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ORIGINAL ARTICLE

Sustainable adaptation of commercial inland fishing?—Lessons learnt from subarctic Lake Inari, Finland

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Abstract

We studied commercial fishers' observations and experience-based knowledge in combination with long-term monitoring data in order to gain a holistic view of the adaptation of fishers to climate change and other drivers on Lake Inari. Fishers' main sustainability concerns included degradation of the environment, overfishing, and lack of decision-making power. The fishery and fishing have changed due to increased water temperature and lake productivity; the open-water period has become longer and winter fishing season shorter and spring-spawning species, such as pike and perch, have become more common. Fishers' responses to reduce risks and cope with future uncertainty included both long- and short-term adaptation—achieved through diversification, flexibility, innovation, and mobility. The responses of fishers to multiple changes are variable and based on individual rather than community behavior. We argue that diverse fishing strategies support the adaptation capacity and sustainability of commercial fishing. Sustainable adaptation of commercial inland fisheries could be further enhanced by better monitoring of the hydrology and fishery, by supporting social relations and communication, and through decision-making based on both scientific and fishers' knowledge.

Keywords Inland fishing · Subarctic · Climate change · Adaptation · Sustainability

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Introduction

Arctic regions have experienced stronger warming than the rest of the world over recent decades: Depending on the region, warming has been two to seven times faster compared to the global average values (Rantanen et al. 2022; IPCC 2023). These changes have implications for the environment and nature-based livelihoods, such as fishing, reindeer herding, and hunting (Salmi 2005; Markkula et al. 2019; Rasmus et al. 2020; 2022a, b). Coastal waters worldwide have been studied intensively to identify climate change impacts and adaptation strategies of fishers and their communities (Berkes and Armitage 2010; Ford et al. 2013; Galappaththi et al. 2019), but corresponding studies on inland waters in cold climate are less common (Wrona et al. 2013; Rolls et al. 2017; Campana et al. 2020).

Fishing can be affected both by the direct effects of increasing temperatures on fish stock and indirect effects of changing environment (Jeppesen et al. 2012; Helminen and Sarvala 2021; Mustonen et al. 2022). Environmental changes are modifying fish communities and range expansion of new species particularly in the Arctic, where temperatures have previously restricted the dominance and establishment of species adapted to warmer water temperatures (Jeppesen et al. 2012; Hayden et al. 2017; Campana et al. 2020). It is estimated that fishery of subarctic lakes, which can currently be characterized as salmon-dominated, will gradually change and become increasingly perch-dominated, to be followed by cyprinid-dominated fishery, due to increased temperature and productivity (Hayden et al. 2017). Indirect effects of climate change on inland fisheries and fishing can be manifested through combined impacts of increased temperatures and precipitation, which enhance carbon and nutrient flow from surrounding catchments and lead to increased productivity and modification of lake fisheries (Wrona et al. 2013). Climate change can also modify the seasonality of fishing by lengthening the open-water season and shortening the winter fishing season (Mustonen et al. 2022).

Fishing communities face simultaneously multiple pressures and risks due to climate change, socio-economic changes, and intensifying land use. These drivers can cause cumulative impacts on fishing and its operational environment (Salmi 2005; Badjeck et al. 2010; Galappaththi et al. 2019; Tingley et al. 2019). Lack of young fishers starting a career in fishing has been one reason for changes in commercial fishing in Finland during the past decades. The methods, gear and vessels have developed, which have enabled intensification of fishing with ever-larger catches. At the same time, costs have increased so that fewer and fewer fishers can afford commercial fishing. Also infrastructure for the fish industry has developed. The increasing demand for fish and the improved price are recent positive developments. Fish is considered environment-friendly and healthy nutrition for humans as well as for domestic and farmed animals (FAO 2024; Sustainable fisheries 2024). In inland waters of Finland, the total catch in 2021 was 5.1 million kg, from which 3/5 was vendace (*Coregonus albula*) or pike-perch (*Sander lucioperca*) (Natural Resources Institute 2021). The total number of active fishers operating in inland waters of Finland was 1298 (CEDTE 2023).

For many coastal and inland fisheries worldwide, reducing vulnerability and increasing adaptive capacity to confront impacts of rapid changes is an urgent issue (Badjeck et al. 2010; Berkes and Armitage 2010; Ford et al. 2013; Galappaththi et al. 2019; Nyboer et al. 2022). *Adaptation strategies* are anticipatory or reactive actions that can be undertaken to mitigate adverse effects, and/or take advantage of opportunities and/or cope with consequences of disturbances—and adaptive capacity is defined here as the ability to undertake these actions (Folke 2006; Smit and Wandel 2006; Parry et al. 2007; Hovelsrud and Smit 2010; Sarkki et al. 2024). *Coping strategy* is defined here as a specific most often reactive response or effort that fishers themselves employ in their work to minimize the damage to their livelihood due to unfavorable conditions in their operational environment (Badjeck et al. 2010; Berkes and Armitage 2010; Galappaththi et al. 2019).

In our work, we define *sustainable adaptation* in the context of commercial fishing as actions aimed at offering good opportunities for current and future generations to practice their livelihood and take into account the ecological, economic, social, and cultural dimensions of sustainability in the livelihood activities and decision-making (Allison and Horemans 2006; SDG Report 2023). Sustainable adaptation in commercial fishing is management and maintenance of fish populations at a healthy level to avoid their exploitation, to secure their reproduction, and to target fishing to diverse species (IFA 2021; SDG Report 2023). A livelihood adaptation is sustainable if fishers are able to maintain or improve their standard of living related to well-being and income or other human development goals, reduce their vulnerability to external shocks and trends, and ensure that fishers' knowledge, values, traditional fishing methods, and livelihood-specific vocabulary are transmitted to new generations (Allison and Horemans 2006; SDG Report (2023).

Our choice of approach reflects our ultimate aim of advancing the development of sustainable adaptation actions not only at the individual and collective levels, but also more widely at institutional levels, with the objective of increasing the vitality and sustainability of the socio-ecological systems, such as fishing. To achieve sustainable adaptation, practitioners' experiences of the impacts of climatic and environmental changes and the coping strategies need to be identified and understood. Fishers who have practiced their livelihood long exhibit detailed knowledge of the fishery, fish behavior, and the weather, snow, and ice conditions of the water area in different seasons and times of the day (Salmi 2005; Smith et al. 2016). Our previous studies have shown that combining practitioners' observations and traditional and experience-based data with scientific observations enables a more holistic and effective dialogue between the local practitioners, researchers, and policy makers (Turunen et al. 2016; 2020; Forbes et al. 2020; Rasmus et al. 2020). Only a few, if any, results have been published to date about the adaptation of commercial fishing in subarctic inland waters.

The goal of this article is twofold. First, by using interviews of commercial fishers and long-term monitoring data on the subarctic Lake Inari in northern Finland, we determine the relationships between patterns in climate and the environment (hydrology and temperature) and patterns in the socio-economics of commercial fishing (seasonality, status, profitability etc.). Second, we examine the adaptation strategies of fishers, and discuss the sustainability and governance of these strategies.

Material and methods

Study area

Lake Inari in northern Finland (68°57′N, 27°40′E) is a subarctic, regulated lake in the Paatsjoki watershed. It drains northeast into the Arctic Ocean, first through Russia and then as a borderline watercourse between Russia and Norway (Fig. 1). Lake Inari is the second largest lake in Finland with its surface area of 1083 km^2. The lake has stony and steep shores, bays and sandy shores; fjords, long inlets, open-water areas, and islands. The size of the lake runoff area including the lake is 14,512 km^2. The largest rivers flowing into the lake are the Juutuanjoki River and the Ivalojoki River. Lake Inari discharges through the Paatsjoki river to the Varangi fjord of the Barents Sea.

Regulation of Lake Inari for hydroelectric power generation has continued since 1941. There are seven hydropower stations in Paatsjoki. Regulation is based on the state treaty signed in 1959 by the Soviet Union, Norway, and Finland. The annual water-level fluctuation due to the regulation is 1.5 m in practice and the maximum variation according to the permit conditions is 2.36 m (Mutenia and Salonen 1994; Marttunen et al. 1997). The ice-free season on Lake Inari lasts usually from May–June to October–November. The lake is quite deep (maximum depth 92 m, mean depth 14.3 m), clear, and oligotrophic (low nutrient levels and productivity). Its Secchi depth ranges from 3 to 4 m in the southern and from 7 to 10 m in the northern parts.

The original fish community of Lake Inari includes ten species: whitefish (*Coregonus lavaretus s.l.*), brown trout (*Salmo trutta*), Arctic char (*Salvelinus alpinus*), grayling (*Thymallus thymallus*), perch (*Perca fluviatilis*), pike (*Esox lucius*), and burbot (*Lota lota*), which are the most abundant native species. Minnows (*Phoxinus phoxinus*) are the only cyprinid species in the lake (Salonen 2004; 2021). Three-spined stickleback (*Gasterosteus aculeatus*) and ten-spined stickleback (*Pungitius pungitius*) are significant prey species of brown trout, for example.

The profound impacts of water-level changes on fisheries caused by the regulation have been compensated by large obligatory stocking programs including whitefish and piscivorous species such as brown trout and Arctic char, since the 1970s (KHO 1975). Three non-native species, vendace, land-locked salmon (*Salmo salar m. sebago*), and lake trout (*Salvelinus namaycmetreush*), have been introduced to the lake. There are many whitefish morphs in the lake (Toivonen 1966; Marttunen et al. 1997; Salonen 2021).

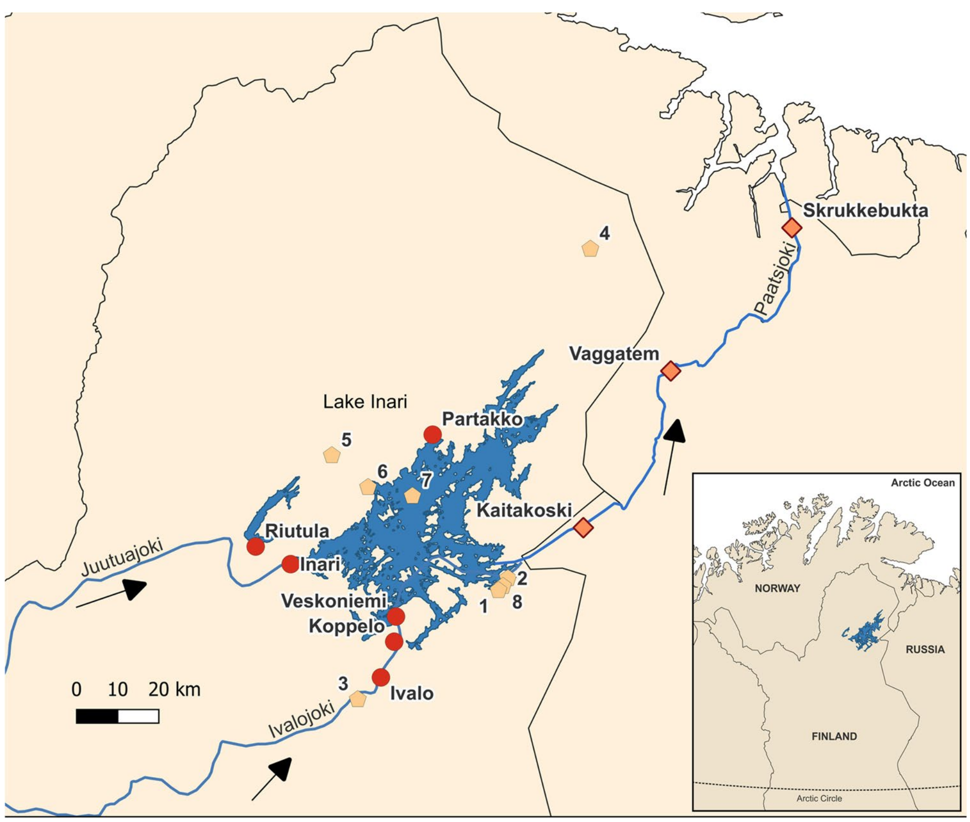

Fig. 1 Location of Lake Inari. Map: ©Arto Vitikka, Arctic Centre, University of Lapland, 2023. Red circles denote villages where the fishers of our study live. Orange squares denote Kaitakoski, a hydropower station closest to Lake Inari in Russia; and Vaggatem and Skrukkebukta, the biggest lake expansions of Paatsjoki in Norway. Yellow numbered pentagons denote the hydrological stations used: (1) Nellim and (2) Paksuvuono (Syke; Finnish Environment Institute); and the meteorological stations (FMI; Finnish Meteorological Institute): (3) Ivalo airport, (4) Kirakkajärvi, (5) Kaamanen, (6) Väylä, (7) Seitalaassa, and (8) Nellim. Data: ©Syke 2023, ©National Land Survey of Finland 2023, ©Runfola et al. (2020)

Commercial fishing on Lake Inari

The roots of commercial fishing on Lake Inari are in the traditional fishing of the Indigenous Inari Sámi. The way of life of the Inari Sámi has been based on livelihoods, such as fishing, hunting, reindeer herding, and agriculture. Year-round fishing has been an important traditional livelihood (Näkkäläjärvi 2007; Lehtola 2022). Local people have made a living from it for centuries and it has helped them survive through difficult times. It has ensured livelihood for local people for centuries and helped them survive through difficult times. Sámi values emphasize spending resources, such as fish, in such a way that their continued availability in the future can be ensured. The Inari Sámi fishing tradition has long been threatened by the outmigration of Sámi from their homeland. Both subsistence and commercial fishing are still very important for the local people, regardless of their ethnic background.

The total fish catch on Lake Inari during the 2000s has varied between 148,000 and 192,000 kg; in 2019, the total catch was 153,000 kg (IFA 2021). In recent years, 30–39% of the total catch has come from commercial fishing, 37–50% from fishing for domestic use, and 20% from fishing by non-local recreational fishers (IMG 2021). Lake Inari has long traditions in year-round commercial fishing, but the main focus is on the open-water season. The catch has been annually ca. 40,000 kg (Natural Resources Institute 2021). Half of this amount is whitefish, and other important catch species include brown trout, vendace, and Arctic char, but nowadays demand for pike, perch, grayling, and burbot is also increasing. During the open-water season, fish is caught mainly by gillnets and trapnets, whereas in winter, gillnets under the ice is the most common method (Fig. 2). Fishing on Lake Inari is regulated by the Fishing rule of Inari Fishing Area (IFA 2021), Fishing Act (379/2015), and Government Decree on Fishing (1349/2015).

In the Inari Municipality, the number of commercial fishers has ranged 42–50 over the period from 2019 to 2023 (CEDTE 2023) (Appendix A). Fishers, all private entrepreneurs, sell whitefish to wholesale companies, restaurants, institutional kitchens, and/or fish shops in northern Finland. The Inari municipality has supported commercial fishing by investing in infrastructure including two fishing ports and fish halls in compliance with EU regulations.

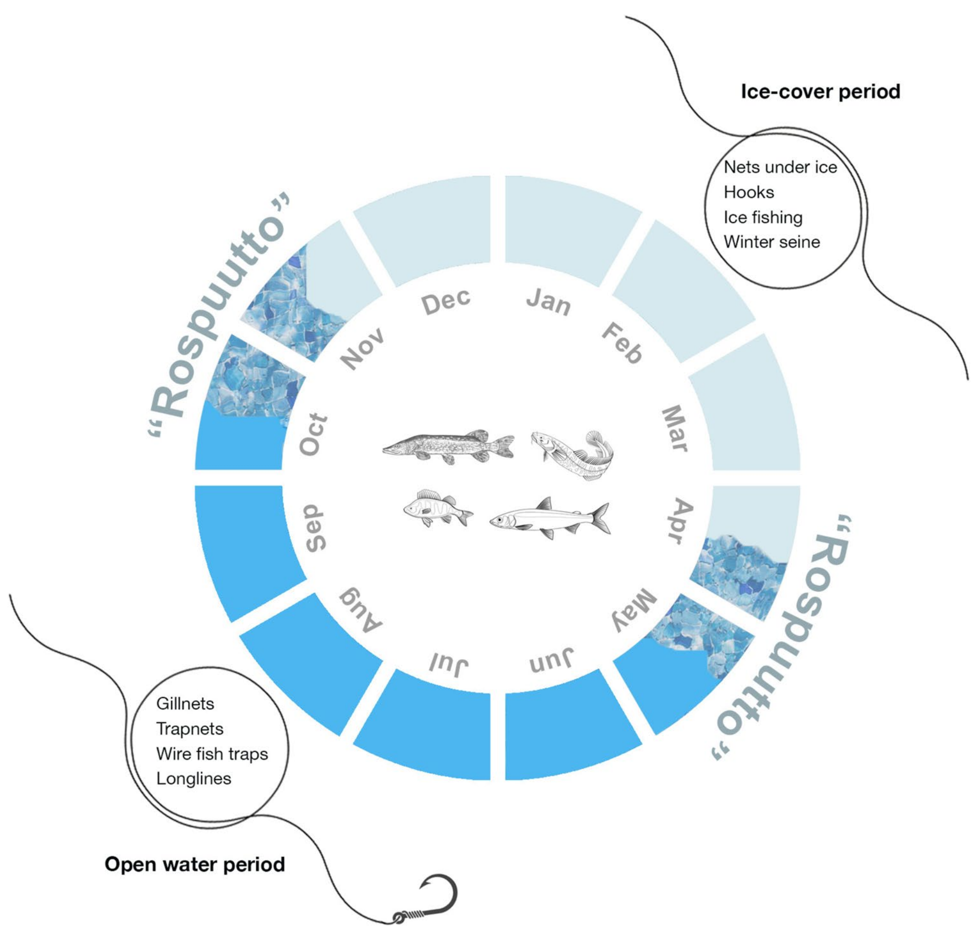

Fig. 2 Seasonal cycle of commercial fishing on Lake Inari. The ice-free season lasts from May–June to October–November (often December in large open-water areas). "Rospuutto" is a period lasting from a few days to weeks, when the carrying capacity of ice cover is not high enough for safe moving and fishing on the ice. Perch, pike, and grayling are spring-spawning species; whitefish, brown trout, and arctic char are autumn-spawning species; and burbot is a winter-spawning species. Also, the main gear used for open-water and ice-cover periods are shown ©Philip Burgess

Hydrological and meteorological observations

To examine the variability and decadal changes in weather, water, ice, and snow indices relevant for fishing, we used data from several hydrological and meteorological observational stations around Lake Inari (Fig. 1, Appendix B). Some hydrological quantities have been monitored since the 1920s (freezing and ice break, precipitation, in-flow from rivers), but systematic time series are generally available only since the beginning of the 1960s. Also, most of the long-term meteorological time series available from northern Finland start from the 1950s or the early 1960s. The hydrological data for this study were collected, cleaned, and quality controlled by the Finnish Environment Institute (Syke) and the meteorological data by the Finnish Meteorological Institute (FMI), respectively.

The hydrological data used is based on the observations conducted by the Finnish Environment Institute (Syke) (Appendix B). The data included annual freezing and ice break-up dates of large open-water areas in Lake Inari, ice thickness measured in the Paksuvuono station in the end of December and March, and daily observations of surface water temperature in the Nellim station (measured at the depth of 0.5 m, from the station shore). The surface water observations were used to calculate the cumulative temperature sum (°C days) of surface water by summing the daily water temperatures during the whole open-water season. Observations of freezing and ice break-up dates began already in 1925. The cumulative temperature sum could be calculated from 1951 onwards and the ice thickness data is available from 1961 onwards.

The meteorological data used included monthly mean temperatures from six weather stations operated by the Finnish Meteorological Institute (FMI) (Appendix B) for the 30-year period 1991–2020, wherever possible. In addition, we used gridded observational data (FMI_ClimGrid; Aalto et al. 2016) of daily mean temperature and snow depth for the period 1961–2020 to study the spatial variability and long-term changes in some seasonal weather indices. This gridded climate dataset covers the whole of Finland with a spatial resolution of 10 km × 10 km.

Possible trends and their statistical significances in the hydrological and meteorological long-term time series were analyzed using the non-parametric Mann–Kendall trend test. The test is reliable also when data are not normally distributed. Missing values were imputed with the Kalman filter. These statistical analyses were conducted in the R environment (R Core Team 2023). In the analyses of the FMI ClimGrid data, Student's *t*-test was used to check the significance of a linear regression coefficient per each grid point.

Interviews

We conducted 11 semi-structured interviews with commercial fishers. This represents over half of all the commercial fishers practicing their livelihood year round in the Inari municipality (CEDTE 2023). The interviews were conducted during 2021–2022 by the authors (MM, MTT, ES). One of them is living in a household practicing commercial fishing year round (MM). The authors selected the participants purposefully aiming at getting as representative a sample as possible regarding age, fishing experience, place of residence, fishing place, and fishing strategies of the participants. All fishers contacted agreed to participate in the study. We informed the practitioners of the purpose of the study and how the interview data will be used. Practitioners were provided with an information sheet about the study, and written, informed consent in Finnish was obtained from all practitioners (Kohonen et al. 2019).

For all practitioners, fishing was the principal source of income. Income sources from related activities included making fish products, gear repair, and production as well as fishing tourism. Income sources outside fishing included construction, transport, freight forwarding, electrical power work, auto mechanics, assistance in research and monitoring, reindeer herding, forestry, hunting, gathering berries and mushrooms, and pension. The practitioners were all male. Their age ranged from 30 to 85 years average age being 59 years. There are no registered female commercial fishers operating in Inari. All practitioners have practiced year-round fishing for decades. Most of the fishers inherited their occupation from their parents, and most of them had lived in Inari for their whole life.

The semi-structured interviews consisted of questions about seasonal cycle of fishing; past and present status of fishery and fishing; profitability and sustainability of fishing; observations of meteorological, hydrological, and environmental, but also socio-economic changes and their impacts on fishing and fishery; coping with and adaptation to different changes; and future of fishing. Our qualitative method was not a strict thematic analysis, but rather an applied thematic analysis (Creswell and Creswell 2018). The main steps in the analysis included systematic reading of individual transcripts and organizing the data according to the questions and fishers' responses, which in combination formed the themes presented in the Results section. The interviews were conducted in Finnish, tape-recorded, transcribed, and analyzed. Due to the in-depth nature of the interviews, which lasted up to 5 h, data saturation was reached already after 8–10 interviews (Eskola and Suoranta 2000). The data were anonymized by using the codes (H1–H11) for the participants.

Results

Climatic, environmental, and socio-economic changes

Commercial fishing has a clear seasonal cycle on Lake Inari. The open-water season usually starts in May–June, when the lake becomes ice-free (Fig. 2). Fishers use boats, and the fish is caught mainly by using gillnets, trapnets, and wire fish traps (H1–H11). Fishing is conducted until autumn "rospuutto," which is defined as a period lasting from a few days to weeks, sometimes even from 1 to 2 months in October–November (December), when freezing of the lake has started, but ice cover is not thick enough to carry the fisher and their gear. When weather conditions are too challenging for operating on the lake, fishers have to take days off, and do not get income from fishing.

Winter fishing is practiced during the ice-covered period, which starts in November–December, when the ice cover has reached the required carrying capacity and moving and fishing on the ice is safe. Fishers usually drive a snowmobile to the fishing site. They catch fish with gillnets under the ice. In recent years, only one group of fishers has used winter seine, but in 1989 during "the vendace boom" (Salonen 2021), there were seven fisher groups using winter seines. The winter fishing season is usually over in May, when ice again becomes too weak for moving and fishing (spring "rospuutto").

The seasonal conditions have been changing during the past decades. Both the fishers' experience-based knowledge (Table 1, Appendix C) and long-term monitoring data on Lake Inari (Fig. 3, Appendix D) show that the open-water period has become longer, especially due to earlier ice break-up. A significant shift is seen; ice break-up is happening approximately 1 day earlier per 14 years ($p=0.05$), on average (Fig. 3b). The ice formation date shows larger interannual variability and thus no statistically significant trend can be detected in the timing of the freezing (Fig. 3a). Also, summer water temperatures have increased, and growing seasons have become longer (Puro-Tahvanainen et al. 2019). Both the water temperatures at the end of August (Fig. 3c) and especially the cumulative temperature sum of surface water over the whole open-water season (Fig. 3d) show statistically significant increasing trends with p-values of 0.024 and 0.004, respectively. Fishers' observations of increased abundance of the spring-spawning species—pike and perch—indicate that a gradual change of lake fishery due to increased water temperature and production is underway. Autumns are nowadays longer, but according to fishers' presumption, the winds have become stronger and windy weather in general more common which, together with more variable and longer "rospuutto" periods, increases the number of no income days. This, in turn, decreases the profitability of commercial fishing. The winter fishing season has become milder. Early winter ice has become significantly ($p=0.005$) thinner (Fig. 3f) but the ice thickness in late March does not show any statistically significant trend (Fig. 3f).

Commercial fishers expressed concerns related to ecological, social, and economic facets of sustainability. Fishers were worried about the state of fishery, particularly degradation of the environment and loss of aquatic habitats. The various changes in seasonal weather conditions with impacts on fishery and fishing together with different coping strategies reported by fishers are presented in Table 1 and Appendix C. The fishers had questions about the impacts of climate change: "*Will ice be strong enough for winter fishing in the future?*" "*Does profitability of fishing decrease in the future due to climate change?*" They were also worried about the water quality due to increased productivity caused by waste waters, and other land uses within the catchment area (Puro-Tahvanainen et al. 2019; IFA 2021).

Most of the fishers held the view that Lake Inari is exposed to overfishing, because fishing pressure is too high due to too many fishers, a large number of effective traps per fisher, and an intensive motorization (H2–3). One of the practitioners commented: "*Fishing effort on Lake Inari has increased a hundred times compared to what it used to be…. Fishing round the year with a very large amount of gear is the only possibility to live from it*" (H3). Many were concerned about the continuity of the livelihood, but at the same time they were against the entry of new fishers, because most of the fishers already now have to have additional businesses to make their living (H4). Some fishers hoped that one would not try to find a solution from the amount of catches, because the stocks would not sustain it (H7–8). One of the fishers pointed out that fishing should be regulated more effectively: "*… fishing during the spawning time is problematic, roe is valuable, but it can be fatal for the fish*".

Fishers viewed that they have a lack of decision-making power, and that they should be heard more when decisions regarding the fishery, and particularly stocking, are made. The researchers recommended reducing the amount of stocked whitefish from 1 into 0.15 million fingerlings for the period 2016–2020, and replacing them with predatory fish, which has been followed strictly (Rytkönen et al. 2015; Niva et al. 2021). The decision was justified by the fact that a reduced amount of stocked whitefish would not only prevent the formation of overdense stocks suffering from parasites and disease, but would also improve the growth and health of whitefish (Rytkönen et al. 2015; Niva et al. 2021). Most of the fishers had contradictory views on reducing whitefish stocking: "*Whitefish should stay there* [in the lake]*, because it brings bread to the table of*

Table 1 Impacts of difficult weather conditions on commercial fishing, and the strategies applied by fishers to cope with them during different seasons. Most of the weather conditions listed will become more common in the future due to climate change, with the exception of short/no "rospuutto," long periods of extremely low temperatures, and late ice break-up. The coping strategies of fishers mainly represent reactive adaptation

Weather conditions	Impact on fishery/fishing	Coping strategy
Summer		
Long hot periods	Higher water temperatures Quality of fish deteriorated in gillnets More frequent checking of gillnets > Increased working hours and travel expenses Fish move less > reduced catch Decreased water quality, slimy traps	Avoid hot periods Decrease number of gillnets, but check them more frequently Shift from gillnets to trapnets in which fish stay alive Change fishing place
Warmer and longer growing season	Higher water temperatures Spring-spawning species, such as pike and perch, become more common Autumn- and winter-spawning species, such as salmonids, move into deeper waters Decreased water quality, slimy traps	Catch pike and perch Change fishing place to catch salmonids Avoid fishing places of decreased water quality Change fishing place
Long-lasting heavy rains	Reduced catch Lost fishing time > less income	Avoid heavy rains Use no income days for supporting activities
Increased and harder winds, storms	Moving and fishing difficult or impossible Difficult to handle boat and gear Lost fishing time > less income Difficult to predict fish movements > less catch	Avoid windy places Larger and safer boats; safety clothing Use no income days for supporting activities
Autumn		
Warm autumn, late formation of snow and ice cover	High water temperatures Extended open-water season > More income	Utilize extended open-water season
Long "rospuutto" period	Moving and fishing on weak ice difficult or impossible Increased risk for drowning accidents Lost fishing time > less income	Avoid weak ice Safety clothing and equipment Use no income days for supporting activities
Short/no "rospuutto" period	Extended fishing time, no break between open-water and ice-covered seasons Higher availability of autumn-spawning species More income due to longer fishing seasons	Utilize extended fishing time Catch the most valuable autumn-spawning species (whitefish)
Increased and strong winds, storms	Moving and fishing difficult or impossible Difficult to handle boat and gear Lost fishing time > less income Difficult to predict fish movements > less catch	Avoid windy places Larger and safer boats; safety clothing Use no income days for supporting activities
Winter		
Poor ice conditions: (weak ice/water on ice/snow on ice/slush)	Moving and fishing difficult or impossible Increased risk for drowning accidents Lost fishing time > less income Heavy gear, such as winter seine, cannot be used	Avoid weak ice New technical solutions (plastic sledge) Use no income days for supporting activities
Deep snow	Moving and fishing difficult Increased working hours and travel expenses	Clear the way to the fishing site on the day before fishing New technical solutions: plastic sledge
Ice formation in the snow pack	Moving and fishing difficult Increased working hours and travel expenses	Clear the way to the fishing site on the day before fishing
Short ice-covered period	Longer open-water period More income from open-water fishing	Use boat instead of snowmobile for moving
Long periods of extremely low temperatures	Moving and fishing difficult or impossible Freezing of vehicles and gear Deteriorated quality of fish Lost fishing time > less income	Use no income days for supporting activities
Mild winter	More favorable fishing conditions Ice remains weak, water flooded on ice > moving and fishing difficult	Utilize favorable conditions

Table 1 (continued)

Weather conditions	Impact on fishery/fishing	Coping strategy
Spring		
Early ice break-up	Earlier onset and longer duration of open-water period	Utilize longer open-water period for fishing Catch spring-spawning species (pike, perch)
Late ice break-up	Longer ice-covered period Later onset and shorter duration of the open-water period	Utilize extended period for winter fishing
Long "rospuutto" period	Moving and fishing on ice risky, difficult or impossible Increased risk for drowning accidents Lost fishing time > less income	Avoid weak ice Safety clothing and equipment Use of new technical solutions (plastic sledge) Use no income days for supporting activities
Short/no "rospuutto" period	Extended fishing time, no break between open-water and ice-covered season Moving and fishing easier Abundant availability of spring-spawning species, (pike and perch)	Utilize increased fishing time Utilize increased availability of spring-spawning species

Fig. 3 Long-term hydrological observations in Lake Inari. (**a**) Freezing dates and (**b**) ice break-up dates of large open-water bodies, (**c**) surface water temperature in Nellim on 31 August, (**d**) cumulative temperature sum of surface water in Nellim during the open-water season, and (**e**) ice thickness in Paksuvuono on 30 December and (**f**) on 30 March. Kendall's Tau values and *p*-values are shown for time series with statistically significant trends according to the Mann–Kendall trend test. Data: ©Syke

most of the [commercial] *fishers*" (H2). "*The practice of the livelihood would be finished without stocking*" (H3). The fishers also criticized the ratio of stocked species by arguing that brown trout and Arctic char, which have been used to compensate for the reduced amount of whitefish, serve the aims of the Inari municipality (H2–3, H6, H11), which is willing to get money from fishing tourists (H2–3, H11). In response to fishers' claims, the amount of stocked whitefish was increased from 0.15 million to 0.4 million in 2020, and to 0.6 million in 2021 (Niva et al. 2021).

Fishers held the view that their livelihood has a weak status compared to other northern livelihoods (H3–4, H6): "*Fishing as a livelihood is in a disadvantaged position if compared to reindeer husbandry, for example. Position of fishing is weak due to lack of organizations protecting the interests* [of fishers]" (H3). The weak status of fishing was evident particularly after winter 2019–2020, when exceptionally difficult snow and ice conditions (Kumpula et al. 2020) increased travel expenses and work in fishing, but unlike reindeer herders, fishers did not get any compensation from the state. In the fishers' view, the subsidies policy of fishing should be developed: those who get subsistence 100% from fishing, including early-career fishers, should be supported—not those who get pension (H2).

Despite all the sustainability concerns and future uncertainty, the fishers shared a rather optimistic view of their future; they agreed that fish from Lake Inari has a good reputation among consumers, its demand is high and increasing, but the price paid for the fish could be higher.

Adaptation strategies of fishers

Fishers are adapting to the effects of multiple drivers and future uncertainty by diversification, flexibility, innovation, and mobility of their businesses and fishing practices. To sustain their households, all fishers have multiple sources of income either within fishing—such as preparing fish products, tourism, and gear repair and production—or outside fishing (see "Interviews"). Some fishers were eager to prepare fish products due to the improved value of fish, and some had plans to prepare fillets, mass, and cold- and warm-smoked-fish products from both their own catch and that of other fishers (H9). However, not all fishers saw preparing fish products as an attractive option, as pointed out by one fisher: "*Cutting fillets from fish is not always profitable, firstly, because 35–60% of the weight is lost depending on the species, and secondly because of the great amount of working hours which have to be spent* [at fish hall] *for the different stages*" (H3). Many fishers mentioned that preparing fish products in the hall might be a good choice for "*no income*" periods, when conditions are too challenging for fishing, but what all practitioners valued the most was the time spent on the lake.

The adaptation strategies of fishers were based on flexible utilization of diversity of species according to availability, gear, methods, and locations for decreasing risks caused by difficult weathers, snow and ice conditions, and other changes in their operational environment (H7) (Table 1). To catch diverse species with variable traps from different parts of the lake and nearby water areas makes it less risky compared to fishing with a focus on only one species, one method, one place, and one time. Although Lake Inari is an oligotrophic lake, its diverse fishery provides a wide selection of species to be caught round the year (Fig. 2). Some fishers have started to focus on catching perch and pike, which have become more abundant due to climate change, and whose demand is increasing. Some fishers catch almost all possible species. During hot periods, some fishers had replaced gillnets with trapnets, which helps keep fish alive longer after they have been caught in the net.

One of the practitioners emphasized an effort to catch fish from underfished nearby water areas and by using only little machinery: "*… it would decrease the need for investments and loans to be paid. Staying overnight at fishing places decreases the need for moving back and forth*" (H7). In addition, utilizing the variation in the length of the open-water season and ice-covered season in different parts of the lake can be helpful for fishers. Ice is usually formed first on the shallow bays, whereas the large open-water areas are the last to freeze over. Utilizing the areas in which ice is formed later or breaks up earlier can provide a great advantage: "*I have been lucky to be able to continue fishing in open waters by moving to a place which stays free of ice two or three weeks longer than other places*". I have been fishing by boat even on the 22nd of November" (H5). In recent years, fishers have also developed technical solutions for coping with changing ice and snow conditions. One of the most important inventions is a boat-like plastic sledge, which does not get stuck into slush (M. Ahonen, pers. comm.)

Given their status as private entrepreneurs who are used to having their "*own freedom*" and independence for decades, the fishers in Lake Inari tended to prefer individual rather than community-based adaptation strategies. Some fishers informed that they would like to co-operate more with each other. Fishers mentioned the local cooperative (Lokan luonnonvaraosuuskunta) at the Lokka reservoir in northern Finland as an example of a "*success story*." In this cooperative, fishers—most of whom live in the same village—are participating in a project which aims at ensuring the continuity of fishing, improving the professional skills of both new and established fishers, and developing an innovative fisheries recruitment model for the area (Directorate-General for Maritime Affairs and Fisheries 2023).

Based on the fishers' views, we identified four fishing strategies as ways to adapt to multiple drivers: whitefish strategy, pike and perch strategy, multispecies strategy, and fishing tourism strategy (Table 2, Appendix E). These strategies vary with respect to their goals, investments, risks, and sustainability. The magnitude of investments and risks in the whitefish strategy are estimated to be major. Specialization in one species only runs the risk of not being able to adapt to change. In the pike and perch strategy, the risks are considered minor because, due to climate change, the catches are abundant and the demand is growing. The multispecies strategy, which is easily adaptable to weather conditions, fish availability, and demand, is also a low-risk strategy The risks of fishing tourism are related to the lack of tourists. In terms of sustainability, the whitefish strategy is estimated to be the least sustainable, because the catches are dependent on stocking and selective fishing can lead to a biased fishery composition. The multispecies strategy is considered to be the most sustainable, because fishing pressure is low and directed to several species. The medium sustainability of the pike and perch strategy is based on the rapid regeneration of stocks due to climate change. The fishing tourism strategy enhances local sustainability by targeting to enable an experience for tourists instead of major catches (Table 2, Appendix E).

Discussion

Sustainability and governance of the adaptation strategies

We studied commercial fishers' observations and experience-based knowledge alongside long-term monitoring data to gain a view of the adaptation of fishers to climate change and other drivers on the subarctic Lake Inari in northern Finland. Livelihood diversification, which is defined here as an occupational multiplicity outside and within fishing (Salmi 2005; Badjeck et al. 2010), was found to be one of the most commonly used and powerful long-term planned adaptation strategies among fishers to reduce risks and cope with future uncertainty. Diversification built on alternative activities—either temporarily or permanently—has a great potential to increase both sustainability and profitability of fishing households and to reduce their dependence on fish stocks. In order to diversify their businesses, the practitioners used their detailed experience-based knowledge and skills, although increasing variation and changes in weather, snow, and ice

Table 2 Fishing strategies of commercial fishers on Lake Inari and the estimated magnitude of investments, risks, and sustainability according to the authors: * minor, ** medium, *** major. For more detailed information, see Appendix E

Fishing strategy	Goal	Investments	Risks	Sustainability
Dominant whitefish strategy	To exploit efficiently whitefish, which is the most valuable and competed-for species with high demand	***More and more expensive gear is needed to make a living out of fishing due to depleting stocks and an increasing number of fishers	***Relying only on one species runs the risk of being caught in "the specialization trap" in which a fisher is not able to adapt to change	*The catches are dependent on stocking. Selective fishing can lead to a biased fishery composition (an increase in the abundance of species not removed by fishing)
Pike and perch strategy	To catch spring-spawning species—the pike and the perch	**Requires moderate investments in vehicles and gear	*Due to earlier ice break-up and longer open-water season, the catches are higher than in the past. Demand for products made of pike and perch is growing fast	**The stocks regenerate rapidly due to warmer and longer growing seasons Environment-friendly management of waters
Multispecies strategy	To catch different species	**Does not necessarily require big investments in vehicles and gear	*Less vulnerable to environmental and socio-economic changes Easily adaptable to changing weather conditions, fish availability and demand by consumers, because the distances to fishing places are short, and the gear is diverse and mobile	***Fishing pressure is low and directed to several species and nearby water areas, which are often underfished Rather than aiming for high catches only, the fishers aim to generate higher value through more thorough utilization of smaller catches to prepare fish products
Fishing tourism strategy	To catch different species, to produce an experience	**Making fishing trips with paying tourists means rather high expenses	**Lack of tourists due to pandemics or political tensions. Risks can be decreased by practicing both commercial fishing and fishing tourism	**Increases local sustainability by targeting to provide an experience for tourists instead of major catches

conditions are often making "*reading their operational environment*" harder for fishers, which also has an impact on local fishery more generally (Salmi 2005; Berkes and Armitage 2010; Smith et al. 2016).

We identified four fishing strategies, which characterized fishers' harvesting behavior and allowed fishers to adapt to the changes in their operational environment and society, such as changes in weathers or fish price, by changing their target species and the gear used (Boonstra and Hentati-Sundberg 2014; Yletyinen et al. 2018). Fishers utilized one or several of the described strategies or shifted flexibly between the strategies, depending on the prevailing and expected conditions. We argue that long-lasting and dynamic co-existence of diverse fishing strategies contributes positively to the long-term adaptive capacity and sustainability of the Lake Inari fishery. For further enhancement of sustainability of adaptation, the multispecies strategy and the pike and perch strategy could provide a better solution than the whitefish strategy, because those strategies support environmental management of waters. In northern Europe, diversification strategies of fishers have previously been studied widely in small-scale coastal fisheries and large-scale offshore fisheries. These studies show that diversification greatly contributes to socio-economic sustainability, resource use efficiency, and resilience against environmental changes, among others (Salmi 2005; Hovelsrud et al. 2010; Boonstra and Hentati-Sundberg 2014; Yletyinen et al. 2018).

To sustain sustainability of adaptation, diversification of products from fisheries also implies diversification of markets that should adapt in response to challenges and opportunities posed by climate change. In this context, actions should include measures aimed to increase consumer awareness of fishery products with a sustainability brand with the objective of changing consumer behavior. Value of fish could be increased by utilizing by-catch and making fish products, for example. The emerging trend of fishing for species that have previously been less valued as catch species and are now proliferating should be established as a mainstream activity and exposed to innovative product development. To increase demand, more information on the usability of these fish species for food should be effectively communicated to the potential consumers.

Studies conducted in the Canadian Arctic (Berkes and Armitage 2010) and in Southern Europe (Villasante et al. 2022) have shown that willingness to co-operate and invest in social relations is a key factor for the profitability and sustainability of small-scale fisheries. In our study, fishers' adaptation was based more on individualistic response than community behavior. One reason for the low degree of organized co-operation among fishers on Lake Inari is the logistical challenge involved: Fishers may live long distances from each other and not everyone uses the same harbor or fish halls. Fishers informed that they would be open to education and skills upgrading, such as new development projects in making fish products and fishing tourism, among others, and short courses for making new types of gear for new species, which are becoming more abundant due to warming. Fishers would benefit from participation in social learning forums (Diduck et al. 2005; Berkes and Armitage 2010), and such forums could also be used as platforms for passing the practitioner knowledge and skills on to future generations of fishers. The adaptation strategies identified among fishers on Lake Inari are in agreement with previous studies conducted in both the Southern and Northern Hemisphere, which have found that diverse and flexible livelihood systems, education and skills upgrading, investment in social relations and networks, and the experience-based and traditional knowledge of fishers are key elements of sustainable adaptation in fishing communities (Salmi 2005; Allison and Horemans 2006; Badjeck et al. 2010; Galappaththi et al. 2019; Tingley et al. 2019; Mustonen et al. 2022) (Fig. 4).

The fishers were concerned about the marginalization of their interests, values, and knowledge in the present fisheries policies. They hoped for more effective, truly participatory co-management, which would value their views to a larger extent as has been the case with the stocking and fishing regulations, for example. The establishment of the regional fisheries management units, such as the Inari Fishing Area (IFA 2021) with its own operational and management plan, has already improved the effectiveness of decision-making and co-management scheme, and thus increased social sustainability. These co-management units gather owners of the water areas, fishers, authorities, and researchers together. However, management of fisheries cannot be resolved by technical management tools alone, because transfer of knowledge and sustainable use of resources are fundamentally related to the development of mutual trust (Salmi 2013). Furthermore, co-management requires perpetual investment in social relations, education, and communication. A review on the inputs needed for sustainability of inland fisheries in Europe considered communication, information dissemination, education, institutional restructuring, among others, as key elements (Arlinghaus et al. 2002). The review found that the sustainable inland fisheries are characterized by precautionary approaches and principles, adaptive management, participation of all stakeholders, and application of appropriate science as well as integrated management and approaches (Arlinghaus et al. 2002).

The Ministry of Agriculture and Forestry in Finland has prepared an action plan serving as a tool for steering and informing adaptation actions that also covers commercial fishing (MAF 2023). The ministry emphasizes that, in changing climate, improving the prerequisites for natural reproduction of fish stocks would be an important adaptive measure (Rytkönen et al. 2015; Peltonen-Sainio et al. 2017; MAF 2023), which could contribute positively to sustainability. So far, the adaptation measures to compensate for the negative impacts of regulation have included extensive obligatory stocking and clearance of shores and seine places as well as repair of shore protections (IFA 2021). Adaptive water-level regulation would be one solution for overcoming the negative effects of climate change such as shortened winter, increased discharge in early winters, and earlier spring flooding (Dubrovin 2015). For Lake Inari, increase in spring and early summer water levels would have beneficial impacts on fishing (Rytkönen et al. 2015). For example, reproduction of autumn-spawning species, such as the whitefish, would be improved, because their spawn is vulnerable to low water levels. Due to the current geopolitical tensions caused by the Russian war in Ukraine, however, changes in water-level regulation remain uncertain. Another adaptive measure already in place is to improve commercial utilization of the species that are becoming more abundant due to climate change, such as pike and perch. This will increase sustainability by saving fish stocks and by enabling environment-friendly management of fisheries (MAF 2023). In addition, MAF (2023) emphasizes the significance of improving fishing safety to respond to stronger winds and more frequent extreme weather events, as well as the importance of development of supporting infrastructures for fishing.

Long time series from the study region have seldom been used in research despite the fact that they provide valuable information on the environmental change and complement the experiential knowledge of commercial fishers. However, the monitoring datasets—especially ones about the snow and ice conditions—are still rather insufficient, and it is the winter fishers who possess the most in-depth knowledge about the variation of ice and snow cover structure on Lake Inari and adjacent water areas. Managing sustainable fisheries is a dynamic process that requires constant attention to new scientific and local knowledge that can inform management actions. Fish production on Lake Inari as a whole and the sustainability of fishing should be evaluated more carefully. At present, monitoring of fish communities is based on research by Natural Resources Institute and bookkeeping by the commercial fishers (Government Decree on Fishing 1349/2015; IFA 2021; Niva et al. 2021). Monitoring should be developed so that fish stocking would support the development of natural reproduction of fish and simultaneously enable profitability of fishing. It would be vital to find a long-term constructive solution based on co-management, which would satisfy commercial fishers, researchers, and authorities. We recommend establishing a more effective and co-productive long-term monitoring of hydrology and the state of fishery on Lake Inari as an anticipatory adaptive measure to respond to the uncertainty and potential future threats, such as alien species and deterioration of

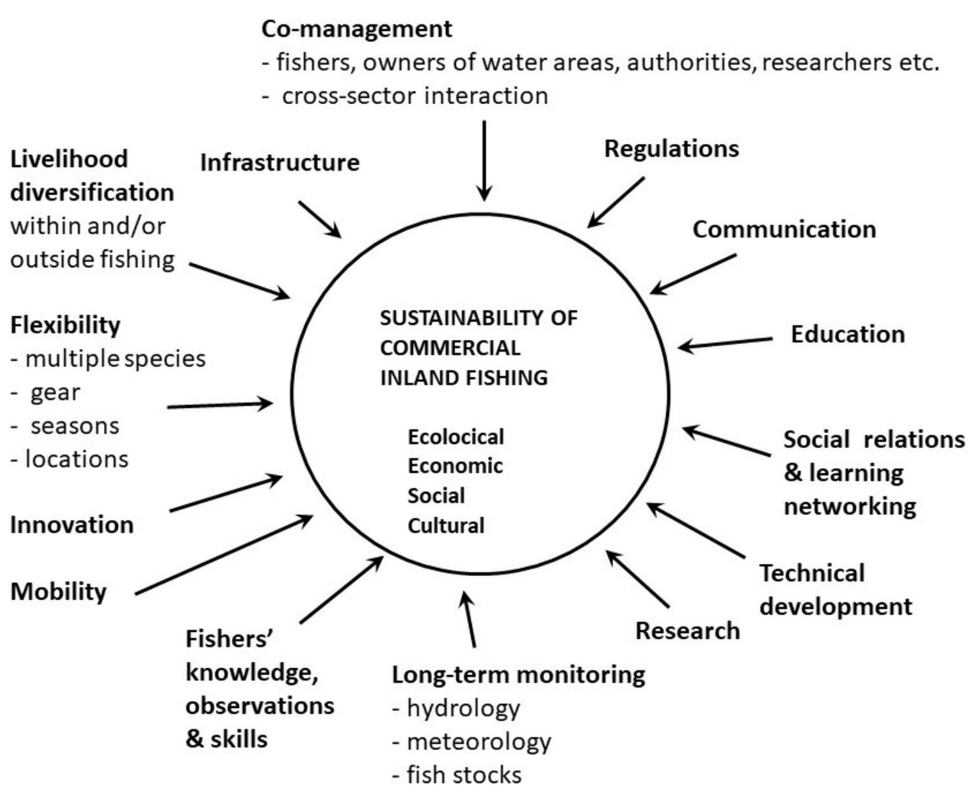

Fig. 4 The key elements supporting sustainable adaptation of commercial inland fishing. Some of the elements apply to the level of the individual fisher or fisher groups and some to the fishing governance level. All facets of sustainability—the ecological, the economic, the social, and the cultural—are taken into account

water quality as well as emergence of parasites and diseases. Increasing access to climate information and forecasting with early warning systems would be important for the commercial fishers, as well. These measures, together with effective co-management in which decision-making is based on both scientific and fishers' experience-based knowledge, would help strengthen and maintain the core structures and functions of commercial inland fishing in northern regions (Fig. 4).

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Author contribution Minna Turunen: planning the research, main author and responsible writer of the manuscript, collection and analysis of the interview data. Sirpa Rasmus: planning the research, participating researcher in analysis of FMI's and SYKE's data and interview data, manuscript writing. Marja Montonen: participating researcher in collection and analysis of the interview data. Erno Salonen: participating researcher in analysis of FMI's and SYKE's data, manuscript writing. Ilari Lehtonen: participating researcher in handling and analysis of FMI's and SYKE's data, manuscript writing.

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Data availability The interview material of this study is confidential. The meteorological data analyzed is open, and can be found here: https://en.ilmatieteenlaitos.fi/open-data-sets_available. Hydrological data is open and for most parts found here: https://www.syke.fi/en-US/Open_information/Open_web_services. Data can also be received on request from the authors.

Declarations

Competing interests The authors declare no competing interests.

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