisher. Income provision from fishing and other activities with limited supply of household labour is included in the decision problem of the subsistence fisher. Climate change is assumed to affect the fish population and the net value of fishing for both fisher types. The model is used for calculating the level of fishing efforts which maximizes the total net value of the fish population when either both or one of the fisher types have access to fishing.

The numerical bio-economic model is applied to fishing of Arctic char (*Salvelinus alpinus*) in Lake Abiskojaure in the inland of northern Sweden. Arctic char is the only fish species in this lake, which is common for mountain lakes in Scandinavia (Rasmussen et al., 2019) and other parts of the circumarctic region. Abiskojaure is situated above the Arctic circle and representative for the sub-Arctic region, a region of the Arctic that undergoes rapid rates of climate warming (Bitanja & Andry, 2017; IPCC, 2021). Long-term catch data for the lake are available from environmental monitoring programs, which allows for the parameterization of the bio-economic model of an otherwise data-poor fishery.

The main contribution of this study to the scientific literature on economic effects of climate change on fishery is twofold; the comparison of non-commercial fisher types (recreational and subsistence), and the consideration of impacts of climate change on fish populations and on net values of fishers' harvests. The study is organized as follows. Section 2 provides the conceptual bio-economic model, which underlies the numerical calculations and is used to derive general conclusions. Data retrieval for parameterizing the model is described in Sect. 3, and the numerical results are presented in Sect. 4. The study ends with a discussion and main conclusions.

2 Conceptual approach with the bio-economic model

Effects of climate change are calculated as difference in fishers' net value of fishing with and without the climate effects. The total net values in both cases are calculated as the maximum sum of discounted annual flows of net values under a certain period of time with the use of a discrete dynamic optimization model. The model follows the theoretical contributions by Bishop and Sample (1980) and Xuan and Armstrong (2016) by calculating optimal allocation of harvest between two fisher types; those that fish for recreational purposes and those where the fish as a source of food and income. Optimal combination of harvest between the fisher types requires an assumption of common fishing rights. In practice, fishing rights are regulated in most countries, and the case with exclusive right to either fisher type is therefore also considered.

The two fisher types are not mutually exclusive, the recreationalist may appreciate the fish as a food resource and the subsistence fisher may assign fishing a recreational value (e.g. Nieman et al., 2021). A simplification is made in the subsequent analysis by assuming pure types in order to analyze differences in climate change responses. Due to the difficulty of obtaining data on net values of fishing and fish population dynamics (described in Sect. 3) further simplifications are made by considering only one lake with one fish species.

The fish population size in each period of time, P_t, is measured in terms of number of fish and is determined by the population in previous period, population growth, and harvest by the two fisher types. The harvest for each type depends on the fishing effort, catch per effort, and P_t. Effort is measured in terms of days of fishing, D^S_t and D^R_t by the subsistence and the recreational fisher, respectively. The harvest for the subsistence and recreational fisher is then written as $H^S_t = a^s D^S_t P_t$ and $H^R_t = a^R D^R_t P_t$, respectively, where a^S and a^R are the catchability coefficients. Regarding climate change effects, K several studies show impacts on the biological conditions

for the population growth (Hein et al., 2012; Jeppesen et al., 2012; Huang et al., 2021; Svenning et al., 2022). Fish population dynamics is then written as:

$$P_{t+1} - P_t = g_t(P_t, K) - a^R D_t^R P_t - a^S D_t^S P_t, P_0 = \overline{P} \tag{1}$$

where $g_t(P_t, K)$ is the population growth function, K is the climate change, and P_0 is the initial condition on the population size.

A simple logistic growth function is used and the climate change could then in principle affect the intrinsic growth rate, r, and/or the maximum viable population, P^{Msx}. Due to lack of data on climate effects on r, which is described more fully in Sect. 3, it is assumed that climate change has impacts on only P^{Max}. The logistic growth function is then written as:

$$g_t(P_t, K) = r P_t \left(1 - \frac{P^t}{P^{Max}(K)} \right) \tag{2}$$

The population growth increases when K raises P^{Max}, and vice versa.

The net value for the subsistence fisher is determined by the value of the fish harvest as one of several sources of income. It is quite common that subsistence fishing, mainly by the Sami, who are the only indigenous people in Sweden, obtain incomes from different activities, such as fishing, reindeer herding and tourism (e.g. Sikku, 2016). The household production function approach is used to account for this, which has been much applied to value environmental resources where households combine own labor resources with natural resources to obtain income used for food or for purchasing different consumption goods (e.g. Mäler et al., 2005). The household then allocates its resources measured in labor days between fishing, $D^S{}_t$, and other income generating activities, $D^O{}_t$. The total amount of labour is limited so that $D_t^S + D_t^O = \overline{D}$.

Income from harvest is obtained from selling the fish at the price, p, which would also be the unit cost avoided if the household had to buy the fish on the market and use it for own consumption. Total income, Y_t, is determined by the values from fish harvest and incomes from other activities, O_t, which may be affected by climate change such as effects on reindeer herding (Furberg et al., 2011; Rosqvist et al., 2022). Income from other sources then depends on the quantity of labor days devoted to the activity and climate change $O_t = O_t(D_t^O; K_t)$, which is assumed to be concave in D_t^O. The net value for the subsistence fisher in each period of time, NV_t^S, is then written as:

$$NV_t^S = Y_t, \quad \text{where } Y_t = p_t H_t^S + O_t \text{ and } D_t^S + D_t^O = \overline{D} \tag{3}$$

It is assumed that the constraint on labour days binds, which implies that increases in $D^S t$ reduce $D^O{}_t$ with associated losses in O_t. This constitutes an opportunity cost of fishing, $C^S = C^S(D_t^S; K)$, and the net value of fishing, NV_t^{SF} can then be written as;

$$NV_t^{SF} = p_t H_t^S - C^S(D_t^S; K) \tag{3'}$$

Since $O_t = O_t(D_t^O; K)$ is assumed to be concave in D_t^O, the cost function $C^S(D_t^S; K)$ is increasing at a non-decreasing rate in D_t^S.

The net value for the recreationalist fisher in each period of time, NV_t^R, includes the utility of and cost of fish harvest. Several studies show that the utility of fishing is determined by a number of factors, such as social context, nature experience, and harvest (e.g. Hind, 2015). Most studies estimate WTP for fishing during a certain time interval such as a day, trip or season where the WTP is measured as consumer surplus, i.e. the value in excess of the cost of fishing (meta-analysis in Gren & Marbuah, 2022). A simplification is made in the current study by assigning recreational value only to the number of fishing days, and not to changes in fish catches. Non-zero harvest of the fishing days is captured by the catchability coefficient. The net value is then measured in terms of consumer surplus, CS, as a concave function of fishing days, D_t^R, which can be affected by climate change, K, $CS_t = CS(D_t^R; K)$ (e.g. Jeppesen et al., 2012; Huang et al., 2021). The annual net value for the recreational fisher, NV_t^R, is then written as:

$$NV_t^R = CS\left(D_t^R; K\right). \tag{4}$$

The overall decision problem under common fishing access is formulated as choosing the allocation of efforts between the two fisher types, which maximizes the sum of discounted net values of fishing over a certain period of time, T, given Eqs. (3′), (4) and the constraint on the fish population dynamics;

$$\underset{D_t^R, D_t^S}{Max} NV = \sum_{t=1}^{T} \rho_t (NV_t^R + NV_t^{SF}) \text{ subject to Eq. (1)} \tag{5}$$

where $\rho_t = 1/(1 + i)^t$ is the discount factor with i as the discount rate. The decision problem is slightly different under exclusive access where either NV^{SF} or NV^R is maximized by the subsistence and recreational fisher, respectively. When the subsistence fisher has the access right, NV^R is deleted from the decision problem, and similar for the recreational fisher type.

The dynamic optimization problem in Eq. (5) is solved by constructing a discrete dynamic Lagrange expression and deriving the associated first-order conditions for optimal allocation of efforts between the fisher types (Supplementary material Section A). The first-order conditions show that, in each period of time, the allocation of fishing days between the two fisher types is obtained where their marginal net values are equal and correspond to the so-called marginal user cost. The latter shows the net value foregone by harvesting in period t which is the future net values from not harvesting and letting the fish stock grow. Another first-order condition is that it should not be possible to increase total net value by reallocating the timing of harvest. The fisher can decide on immediate harvest and earn the income or delayed harvest and gain from the fish population growth in each period of time. A relatively high discount rate compared to the fish population growth rate favors immediate fishing, and vice versa.

The impact of climate change is analyzed by applying the implicit function theorem on the optimal choices of fishing days (Supplementary material Section A). The effect

of changes in K on fishing efforts for the subsistence and recreational fisher is then given by;

$$\frac{\partial D_t^S}{\partial K} < (>)0 \text{ when } -\rho_t \frac{1}{a^S P_t} \frac{\partial^2 C^S}{\partial D_t^S \partial K} - \frac{\partial \mu_{t+1}}{\partial K} < (>)0 \qquad (6)$$

$$\frac{\partial D_t^R}{\partial K} < (>)0 \text{ when } \rho_t \frac{1}{a^R P_t} \frac{\partial^2 CS}{\partial D_t^R \partial K} - \frac{\partial \mu_{t+1}}{\partial K} < (>)0, \qquad (7)$$

where μ_{t+1} is the marginal user cost of fishing. According to Eqs. (6) and (7), the fishing effort is decreasing in K when the second expression is negative, and vice versa. The first term of the conditions shows the climate effect on the marginal cost of fishing effort for the subsistence fisher and on the marginal consumer surplus for the recreational fisher in Eqs. (6) and (7), respectively. The second term in the conditions is the same in both equations and $\frac{\partial \mu_{t+1}}{\partial K} < (>)0$ when $\frac{\partial P^{Max}}{\partial K} > (<)0$ (Supplementary material Section A).

Based on Eqs. (6) and (7), qualitative results can be obtained under different combinations of climate impacts and fishing access rights, which are summarized in Table 1.

Starting with the most simple case, single impact on fish population under exclusive access, the negative (positive) sign of $\frac{\partial P^{Max}}{\partial K}$ increases (decreases) the marginal user cost, which, in turn, gives incentives to decrease (increase) fishing effort for both fisher types. This effect is unambiguous with exclusive fishing access rights, but inconclusive with common access since the optimal allocation of fishing efforts is determined by the marginal fishing cost and marginal consumer surplus. Depending on the magnitude of

Table 1 Summary of economic effects for different combinations of climate effects and fishing access rights (Supplementary material Section A)

Climate effects	Common access	Exclusive access
Single effect on fish population		
Negative (positive) $\frac{\partial P^{Max}}{\partial K}$	NV decreases (increases) but inconclusive effects on NV^{SF} and NV^R	Decrease (increase) in NV^{SF} or NV^R
Simultaneous effects on fish population, and net values		
Negative (positive) $\frac{\partial P^{Max}}{\partial K}$, $\frac{\partial^2 C^S}{\partial D_t^R \partial K}$ and positive (negative) $\frac{\partial^2 C^S}{\partial D_t^S \partial K}$	NV decreases (increases) but inconclusive effects on NV^{SF} and NV^R	Decrease (increase) in NV^{SF} or NV^R
Negative (positive) $\frac{\partial P^{Max}}{\partial K}$, $\frac{\partial^2 C^S}{\partial D_t^S \partial K}$ and positive (negative) $\frac{\partial^2 C^S}{\partial D_t^R \partial K}$	Inconclusive effects on NV, NV^{SF} and NV^R	Inconclusive effects on NV^{SF} or NV^R

relative change, the fishing effort could then increase or decrease for one of the fisher types when $\frac{\partial P^{Max}}{\partial K} < 0$ and $\frac{\partial P^{Max}}{\partial K} > 0$, respectively.

Regarding simultaneous climate effects, when $\frac{\partial P^{Max}}{\partial K} < 0$ the direction of climate change impact on fishing efforts is reinforced under exclusive access rights when the first term in Eq. (6) is positive and that in Eq. (7) is negative. The climate change then increases the marginal fishing cost (i.e. opportunity cost of alternative activity) for the subsistence fisher and reduces the marginal consumer surplus for the recreational fisher. Under common access rights, the effect on each fisher type is inconclusive since the allocation is determined by the relative impacts on the marginal fishing cost and consumer surplus. The impacts are also inconclusive when the climate change reduces the marginal cost of fishing for the subsistence fisher and increases the marginal net value for the recreational fisher.

Similar qualitative results are obtained for $\frac{\partial P^{Max}}{\partial K} > 0$ but the direction of change is reversed. The marginal user cost is then reduced because of the higher fish population growth, which gives incentives to increase fishing efforts for both fisher types. This impact is reinforced (counteracted) by climate impacts reducing (increasing) the marginal fishing cost for the subsistence fisher and increasing (decreasing) the marginal consumer surplus for the recreational fisher.

3 Data retrieval

Despite the simple decision models, data retrieval is a challenge for both fisher types. There are so far no operationalized fish population models for lakes in Sweden, not even for commercially fishery in the largest lakes (Sundelöf et al., 2022). The choice of Arctic char in Lake Abiskojaure as a case study is based on the possibility for parameterizing the fish population function. To this end, data from the national environmental monitoring program (Fölster et al., 2014) is used, which includes regular standard sampling of fish assemblages in a sample of the smaller lakes, including north Swedish lakes with Arctic char (Holmgren, 2021). With a lake area of 282 ha, it is representative for other non-regulated headwater lakes in the Swedish sub-Arctic region. Lake Abiskojaure is part of a national park, where recreational fishery is forbidden. The Sami people have the rights to fish in the lake (Hjulman-Andersson, 2017). Recreational fishing for Arctic char is, however, allowed in other lakes of the surrounding area, but catch statistics are not systematically registered. In this study we therefore use monitoring data from Lake Abiskojaure, as the best available local source for estimation of some fish population parameters.

Other data retrieval difficulties are associated with the formulation and parameterization of fishers' value and cost of fishing in Lake Abiskojaure. There is no data neither on harvest by the fisher types in the lake nor on consumer surplus of the recreational fisher and price and costs of fishing for the subsistence fisher. All values and costs are expressed in Swedish krona (SEK) in 2020 prices (10.14 SEK = 1 Euro). Unless otherwise stated, detailed description of the data is found in Supplementary material Section B.

3.1 A numerical model of fish population dynamics

Studies on the intrinsic growth rate of Artic char in Swedish lakes are entirely lacking and calculations are therefore made by means of a Leslie matrix, which has a long tradition in ecology (Leslie, 1945). The Leslie matrix requires data on number of fish in different age classes, survival rates, and reproduction per female, which are calculated by means of the long time series of environmental monitoring, with annual fish sampling in the lake since 1994. Given these data on survival and reproduction rates, the intrinsic growth rate is calculated at steady state, which gives an intrinsic growth rate of 0.28 (Supplementary material, Section B, Table S1). This is slightly lower than estimates of the intrinsic growth rate of Arctic char in Canada (Zhu et al., 2017) who obtained estimates ranging between 0.33 and 0.36 depending on model choice, and markedly lower than that of 0.77 reported by Kourantidou (2022).

There is no information on neither the actual nor maximum population size in Lake Abiskojaure. Reported densities of Arctic char in other Swedish lakes ranged between 107 and 1100 individuals/ha (Hedlund, 2002). By using the minimum of this interval, the population in Lake Abiskojaure (area 282 ha) population size is conservatively estimated to at least 30 100 individuals. Regarding maximum population size, a logistic population growth function is used and P^{Max} is then twice the population at the maximum sustainable yield (MSY) level (e.g. Tsikiliras, 2018). Assuming MSY at P^0 = 30,100 gives P^{Max} = 60,200.

With respect to climate change impacts, there is no study on impacts on Arctic char abundance in lake Abiskojaure, but only on the distribution of the fish species in Northern Sweden (Hein et al., 2012). The study estimated the probability of presence of Arctic char in Swedish lakes as a function of annual average air temperature, lake size, and coexistence with brown trout and pike. Although several other factors affect fish population dynamics and associated catches, they can in most cases be related to the air temperature (Jones et al., 2020). The annual average air temperature in Abisko where the lake is located was 0.5 °C in 2020 and is expected to reach approximately 5 °C within 70 years in the worst case scenario of increasing emission of carbon dioxides (SMHI, 2022). Simplifications are made in the current study by approximating the probability of occurrence as population size. According to Hein et al. (2012) the probability of fish presence shows a linear decline with increasing average annual air temperature, and is reduced to 0.30 at 5 °C within a 70 year perspective. Assuming a linear decline to 30% of the reference population of 30,100 within 70 years, gives P^{Max} = 60,200(1 − 0.176 g) where g is the temperature increase in °C.

The catchability coefficients for the subsistence and recreational fisher are obtained from estimated harvest, fishing days, and P_0 in 2020. Calculations of harvest for both fisher types are based on estimates of catch per day in the Northern Sweden multiplied by calculated number of fishing days in Lake Abiskojaure. The catch per day for the subsistence fisher is calculated based on the assumptions that Sami use gillnets and that the catch per gillnet can be related to the catch from standard efforts in the Swedish monitoring program which gives 10 fish per D^S_t. Data on catch per day of recreational fishing is obtained from Carlén et al. (2021), who reported an average catch of 3 fish per D^R_t. This corresponds to the regulations in the Norrbotten county,

where the Abiskojaure lake is located, according to which the catch is limited to a maximum of 3 fish/day and person. There is no data on number of fishing days at Abiskojaure lake for any fisher type. It is therefore assumed that the fishing days per ha surface water area for each fisher type is the same as for the entire Northern region in which the Abiskojaure lake is located (see Supplementary material Section B for more details). The calculations give $a^S = 0.00033$ and $a^R = 0.00011$.

Given all assumptions and calculations, the parameterized logistic fish population model is written as:

$$P_{t+1} = P_t \left(1 + 0.28 \left(1 - \frac{P_t}{60200 * (1 - 0{,}176g)} \right) \right) - 0.00033 D_t^S - 0.00011 D_t^R) \tag{8}$$

with $P_0 = 30{,}100$.

3.2 Values and cost of fishing

Subsistence fishing is a common complementary activity for Sami villages to reindeer husbandry, but fishing for household needs is also made by Sami farmers and non-Sami people (OECD, 2019; Larsson & Sjaunja, 2020). There is very little information on the availability and allocation of household resources on these activities. According to Johansson and Lundgren (1998) the income from fishing ranges from 5 to 50% of the income from reindeer herding with lower levels for households with large reindeer populations.

There are no official statistics on sales price of Arctic char in Sweden. Therefore, the sales price of fish is obtained from a listed price at a food retailer of SEK 496/kg of catches from the northern part of the Sami region (Andys Fisk, 2023), which gives an average sales price p of SEK 149/fish in 2020 prices. Costs of fishing are calculated as the net income foregone from reindeer herding based on Sikku (2016) who calculates income provision and labour time spent on reindeer herding, cultural activities, tourism, and food sales for two regions in Sweden Funäsdalen/Mittådalen and Soppero/Idivuoma. The available labour time per subsistence fisher and year is assumed to correspond to the average number of working days for Swedes, which gives $\overline{D} = 253$. According to Sikku (2016) the average days spent on reindeer herding and other activities is 200, which gives $D^S = 53$. At this allocation of D^S and D^O, the average income per day and firm is 1569 SEK, which is assumed to represent the marginal income at the optimal allocation of labour days between fishery and reindeer herding. A cost function for D^S is obtained by assuming a simple quadratic function in total number of fishing days. Such a functional form satisfies the requirements of a cost function convex in D^S. The parameter is calibrated at the average income of SEK 1569 per day.

Impacts of climate change on costs of fishing for the subsistence fisher arise from its effects on temporal and spatial impacts on grazing reindeer herding. In an interview study of reindeer herding Sami in Sweden, respondents reported more rapidly shifting weather conditions with impacts on the freeze–thaw cycle which affect the animals' access to grazing in summer and winter periods (Furberg et al., 2011; Rosqvist et al., 2022). Another interview study pointed out the increased economic vulnerability for

the Sami in Finland due to climate change in combination with other stressors such as increased competition for land use (Turunen et al., 2021). These impacts are likely to reduce net values from reindeer herding, and there is a fear of zero net incomes within the current Sami generation (Furberg et al., 2011) which, in turn, implies lower opportunity cost of fishing. However, there is no quantification of the impact of temperature increases on the incomes from reindeer herding, and it is simply assumed that the net income from reindeer herding and thereby cost of fishing shows a linear decline in increased temperature and ceases at an increase in temperature by 5 °C. The net value for the subsistence fisher is then written as:

$$NV_t^{SF} = 149 * H_t^S - 3.68 * (1 - 0.2g) * \left(D_t^S\right)^2 \tag{9}$$

At 5 °C, the cost of fishing is zero since, by assumption, the income from reindeer herding ceases at this level.

The recreational value of fishing in northern Sweden has been estimated by two studies; Paulrud and Laitala (2004) and Carlén et al. (2021). The former evaluated welfare impacts of different fishery regulations, and the latter, which is used in current study, calculated values per day. The results showed an average consumer surplus of fishing in Northern Sweden of SEK 188/day in 2020 prices. A concave utility function in money metric was obtained by assigning a square root function of the value in total number of recreational fishing days. The parameter value in the function was then calibrated at the average value per day and the initial number of fishing days in the lake (403 days in Supplementary material Section B).

Regarding impacts of climate change, Dundas et al. (2020) found that increases in temperature from levels below 18 °C raise participation in recreational fishing in New England in USA. According to SMHI (2022), the annual average temperature in the Abisko region was 0.5 °C in 2020, which can increase by up to 5 °C in the RCP8,5 climate scenario. Increase in temperature from a low level would then raise D_t^R due to more pleasant weather. Some fishing takes place in winter season but most of the recreational fishing is made in the spring/summer season (Carlén et al., 2021). Dundas et al. (2020) showed that the recreational fishery could increase at a declining rate by 25% up to 5 °C. In order to ensure a concave net value function in D_t^R, the increase in net value per fishing day as a function of temperature is defined as $0.25(1 - \frac{1}{e^{1.5g}})$ where $0 \leq g \leq 5$ is the temperature increase in °C. The net value function for the recreational fishery is then given as:

$$NV_t^R = 7552 * \left[D_t^R * (1 + 0.25 * \left(1 - \frac{1}{e^{1.5g}}\right))\right]^{1/2} \tag{10}$$

In the baseline when $g = 0$, the second term within brackets at the right hand side of Eq. (10) is zero.

3.3 Time perspective and discount rate

A maximum Arctic char age of 20 years has been reported for Swedish mountain lakes (Kinnerbäck, 2013). To cover all age classes in the population, a 20 year perspective

is therefore used. An end condition of a minimum fish population size in the final year is introduced in order to avoid resource depletion which can occur in optimization models with a finite time period. Since initial population can not be preserved at large increases in the temperature, the end condition is adjusted in proportion to the impact of the rising temperature.

Regarding discount rate, it is quite likely that the two types of fishers have different private discount rates because of different investment opportunities and valuation of time. Without any data or information, the usual assumption is made in this paper that the discount rate corresponds to the average growth rate of gross domestic product (e.g. Boardman et al., 2011), since this reflects average rate of return on investment. The growth rate amounts to 2.7% per year over the period 1950–2018 (NIER 2019).

4 Results

Calculations are made for temperature increases in discrete steps of 0.5 °C, from the average base line of 0.5 °C, which constitutes the base case, up to 5 °C, for the different cases presented in Table 1, i.e. climate effects on the fish population with and without simultaneous impacts on fishers' values and costs, and common versus exclusive fishing rights. All calculations are made with the mathematical programming code developed by GAMS (Rosenthal, 2008).

The results with common fishing access show that the sum of average annual net values for the two fisher types decreases from 451 kSEK in the base case to 184 kSEK at 5 °C increase with climate impact only on the fish population. As expected, the
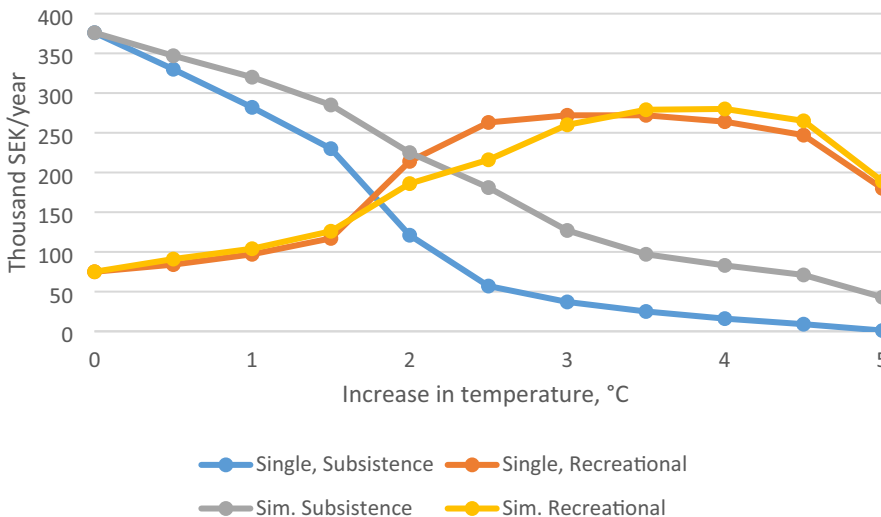
Fig. 1 Discounted average annual net values for subsistence and recreational fisher from temperature impact on only fish population (Single) and also on fishers' net value (Sim.) at different °C increases from the base line without temperature increase

decrease is lower and amounts to 232 kSEK when there are direct climate effects also on the fishers' net value. However, the economic effects on the two fisher types are very different (Fig. 1).

In the base case without temperature increases, the annual average net value for the subsistence fisher is higher than that for the recreational fisher. At temperature increases exceeding 2 °C, the net values are higher for the recreational than the subsistence fisher since the temperature increases imply relatively smaller negative impacts on marginal consumer surplus for the recreational than on marginal fishing cost for the subsistence fisher. The results in Fig. 1 also show that the consideration of simultaneous climate effects has a larger positive effect on net values for the subsistence than the recreational fisher. While it is always positive for the subsistence fisher, the consideration can imply lower benefits for the recreational fisher when the negative impact through the fish population dominates the positive effect on marginal consumer surplus (between 2 and 3.5 °C).

However, the development of the fish population size shows minor differences between the single versus simultaneous impacts of temperature increases (Fig. 2).

As shown in Fig. 2, the optimal fish stock is increasing over the first 10 years in the base case, and then declines slowly until the end year. The fish population shows a steady decline during the entire period when the temperature increase is 2 °C. At 4 °C, there is a rapid reduction in the population during the first five years because of the direct impact on the fish population and the relatively early harvest. The harvest is reduced from year 10 in order to achieve the end condition of a minimum population size in year 20.
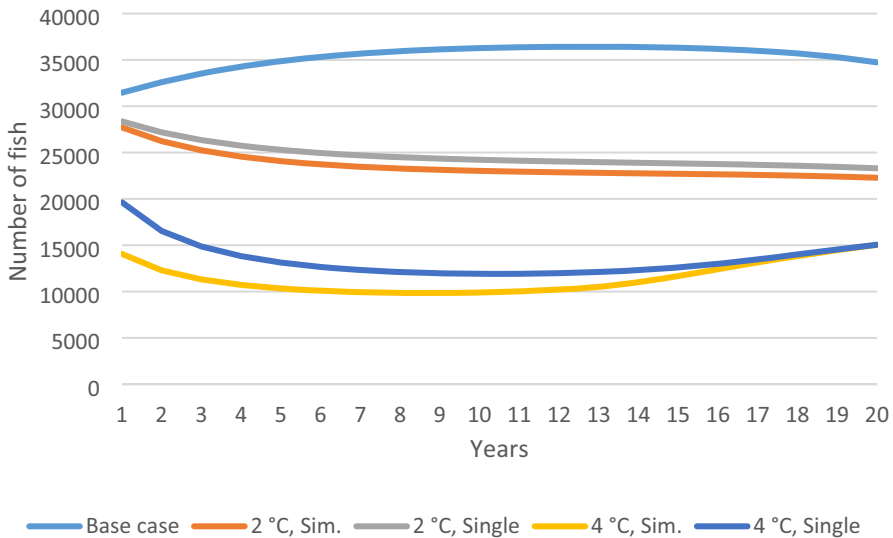

Fig. 2 Optimal development of the fish stock in the base case and for different combinations of temperature increases and climate impacts with common access for subsistence and recreational fisher
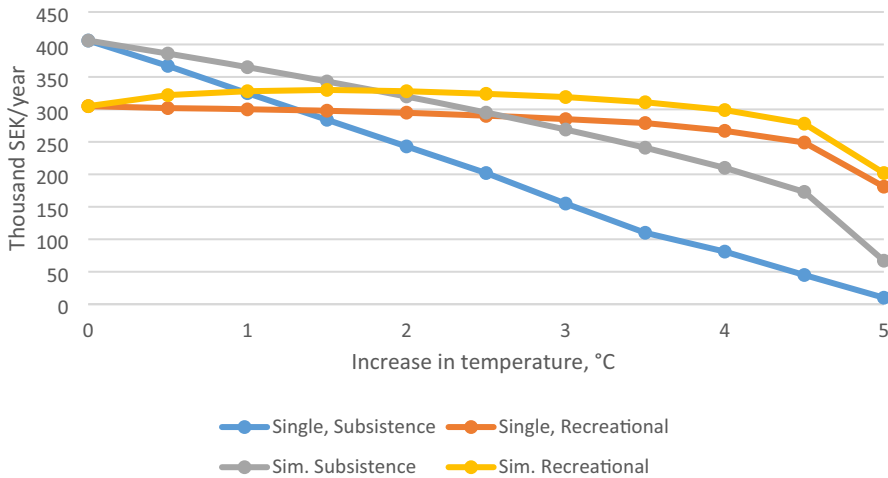
Fig. 3 Average annual net values with exclusive fishing access for either the subsistence or the recreational fisher at different temperature increases and impact on only fish population (Single) and also on fishermen (Sim.)

With exclusive access for either the subsistence or the recreational fisher, the annual average net values are higher for both fisher types than with common access for all combinations of temperature increases and climate effects (Fig. 3).

The average annual net value is higher for the subsistence fisher for temperature increases up to 1.5 °C. The net values are also increasing for the recreational fisher below this level. Similar to the common access regime, the difference in net values between the single and simultaneous climate effects is larger for the subsistence than for the recreational fisher. The optimal development over time of the fish population is increasing in the base case when subsistence fisher has exclusive fishing access, and is decreasing when the recreational fisher owns the access (Fig. 4 in Appendix). There is a small difference between the single and simultaneous climate effects for the subsistence fisher, but no effect for the recreational fisher.

When comparing the numerical with the theoretical expectations displayed in Table 1, the numerical results showed large differences in economic impacts depending on fisher type (Table 2).

A decrease in the fish population growth reduces the annual average net values for the subsistence fisher by 13% at temperature increase by 0.5 °C, which can reach 99% at 5 °C increase under common access. On the other hand, the average annual net values for the recreational fisher can increase by up to 263%. Reasons for these differences under common access are the relatively high increases in harvest cost due to reduced population for the subsistence fisher and the large effect on marginal consumer surplus and low net value of recreational fishing in the base case. This is also shown by the larger reductions in net values for the subsistence than the recreational fisher under exclusive fishing access. This pattern of economic effects is the same with simultaneous climate effects on the fish population and the net values of the fisher types, but the magnitude of impact on the net value is decreased.

Table 2 Summary of calculated economic effects for different combinations of temperature increases (0.5 to 5 °C) in and fishing access rights, % change in average annual net value from the base case

Climate effects	Common access		Exclusive access	
	Subsistence	Recreational	Subsistence	Recreational
$\frac{\partial P^{Max}}{\partial K} < 0$	− 99 to − 13	11–263	− 97	− 41 to − 1
$\frac{\partial P^{Max}}{\partial K} < 0$, $\frac{\partial^2 C^S}{\partial D_t^S \partial K} < 0$ and $\frac{\partial^2 C^S}{\partial D_t^R \partial K} < 0$	− 89 to − 8	17–273	− 83	− 34 to 8

5 Discussion and conclusions

Our conceptual analysis shows that the economic impact of climate change is inconclusive for both fisher types when there is common fishing access. This is also the case with exclusive fishing access for one fisher type when the climate effect on fish population growth and simultaneous effects on fishers' net value act in opposite directions. For example, a decrease in fish population size from climate change promotes lower harvests, which reduces net values. This decrease can be counteracted by an increase in net values from reduced marginal fishing cost for the subsistence fisher or increased marginal value of fishing for the recreational fisher. The net effect may then even be an increase in harvest and net values.

Based on available data in the application to Arctic char in the Abiskojarue lake, the main scenario was opposite direction of separate climate impacts, measured as temperature increases, on fish population and on the net values of the two fisher types. Separate climate effect was expected to decrease the fish population, to increase net value for the subsistence fisher from reduced opportunity cost of fishing, and to raise the value of fishing for the recreational fisher because of improved weather conditions. The net effect of these two counteracting forces was a decrease in average net value for the subsistence fisher, which could imply a decrease in net values from the base case without temperature increase of almost 100% in the worst climate change scenario. The corresponding decrease in net values for the recreational fisher was smaller, and could even turn into increases with common access to the fishery. However, common to both fisher types is that the development of the fish population size over the time period was relatively unaffected by consideration of single or simultaneous climate effects.

Our numerical results cannot be compared with other studies as similar estimates of economic impacts of climate change on subsistence and recreational fisher have not been published. Kourantidou et al. (2022) found an increase in the intrinsic growth rate of anadromous Northern Labrador Arctic char by 78% from a temperature increase by 1 °C, which increased average annual net income for the commercial fishery by approximately 70%. It is less likely that corresponding increase would occur for the diadromous Arctic char in northern Sweden (e.g. Hein et al., 2012). It could nevertheless be interesting to calculate economic effects of such an increase, which would

raise the intrinsic growth rate in our bio-economic model from 0.28 in the base case to 0.50 (Table 3 in Appendix). This climate effect on the intrinsic growth rate instead of on the maximum population size would raise the annual average net benefits for both fisher types. The net average annual net values for the subsistence fisher would increase by, at the most, 60%, which occurs under exclusive access and with simultaneous climate effects (Table 3 in Appendix). The effect on the recreational fisher is smaller and amounts at the most to an increase by 30%.

The results are affected, not only by the choice of parameter values in the constructed bio-economic model but also by the chosen fish population model. An age-structured fish population growth model instead of our simple logistic growth model would allow for harvest targeting of fish depending on size (e.g. Skonhoft et al., 2012). This would generate an additional adjustment possibility to the climate change impacts, which could mitigate the negative effects on net values. Another simplification, although valid for Lake Abiskojarue, was the exclusion of competitions between Arctic char and other fish species. For example, Svenning et al. (2022) showed that warming temperature increased the proportion of brown trout (*Salmo trutta*) compared with Arctic char in northern lakes where they coexist. If the values and costs of fishing are similar for the two species, the effects of climate change on net benefits may be limited. It was also assumed that the recreational fisher puts value on fishing days and not on marginal increases in harvest. The inclusion of such impacts would increase the marginal value of recreational fishing days, but it is unclear if and how this would be affected by climate change. The catchability coefficient was also assumed to be constant, but might very well be affected by climate change. The bio-economic approach as such is not limited by these simplifications in our model, but allows for more complex population growth models and species interaction (e.g. Elofsson et al., 2012).

The theoretical and numerical results thus demonstrated that a decline in the fish population size due to climate change may not result in negative economic effects and that the direction and magnitude of economic effects depend on fishing motives and access rights. This raises the need for a broad perspective on climate effects in a policy context with decisions on if and how to compensate fishers for climate change effects. A crucial assumption was that on optimal harvest decisions for all combinations of access rights and climate effects. It is well known that such outcomes can not be achieved with an open-access regime, but requires cooperation between the fishers and/or governmental regulations (e.g. Bulte et al., 1995). Cooperation may be facilitated for small lakes and groups but can constitute a challenge for large regions. This was pointed out by Pentz and Klenk (2017) who showed the importance of decision rules and cooperation for the sustainable management of commercial fishery under different climate change conditions. Large fishing regions may also face the risk of depletion in the fish stock if there is insufficient regulation and compliance. The analysis and empirical application did not consider open-access fishery, but a bio-economic approach with consideration of climate change impacts and fisher motives can be applied to such fishery.

Declarations
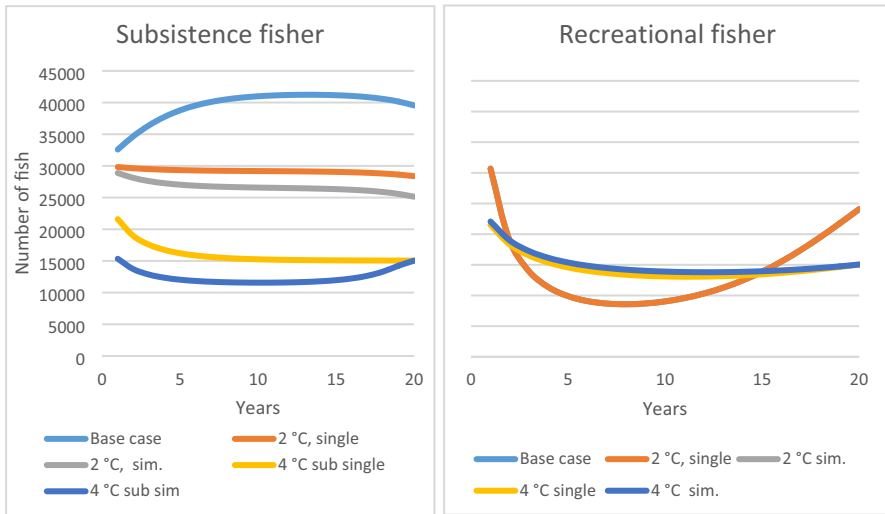
Appendix

See Fig. 4 and Table 3.

Fig. 4 Development over a 20-year period of the optimal fish population size for subsistence and recreational fisher for different combinations of temperature increases and climate effects and with exclusive fishing access to either fisher type

Table 3 Average annual net benefits for subsistence and recreational fisher of different combinations of access rights and climate impacts of a temperature increase by 1 °C which raises the intrinsic growth rate, thousand SEK

Temperature inrease	Intrinsic growth rate[a]	Common access				Exclusive access			
		Single		Simultaneous		Single		Simultaneous	
		Subs		Recr		Subs		Recr	
0	0.28	376	75	376	75	406	305	406	305
0.1	0.33	423	78	440	84	487	312	477	331
0.4	0.38	464	76	484	82	597	333	519	352
1	0.50	536	80	611	84	572	351	649	393

[a]Kourantidou andet al. (2022)

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