Aquaculture 593 (2024) 741350

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aquaculture

Diversification of marine aquaculture in Norway under climate change

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A R T I C L E I N F O

Keywords:
Aquaculture readiness level
ARL®
Challenging conditions index
CCI
Climate action
Species diversification

A B S T R A C T

Recently there has been increased interest in species diversification in aquaculture as a strategy to adapt to climate change. Since species diversification is a long-term strategy, climate change and future farming conditions must be considered. The aim of this study was to evaluate how changing temperatures under different IPCC climate scenarios may affect marine aquaculture species diversification in Norway. Since farm conditions vary between locations, this study focused on four geographic areas (South, West, North and Arctic) and three farms within each area. Using a climate model downscaling of three climate scenarios (Shared Socioeconomic Pathways; SSP1–2.6, SSP2–4.5, and SSP5–8.5), daily temperatures from the years 2020–2099 were evaluated at each farm location to identify challenging conditions for 34 species. A Challenging Conditions Index (CCI) was developed based on species thermal tolerances to compare the 34 potential aquaculture species. The results showed differences in the number of challenging days (hot and cold) between areas, and even within areas, highlighting the need to consider site-specific conditions. For warm-water species more commonly farmed in the Mediterranean (e.g. European seabass, gilthead seabream), the calibrated model projections at the investigated Norwegian farm sites suggest that cold temperatures would still be challenging. Differences in the number of challenging days between the climate scenarios become more apparent towards the mid and end of century, though all scenarios show interannual variation rather than a constant change in conditions over time. Hence, any species selected for diversification purposes will have to be able to tolerate a range of temperature conditions, and species with narrower tolerance ranges could be a risk. These findings underline the importance of considering the interannually varying conditions that species will be exposed to rather than focusing solely on long-term averages. Establishing a new large-scale commercial aquaculture species takes a considerable amount of time and resources. Therefore, to support interpretation of the results and further studies on diversification under climate change, this study also introduces Aquaculture Readiness Level (ARL®) as a consistent evaluation of the research and development status, progress towards commercialisation and climate action orientated production. As species will have to be able to tolerate a range of temperature conditions over different years, the level of knowledge, resources, and innovation will have to be continually enhanced to improve adaptive capacity.

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https://doi.org/10.1016/j.aquaculture.2024.741350
Received 18 November 2023; Received in revised form 2 July 2024; Accepted 11 July 2024
Available online 14 July 2024

1. Introduction

Climate change brings new challenges for aquaculture, potentially affecting the suitability of locations to farm particular species, which could threaten food supplies and livelihoods (Barange et al., 2018). Hence, many countries are starting to consider species diversification as a potential adaptation strategy (Harvey et al., 2017). Species diversification is seen as an attractive adaptation option as national economies and local communities may be able to build resilience and enhance adaptive capacity if there are a range of aquaculture activities rather than focusing solely on farming a single species (Metian et al., 2020; Cai et al., 2023). However, decisions on diversification strategies and species selection must consider the biology of the new species alongside possible impacts from climate change at farm sites.

Climate model projections give an insight into potential climate conditions in the future under different scenarios. Climate scenarios are a way of describing plausible futures and their corresponding greenhouse gas emissions, that can then be used to simulate changing environmental conditions and analyse potential impacts on different ecosystems and communities (van Vuuren et al., 2014). Climate model projections of variables such as sea temperature can provide useful information for aquaculture (Falconer et al., 2020; Falconer et al., 2023). Recent studies have used model projections to evaluate how climate change may affect the suitability to farm up to 200 different marine species at a global scale (Free et al., 2022; Froehlich et al., 2018; Oyinlola et al., 2022). However, better understanding of site-specific conditions and variability between areas is also required to support strategic decisions at a more local scale (Falconer et al., 2020; Falconer et al., 2023). For most global assessments, the grid cell resolution of the projected climate variables is low, typically 0.3–1° latitude and 1° longitude, i.e., around 100 km (Free et al., 2022; Froehlich et al., 2018) and thus not resolving small scale ocean features. Hence, whilst coarse model resolutions may be sufficient for high-level global-scale assessments, high-resolution simulations are needed to adequately resolve the small-scale processes relevant for many key questions about future aquaculture and species diversification potential at specific sites. High resolution climate models are lacking in most areas, but regional climate model projections can be calibrated using farm-level data (Falconer et al., 2020; Falconer et al., 2023), and such methods have been used to simulate potential impacts of climate change on mussels in Spain (Fuentes-Santos et al., 2021), and seabass and meagre in Greece (Stavrakidis-Zachou et al., 2021a).

The suitability of a site for aquaculture depends on many different criteria and considerations (Ross et al., 2013). While there are often trade-offs to be made between desirable factors, a suitable temperature profile is of fundamental importance since temperature is one of the most important abiotic factors affecting survival and growth of aquatic organisms (Lutterschmidt and Hutchison, 1997). The influence of temperature is of practical interest for aquaculture, as temperature influences many key aspects of farming such as growth, behaviour, stress, and health (Cascarano et al., 2021; Hernández et al., 2007; Remen et al., 2015). Farmed species have limited opportunities to move from unfavourable conditions, thus understanding site-specific characteristics and the potential for challenging conditions is essential. As sea temperatures are continuing to increase (IPCC, 2023), knowledge of thermal thresholds and critical temperatures is important in understanding how biology of a species may respond to different thermal regimes. Such information is essential for species diversification.

Use of climate projections alongside thermal thresholds could indicate potential suitability of a species in the farm area, and thus prospects as a new aquaculture species in that location. However, although temperatures at a site may be considered to be suitable, it can take decades to undertake the necessary steps to establish commercial-scale farming of a new species. Even if some of the farming technology is similar, it is not simple to switch from one species to another. Extensive research and development costs are required to domesticate and develop successful commercial species for aquaculture (Teletchea and Fontaine, 2014). Commercialisation of a species requires species specific biological competence, a stable market supply, and appropriate governmental administration and regulation (Pincinato and Asche, 2016; Puvanendran et al., 2022). Due to the complex and time-consuming process of diversifying aquaculture and developing a resilient industry for new species, strategies should also consider how temperature is changing in the short, medium and long-term and implications for the species in potential farming locations. Furthermore, some of the conflicts related to coastal zone management and competition for aquaculture sites could be addressed with site specific temperature knowledge and a wider range of species produced. However, allocating sites to species that are best suited to the local conditions is difficult based on the current knowledge on local environmental conditions and future climate projections.

Norway produced over 1.6 million tons of aquaculture products in 2022, making it one of the top aquaculture producing countries in the world (Norwegian Directorate Of Fisheries, 2023). However, Norway has the lowest species diversification out of the 38 countries/territories that produce at least 100,000 t of aquaculture (Cai et al., 2023). The Norwegian aquaculture sector is dominated by a single species, Atlantic salmon, that accounts for approximately 95% of total production (Norwegian Directorate Of Fisheries, 2023). Reliance on a single species may be a risk, especially as the aquaculture sector is Norway's second largest export industry after oil and gas and was worth over 100 billion NOK in 2022 (Norwegian Directorate Of Fisheries, 2023; Regjeringen, 2021). Recently, the Norwegian Government commissioned a report into the potential for species diversification that identified species that may be appropriate for investment based on key drivers such as environmental sustainability, market potential, development potential, and economy and value creation (Akvaplan-niva, 2019). When considering species diversification there is also a need to assess how climate change may alter farming environments, and potential long-term consequences for different species, new and established. Therefore, the aim of this study was to utilize future climate projections calibrated to aquaculture farm level to evaluate how changing temperatures under different IPCC climate scenarios may affect marine aquaculture species diversification in Norway.

2. Materials and methods

2.1. Future temperature projections

Future temperature projections for three of the Shared Socioeconomic Pathways (SSP) climate scenarios (SSP1–2.6, SSP2–4.5 and SSP5–8.5) were obtained from a regional downscaling of the Norwegian Earth System Model (NorESM) using the NEMO ocean model (Hordoir et al., 2022). The cell resolution of the model is approximately 10 km, which to our knowledge is the best available resolution available for the area. SSP1–2.6 represents a low emissions scenario where there is rapid transition to renewable energy and more sustainable forms of production and resource use (van Vuuren et al., 2017). SSP2–4.5 represents an intermediate emissions scenario where emissions continue to increase but then slowly decline in the second half of the century (Fricko et al., 2017). SSP5–8.5 represents a high emissions scenario where there are high levels of fossil fuel use and many mitigation challenges (Kriegler et al., 2017).

Daily farm level temperature projections at approximately 5-m depth were produced for 2020–2099 by calibrating the 5-day averaged climate model projections using the bias correction Eq. (1) (BC1) approach described in Falconer et al. (2020) with 2016–2020 used as reference. BC1 is a way of producing farm-level projections from global climate models and regional downscalings (Falconer et al., 2020). Daily temperatures were considered appropriate for the present study since averages over time (e.g., weeks, months, seasons, and years) indicate central tendencies of datasets, while organisms must tolerate the entire range of conditions that they experience. Daily farm measurements of temperature at approximately 3–7-m depth were provided by aquaculture companies. Following initial screening of the temperature data, twelve farms were selected based on data availability and location. Farms were grouped into four geographical areas (Arctic, North, West and South) comprising three farms per geographical area to give insight into the range of conditions (Fig. 1). These geographical areas were used for the purposes of this study and to assist with presentation of results and do not represent a formal organization of the country.

2.2. Selection of species

Atlantic salmon dominates Norwegian aquaculture, with small volumes of other species produced (Fig. 2). This study focused on 34 marine species (Table 1), including 17 fish, six bivalves, five crustaceans, three seaweeds, two echinoderms and one tunicate. The species list was compiled based on the species identified in a previously published report on species diversification that was commissioned by the Norwegian Government (Akvaplan-niva, 2019), and additional species that may be of interest. Some of the species are already farmed commercially in Norway, but at very low levels in comparison to Atlantic salmon. Atlantic salmon was included in the analysis for comparison. For presentation of the results, the molluscs, crustaceans, echinoderm, tunicate and seaweeds were aggregated into one grouping 'other species' and the fish species were all grouped together as 'fish species'.

2.3. Aquaculture readiness level (ARL®)

The species were categorised based on Technology Readiness Levels (TRLs) (European Commission, 2014; NASA, 2021) that were adapted and redefined for this study as Aquaculture Readiness Levels (ARL®) (Table 2). TRLs are a way of assessing the development pathway and maturity of new technology and can be an important part of project management (Mankins, 2009). Since they are designed for technology,

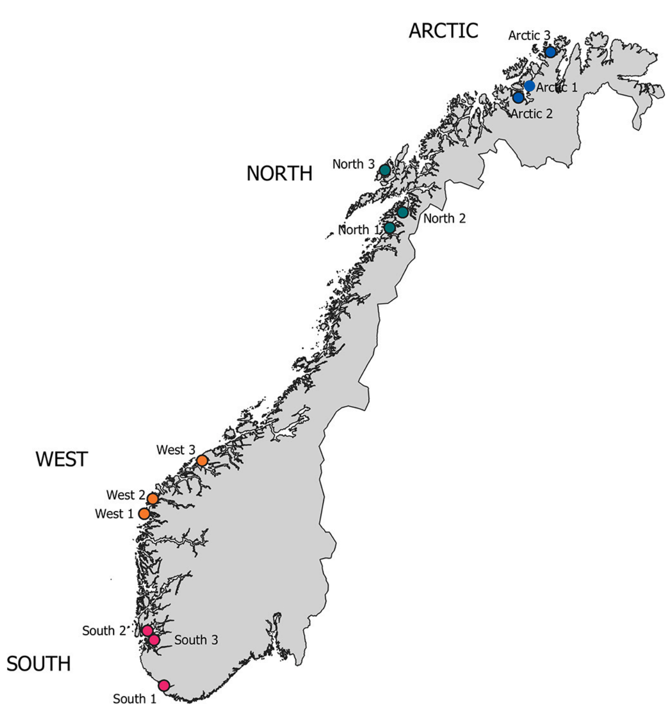

Fig. 1. Locations of the aquaculture sites (represented by circles) used for the temperature projections. The colours are only used for visualization purposes, showing the three farms in each area. South (pink), West (orange) North (green), Arctic (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

there are aspects of the TRLs that are not directly relevant to development of biological products where live animals are used, such as commercial aquaculture species. Therefore, the description of the different stages of the ARL® were changed to represent an idealised pathway to commercial farming of a species. The ARL® has been registered as a trademark in Norway (reg. nr. 330221, https://tidende.patentstyret.no/varemerke) to help increase awareness and recognition of the steps required for species diversification under climate change, and to encourage further use of this approach.

The ARL® are broadly grouped into three categories. ARL® 1–3 cover 'Research' and include levels that focus on the generation of the fundamental knowledge of biology and requirements of the species. ARL® 4–6 cover 'Development' and include levels where there is more focus on the farming technology and production environment. ARL® 7–9 cover 'Commercialisation' and include the levels where there is a greater focus on the economy, market and upscaling production beyond individual pilot or demonstration sites. ARL® 9 describes species that are successfully farmed under commercial, large-scale conditions, with a product that has been delivered to market. For development of products from live animals or plants, the situation is different, as bringing the product to market is not enough. There is a need to consider long-term prospects beyond initial commercialisation, including changing production settings according to the species' needs, as well as adapting to different or variable environmental conditions. Under climate change, these considerations are likely to impact production to a greater extent. To sustain production under climate change, we therefore introduced an additional level to the ARL® system, termed the 'Adaptation' level, ARL® 10. ARL® 10 describes production that has reached a level with sufficient resources and knowledge that facilitates possibilities and flexibility to develop resilience and adapt to challenging conditions. ARL® 10 aligns with the Climate Action terminology used by the United Nations (UN) Sustainable Development Goal (SDG) 13 (UN, 2023), covering strategies that address adaptation and mitigation, to ensure responsible aquaculture production and reduced emissions. ARL® 10 is a level that demands significant efforts, investments, and innovations, delivered at the speed and scale required to ensure that the industry can contribute effectively to the objectives of the Paris Agreement and limit the mean global temperature rise since pre-industrial levels to far below 2 °C, preferably below 1.5 °C (Rogelj et al., 2016), as well as adapt to inevitable changes (Falconer et al., 2022).

The present-day (Year 2023) ARL® of each species for Norway was determined based on production volumes, value and number of licences (Norwegian Directorate Of Fisheries, 2023), as well as research papers, industry news and expert opinions.

2.4. Temperature analysis

To allow comparisons between species, the daily temperatures at the farm sites in the three climate scenarios were reclassified to a common index using fuzzy sets based on known temperature tolerances and, where available, preferred temperatures for aquaculture. Fuzzy sets are a way of reclassifying values into a continuum, where the original values are assigned a new value between 0 and 1 based on membership functions (Zadeh, 1965). Fuzzy sets are an alternative approach to using hard boundaries, e.g. Boolean (true/false) or crisp/distinct groups (e.g. group 1, group 2, group 3, group 4 etc). Due to the uncertainties associated with identifying the exact temperature values at which species would experience challenges, fuzzy sets were considered more appropriate than use of hard boundaries as this allowed gradual membership between 0 (lower and upper limits of temperature) and 1 (preferred temperatures). The trapezoidal membership function (Xiao et al., 2012) was used (Eq. (1)), and the output was named the Challenging Conditions Index (CCI).

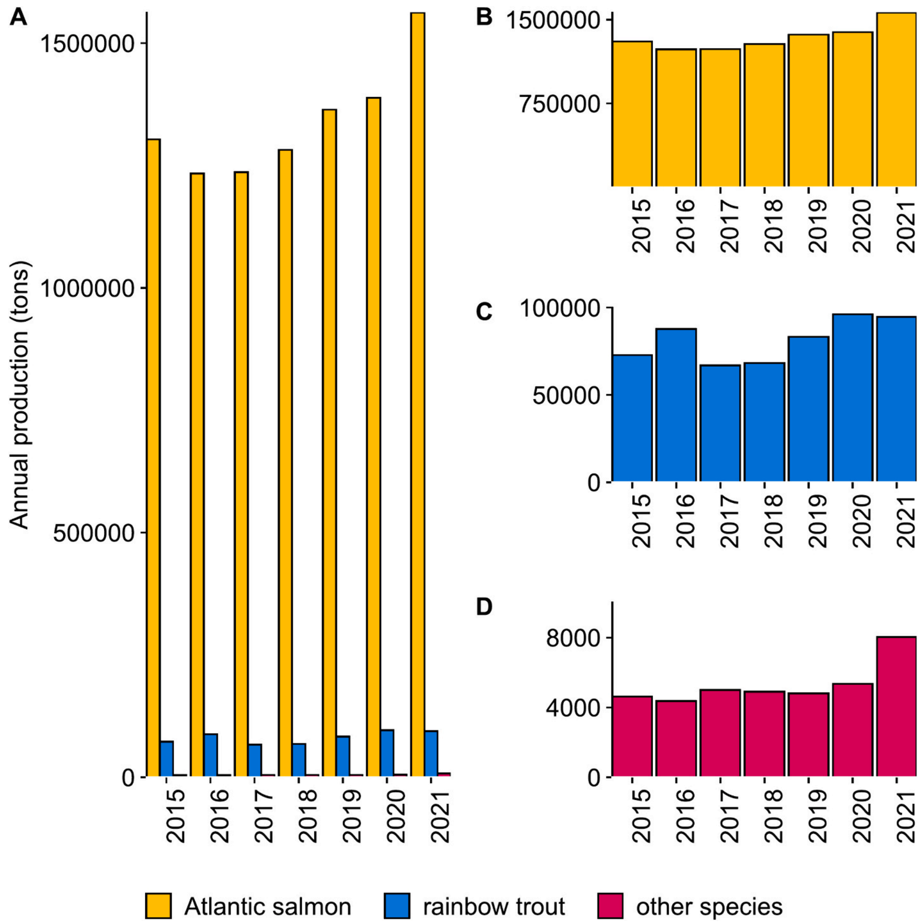

Fig. 2. Total annual aquaculture production in Norway (2015–2021). Data from the Norwegian Directorate of Fisheries (2023). A) shows all of the species in the one plot, and then separate plots for each species, with individual y axes are given in B) Atlantic salmon, C) rainbow trout, C) other species.

$$CCI = \begin{cases} 0, & x < a \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \dfrac{d-x}{d-c}, & c \le x \le d \\ 0, & x > d \end{cases} \tag{1}$$

Where x is the daily temperature, 'a' and 'd' are the lower and upper bounds of sub-optimal temperature range and 'b' and 'c' are the lower and upper bounds of the preferred temperature range for each species. Values for a, b, c, and d were obtained from literature for each species. For species that are already cultured commercially (in Norway or elsewhere) the values of a, b, c, and d represent different aspects of aquaculture rather than just survivability. In contrast, values for potential aquaculture candidate species that are not cultured at present were based on information from studies on wild populations, natural distributions, or capture fisheries. Identification of appropriate values was difficult as species may have different thermal tolerance ranges based on their developmental stage and life stage, e.g. adults and embryos may have narrower ranges than larvae and nonreproductive adults and are thus more vulnerable to warmer conditions (Dahlke et al., 2020), and this may differ from species to species. Likewise, for self-recruiting species (e.g. mussels, (South et al., 2022)), temperature could influence seed availability and viability. Whilst it is acknowledged that there are different temperature considerations throughout the life cycle of each species, only the main grow-out stages were considered in this study. Further details on each species are provided in the Supporting Information.

Daily temperatures for each farm, each scenario, and each year were reclassified to the corresponding CCI value for the 34 selected species for this study using R version 4.1.2 (R Core Team, 2021). Given the vast number of results this generated, it was necessary to use common thresholds to facilitate interpretation and enable comparison between the species, areas, scenarios, and years. Identification of appropriate thresholds for each species is complicated due to huge knowledge gaps (see supplementary material), and the CCI approach was therefore established. A high CCI value indicates that the temperature is closer to the preferred range, whilst a low CCI value is closer to the lower or upper limits. However, additional stressors (e.g. storms, reduced oxygen, acidification, production related stress, diseases etc) will also change the lower and upper temperature limits at which negative impacts occur (Gianguzza et al., 2014). Therefore, the thresholds at which challenging conditions occur will be different depending on the context. For the present study, three thresholds were used: CCI-LT (Low Threshold), CCI-MT (Medium Threshold) and CCI-HT (High Threshold) (Fig. 3, Table 3).

3. Results

3.1. Calibrated temperature projections

The annual mean projected temperatures for each farm are shown in Fig. 4A. Projected temperatures under SSP1–2.6 are relatively stable for the early decades before a more noticeable decrease after approximately 2060. Under SSP2–4.5 the projected temperatures increase until 2060 before decreasing. Projected temperatures under SSP5–8.5 increase over the period with an accelerated increase in later decades. Rates of change

Table 1
Species used in the study.

Group	Species: Common name	Species: Latin name	Reason for inclusion in the study*
Fish	Atlantic salmon	*Salmo salar*	A
	Atlantic halibut	*Hippoglossus hippoglossus*	A, B
	Turbot	*Scophthalmus maximus*	A, B
	Rainbow trout	*Oncorhynchus mykiss*	A
	Atlantic cod	*Gadus morhua*	A, B
	European seabass	*Dicentrarchus labrax*	B
	European hake	*Merluccius merluccius*	B
	Monkfish	*Lophius piscatorius*	B
	Spotted wolffish	*Anarhichas minor*	A, B
	European plaice	*Pleuronectes platessa*	B
	Common sole	*Solea solea*	B
	Gilthead seabream	*Sparus aurata*	B
	Lemon sole	*Microstomus kitt*	B
	Witch flounder	*Glyptocephalus cynoglossus*	B
	John Dory	*Zeus faber*	B
	Pollock	*Pollachius pollachius*	C
	Haddock	*Melanogrammus aeglefinus*	C
Molluscs	European oyster	*Ostrea edulis*	A, B
	Pacific oyster	*Crassostrea gigas*	C
	Scallop	*Pecten maximus*	A, B
	Blue mussels	*Mytilus edulis*	A, B
	European abalone	*Haliotis tuberculata*	C
	Manila clam	*Ruditapes philippinarum*	C
Crustaceans	European lobster	*Homarus gammarus*	A, B
	Norway lobster/ langoustine	*Nephrops norvegicus*	C
	Norwegian shrimp	*Pandalus borealis*	C
	Red king crab	*Paralithodes camtschaticus*	C
	Snow crab	*Chionoecetes opilio*	C
Echinoderm	Green sea urchin	*Strongylocentrotus droebachiensis*	A, B
	Red sea cucumber	*Parastichopus tremulus*	B
Tunicates	Sea vase	*Ciona intestinalis*	B
Seaweed	Sugar kelp	*Saccharina latissima*	A, B
	Dulse/red algae	*Palmaria palmata*	B
	Winged kelp	*Alaria esculenta*	A, B

* A - Already farmed in Norway/already present in Norwegian aquaculture, B – Included in the Akvaplan-niva report, C – Other reason - could be a commercially valuable species, successfully cultured in other countries, would be an alternative to capture fisheries, or thought to have other useful production characteristics. For more information on aquaculture status in Norway see supplementary file.

are not constant, and variability is seen between years and within years, as highlighted in Fig. 4B, due to the natural variability embedded in the system. Some years are thus projected to be warmer than others, and there are differences when the highest and lowest modelled temperatures occur each year. Note that the climate projections include short- and long-term natural variability, which may conceal the expected anthropogenic increase in temperature in periods.

3.2. Aquaculture readiness levels (ARL®)

The ARL® for the selected species based on their status in Norway are given in Table 4. See the supplementary material for further details on the rationale behind the ARL® for each species. For fish species, seven were at the research stage, four at the development stage and six at the commercialisation stage. For other species, six were at the research stage, six at the development stage and five at the commercialisation stage. Atlantic salmon is not one of the species included in the Norwegian diversification strategy, since it is the dominating farmed species, but it was included in this work for comparison as mentioned before.

There were five species that were considered to be at ARL® 1 (monkfish, witch flounder, John Dory, Norwegian lobster/langoustine and Norwegian shrimp), as these species have very limited information on their biological preferences and many unknowns about aquaculture potential, though they are all species caught through capture fisheries and sold on the market. The other species in the Research stages (ARL® 2 and ARL® 3) have some more research into their biology and potential desirable aquaculture traits, e.g., European plaice. Some of the species are new species for aquaculture in Norway (e.g., European seabass and gilthead seabream) but are commercially farmed in other countries, therefore some knowledge, particularly knowledge of biological significance from the Research levels, can be transferred to Norway and were therefore considered to be in the Development levels. However, pollock was an exception and considered ARL® 2, despite some reports that it was farmed commercially by one company in the early 2000's, because it was not apparent if this species was still farmed commercially and if the knowledge would be available to be transferred. Some species in the Development stage have been sold commercially, but production levels are unstable and there are challenges in achieving standardized cost-effective farming systems, e.g., scallop.

Some species were more difficult to assign to ARL® than others, particularly species where there is capture-based production and wild caught juveniles are raised in an aquaculture environment to enhance qualities, e.g., green sea urchin (*Strongylocentrotus droebachiensis*) for roe enhancement. Reliance on wild-caught juveniles could be a limiting factor that affects some species, particularly if there is an unpredictable or unsustainable supply from natural sources. Another important consideration is the intended use of the aquaculture species. Some species may be grown for restocking purposes (e.g., lobsters and red sea cucumbers) and they may not be grown to full adult stage in a sea-based aquaculture setting. Since these species may move towards the Commercialisation stage without full understanding of basic biological principles and closing of the life cycle, the producers may have to revisit earlier ARL® at later stages in order to solve complex challenges in production, i.e., disease development, nutritional demands etc. For example, lobsters were considered to be ARL® 7, as they have been used for restocking purposes and there is one commercial land-based lobster farm. However, if the species is grown to market size in the sea-based containers, then there may be a need to revise the ARL® to fully exploit and commercialize production. Furthermore, it is also important to recognize that some species may go through 'boom and bust' cycles, like Atlantic cod, and the ARL® can be revised if necessary. None of the species were considered to be at ARL® 10 at present.

3.3. Challenging condition index

Fig. 5 shows the values of CCI for each species under their cold and hot temperature limits. The temperature ranges for each species varied considerably. For fish species, European seabass had the largest temperature range between a and d (16 °C), whilst turbot had the smallest (5 °C). For the other species, Pacific oyster had the largest range (25 °C) and snow crab had the smallest (10 °C). There are differences of several degrees between the different CCI values for species with large temperature ranges between a and b, or c and d (e.g. rainbow trout), meaning that choice of threshold will have important consequences for any interpretation of results.

3.3.1. Decadal averages

The analysis generated vast amounts of results, as there were daily temperature values across 80 years for 34 species, 3 climate scenarios, 4 areas with 3 farms each, and then further reclassified into the three different CCIs for the cold and hot conditions. For initial assessment purposes, decadal averages were produced. Fig. 6 shows the average number of challenging days for fish across all farms in each area for each decade, based on CCI-MT, whilst Fig. 7 shows the same for the other species. Some general trends can be observed across all species. The

Table 2
Aquaculture Readiness Levels (ARL®) adapted from Technological Readiness Levels (TRL) (European Commission, 2014; NASA, 2021).

Stage	ARL®	NASA TRL	EU TRL	Aquaculture readiness levels (ARL®)
Research	**1**	Basic principles observed and reported	Basic principles observed	Basic biology observed from wild/fisheries observations, but with many knowledge gaps and uncertainty about aquaculture potential.
	2	Technology concept and/or application formulated	Technology concept formulated	Basic biology understood and species considered potential aquaculture species with characteristics thought to be favourable for farming and an expected market demand for the product.
	3	Analytical and experimental critical function and/or characteristic proof-of concept	Experimental proof of concept	The requirements of the species under aquaculture conditions are understood and there is experimental evidence that the species can be cultured.
Development	**4**	Component and/or breadboard validation in laboratory environment	Technology validated in lab	Testing of aquaculture production technology and husbandry practices for the species
	5	Component and/or breadboard validation in relevant environment	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)	Trials to harvest size and requirements in terms of production technology and husbandry practices in intended environment
	6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)	Species can grow to harvest size in production technology in the intended location, in a cost-effective time frame. Standardisation of production protocols.
Commercialisation	**7**	System prototype demonstration in a space environment	System prototype demonstration in operational environment	Species successfully farmed in prototype rearing system. Refined production protocols. Pilot product quality test.
	8	Actual system completed and "flight qualified" through test and demonstration (ground or space)	System complete and qualified	Species successfully farmed in rearing system at commercially relevant scale at a small number of farms and production is being upscaled to industrialised level.
	9	Actual system "flight proven" through successful mission operations	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)	Species successfully farmed under commercial conditions and product delivered to market, there are companies that produce it at a large scale.
Adaptation	**10**	n/a	n/a	Production has reached a level with sufficient resources and knowledge that facilitates possibilities to develop resilience, flexibility and adapt to challenging conditions, meaning they have reached climate action centred farming.

number of challenging days varies considerably between areas, particularly between the South and the Arctic, which is to be expected given the different temperature profiles (as seen in Fig. 4). As the decades progress towards the mid and end of the century the differences between the climate scenarios also become more apparent. For example, in the Arctic, in 2020–2030, approximately 100–108 days are estimated to be challenging (hot) for witch flounder for all three scenarios, whereas in 2080–2099, approximately 108 days under SSP1–2.6, and 188 days under SSP5–8.5 are estimated to be challenging (hot).

Decadal averages will miss the actual conditions that the species are exposed to, and it is important not to overinterpret the findings, but they can be used as high-level screening to indicate species diversification potential in each area. For the species with preferences for temperatures $\leq$10 °C (i.e., witch flounder, spotted wolffish, red sea cucumber, Norwegian shrimp, and snow crab), the number of hot challenging days could limit the potential for sea-based farming in the South and West, and perhaps even the North and Arctic, especially with SSP5–8.5. For the species with preferences for temperatures $\geq$18 °C (i.e., gilthead seabream, European seabass, common sole, John Dory, European plaice and European abalone) the results show that increasing temperatures in all areas are unlikely to be challenging with regard to hot temperatures (Fig. 6A, Fig. 7A), but cold temperatures would still be challenging for a large part of the year in most decades (Fig. 6B, Fig. 7B). Even in the South, for the decade and scenario with the lowest number of cold challenging days (2090–2099, SSP1–2.6), CCI-MT still suggests that cold temperatures would be challenging for >50% of the year for European seabass, whilst >60% of the year for European abalone, and over 70% of the year would be challenging for gilthead seabream, common sole, John Dory and European plaice. Thus, cold temperatures would still limit the potential for sea-based farming at 5 m depth of those species in all areas.

3.3.2. Differences between years, scenarios, areas, and farms

The mean number of challenging days (cold and hot with CCI-MT) per year across each area is shown in Fig. 8 for fish species, and Fig. 9 for other species. For all species there are differences in the number of challenging days between years, indicating interannual variation rather than a consistent increase/decrease over time. As highlighted previously, there are differences between the three scenarios (as shown in Fig. 4), resulting in some species having more challenging hot days and fewer challenging (cold) days across the years.

For hot challenging conditions for the fish species (Fig. 8), over the whole time period there were two species (witch flounder, spotted wolffish) where the mean number of hot challenging days was $\geq$200 days for at least one year in any area and any scenario. Witch flounder had $\geq$200 hot challenging days in the South (ranging from 75 to 80 years depending on the scenario) and West (ranging from 49 to 73 years depending on the scenario), with some years in both areas having $\geq$300 hot challenging days. Witch flounder also had $\geq$200 hot challenging days in the North (ranging from one to 17 years depending on the scenario) and Arctic (ranging from zero to two years depending on the scenario). Spotted wolffish had $\geq$200 hot challenging days in the South (ranging from 29 to 66 years depending on the scenario) and West (ranging from six to 32 years depending on the scenario). Some fish species such as gilthead seabream and European seabass had no hot challenging days.

For cold challenging conditions for the fish species (Fig. 8), over the whole period there were 9 species (gilthead seabream, European seabass, John Dory, turbot, common sole, European plaice, European hake, rainbow trout, pollock) where the mean number of cold challenging days was $\geq$300 days for at least one year in any area. Particularly notable and worth highlighting was that in the South, gilthead seabream had $\geq$300 cold challenging days for almost every year and scenario, whilst a large proportion of years also had $\geq$300 cold challenging days

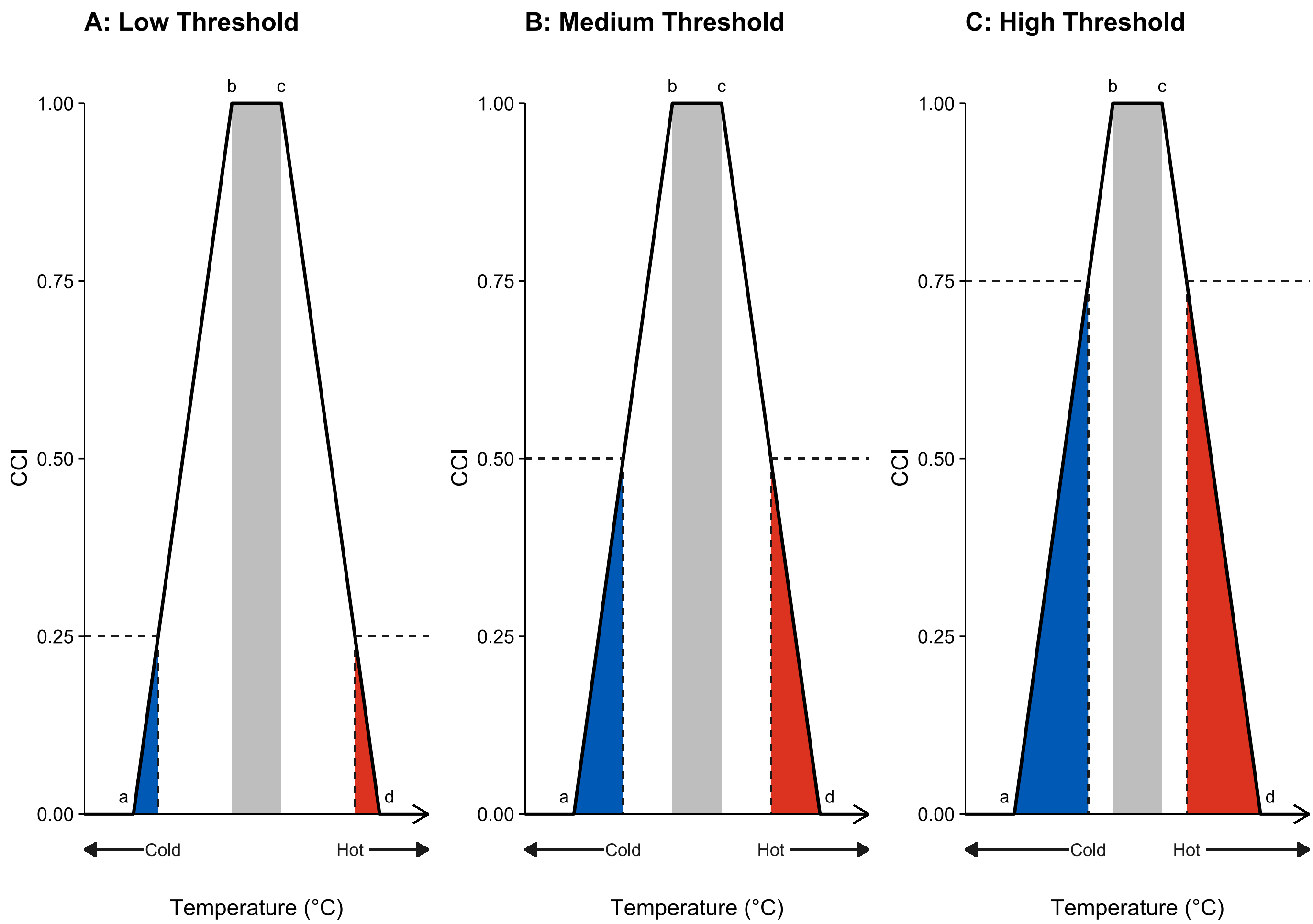

Fig. 3. Schematic illustration of the Challenging Conditions Index (CCI): A) Low Threshold (CCI-LT), B) Medium Threshold (CCI-MT) and C) High Threshold (CCI-HT). See Eq. (1) and Table 3 for further descriptions.

Table 3
Descriptions of the challenging conditions index (CCI).

Threshold	CCI	Biological implications	Management implications
0.25	Low threshold (CCI-LT)	Threshold closest to the lower and upper thermal limits of the species.	Lower flexibility for producers to react, respond and adapt to additional challenges as species near lower/upper temperature limits. This is the least cautious threshold.
0.5	Medium threshold (CCI-MT)	Threshold in the middle of the continuum between the lower/upper limits and preferred temperatures.	Medium flexibility for producers to react, respond and adapt to additional challenges.
0.75	High threshold (CCI-HT)	Threshold closest to the preferred range.	Higher flexibility for producers to react, respond and adapt to additional challenges as species closer to preferred. This is the most cautious threshold.

for European seabass, John Dory, and turbot also (ranging from 37 to 63 years depending on the scenario). Unsurprisingly, these species also had higher numbers of cold challenging days in the other areas, with all four species having ≥300 days for all 80 years in all three scenarios in the North and Arctic.

For hot challenging conditions for the other species (Fig. 9), over the whole period there were two species (Norwegian shrimp, snow crab) where the mean number of hot challenging days was ≥200 cold challenging days for at least one year in any area and any scenario. In the South, almost all years had ≥200 cold challenging days for Norwegian shrimp (ranging from 75 to 80 years depending on the scenario), whilst in the West years with ≥200 cold challenging days for Norwegian shrimp ranged from 49 to 73 years depending on scenario, with fewer years in the North (ranging from one to 17 years depending on scenario) and Arctic (ranging from zero to two years depending on scenario). Snow crab had ≥200 hot challenging days in the South (ranging from 15 to 49 years depending on the scenario) and West (ranging from nine to 48 years depending on the scenario), with some years in both areas having ≥300 hot challenging days.

For cold challenging conditions for the other species (Fig. 9), over the whole period there were 6 species (European abalone, European oyster, Norway lobster, Pacific oyster, European lobster) where the mean number of cold challenging days was ≥300 cold challenging days for at least one year in any area. There were no years with ≥300 cold challenging days for the other species in the south, and with the exception of European abalone, all of the years with ≥300 cold challenging days for the other species were in the Arctic.

For some species, there are clear differences between areas regarding challenging days, highlighting the need to understand how conditions vary between locations. However, it is important to note that area level averages can also be an oversimplification. The variability in the number

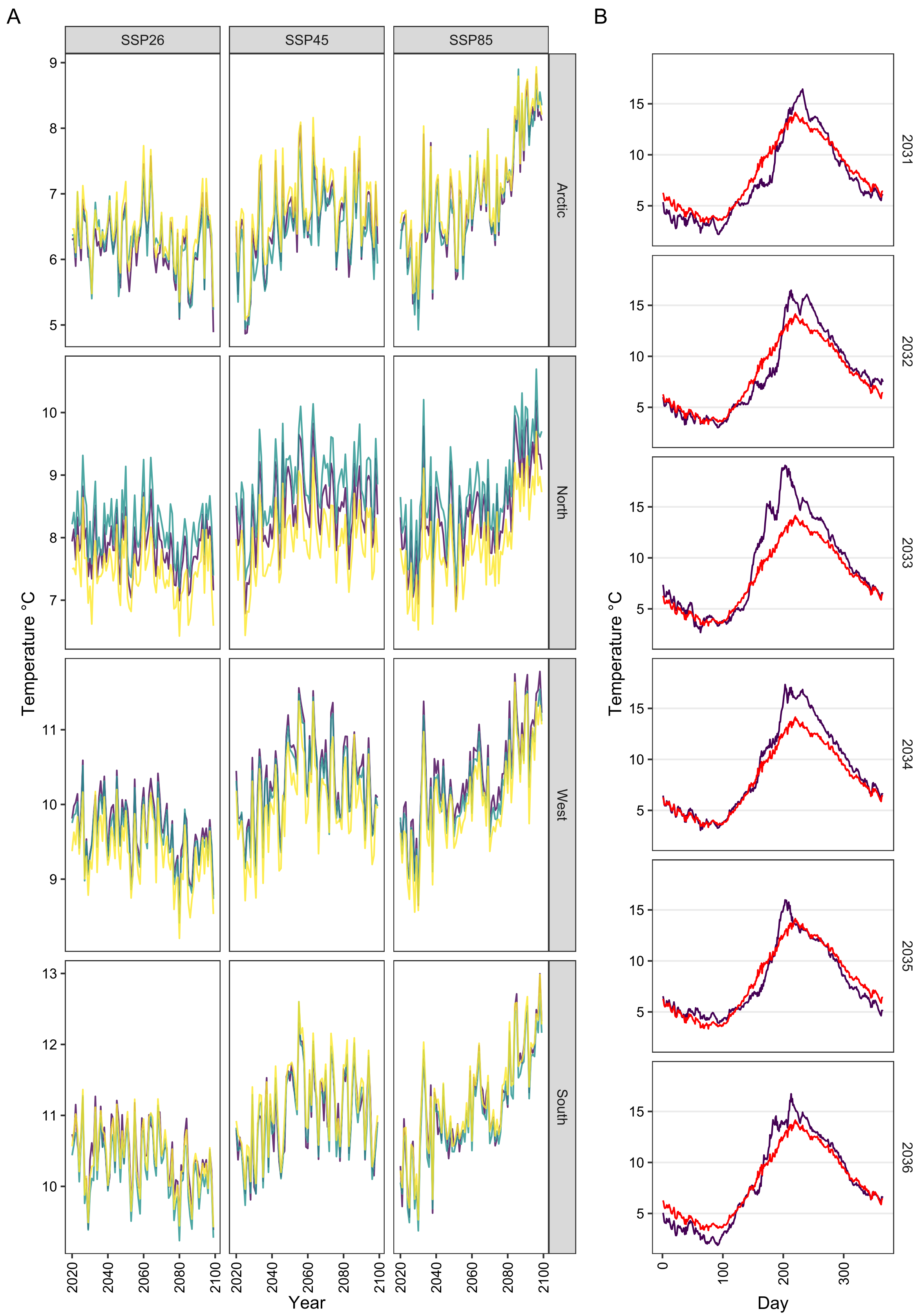

Fig. 4. A) The annual mean calibrated climate model temperature projection for each of the three farms in each of the four regions are represented by three different colours (Dark purple: South 1, West 1, North 1, Arctic 1; Turquoise: South 2, West 2, North 2, Arctic 2; Yellow: South 3, West 3, North 3, Arctic 3). B) The daily temperature at one farm, the red line represents the 5-year mean daily measured temperature (2016–2021) and the dark purple line represents daily calibrated climate model temperatures for Farm 1 in the North (North 1) under SSP2–4.5 individual years from the climate model (2031–2036). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
ARL® for the selected species.

Common name	Latin name	ARL®	Commercial Production
Monkfish	*Lophius piscatorius*	1	NO
Witch flounder	*Glyptocephalus cynoglossus*	1	NO
John Dory	*Zeus faber*	1	NO
Norway lobster/ langoustine	*Nephrops norvegicus*	1	NO
Norwegian shrimp	*Pandalus borealis*	1	NO
European hake	*Merluccius merluccius*	2	NO
Lemon sole	*Microstomus kitt*	2	NO
Pollock	*Pollachius pollachius*	2	NO
Red sea cucumber	*Parastichopus tremulus*	2	NO
Sea vase	*Ciona intestinalis*	2	NO
European plaice	*Pleuronectes platessa*	3	NO
Red king crab	*Paralithodes camtschaticus*	3	NO
Snow crab	*Chionoecetes opilio*	3	NO
European seabass	*Dicentrarchus labrax*	4	NO
Common sole	*Solea solea*	4	NO
Gilthead seabream	*Sparus aurata*	4	NO
Pacific oyster	*Crassostrea gigas*	4	NO
European abalone	*Haliotis tuberculata*	4	NO
Manila clam	*Ruditapes philippinarum*	4	NO
Dulse/red algae	*Palmaria palmata*	4	NO
Scallop	*Pecten maximus*	5	YES
Haddock	*Melanogrammus aeglefinus*	6	NO
Winged kelp	*Alaria esculenta*	6	YES
Spotted wolffish	*Anarhichas minor*	7	YES
European oyster	*Ostrea edulis*	7	YES
European lobster	*Homarus gammarus*	7	YES
Green sea urchin	*Strongylocentrotus droebachiensis*	7	YES
Sugar kelp	*Saccharina latissima*	7	YES
Atlantic halibut	*Hippoglossus hippoglossus*	8	YES
Turbot	*Scophthalmus maximus*	8	YES
Atlantic cod	*Gadus morhua*	8	YES
Blue mussel	*Mytilus edulis*	8	YES
Rainbow trout	*Oncorhynchus mykiss*	9	YES
Atlantic salmon	*Salmo salar*	9	YES

of challenging days between individual farms within an area, is shown with some example species in different areas in Table 5 for hot challenging conditions. The mean number of challenging hot days for 2020–2029 for red sea cucumber (SSP1–2.6) for Farm 1 (88.2 days) and Farm 2 (87.1 days) are almost double that of Farm 3 (49 days). Such differences can have important implications on decisions on where and where not to locate farms, highlighting the need to look at site-specific conditions within an area. Table 5 also further emphasizes the high variability in the number of challenging days per year within decades for individual farms. For example, spotted wolffish in Arctic Farm 2 (SSP2–4.5) ranges from 0 to 134 challenging days (hot) per year in 2030–2039.

3.3.3. Threshold influence

Until now, the results have focused on the CCI-MT, however Fig. 10 shows that the different CCI settings influence the results for an example species, farm, scenario, and period. There is a 1 °C difference between each of the Atlantic salmon CCIs; CCI-LT (Cold) is 5 °C, CCI-MT (Cold) is 6 °C, CCI-HT (Cold) is 7 °C and CCI-LT (Hot) is 17 °C, CCI-MT (Hot) is 16 °C, and CCI-HT (Hot) is 15 °C (as outlined in Fig. 5). The results show that this difference in thresholds, affects the number of challenging days. For example, in 2028 CCI-LT indicates no challenging days either hot or cold, but CCI-MT suggests 7 days would be challenging due to cold temperatures, and CCI-HT indicates 114 challenging days due to cold conditions. Similarly, in 2033, CCI-LT suggests no challenging days, but CCI-MT indicates 15 days would be challenging due to cold temperatures and 36 days would be challenging due to hot temperatures, whilst CCI-HT indicates 104 days would be challenging due to cold temperatures and 93 days would be challenging due to hot temperatures. It is unsurprising that the different CCIs lead to different numbers of challenging days, but it does highlight that a small change in threshold (in this case one degree) can have important implications.

4. Discussion

Species diversification is one of the main adaptation strategies in aquaculture, suggested to make the sector more robust to impacts from climate change (Metian et al., 2020; Cai et al., 2023). However, species diversification is a long-term strategy, with a lot of different considerations (Harvey et al., 2017), including choice of species and site selection. Consequently, there is a need to understand how climate change is affecting farm locations and what the short, medium, and long-term conditions might be. In this study, analysis of future temperature projections over the 21st Century under three different climate scenarios has revealed several important considerations for marine species diversification in Norwegian aquaculture. Although this study has focused on marine aquaculture in Norway, the findings can also inform studies and discussions on species diversification in other countries.

4.1. Aquaculture readiness levels (ARL®)

It takes time to domesticate and commercialize new species, therefore as an indicator of current farming status, this study introduced the ARL®. In an ideal world, ARL® would be sequential and knowledge accumulated before progressing to the next stage. However, in reality some steps may be skipped or rushed for different reasons including lack of investment, overwhelming market demand, and successful early trials. Taking a fast track to market may seem an attractive option, especially since domestication of an aquaculture species is complicated with many uncertainties (Teletchea, 2021), but skipping steps may make that sector less flexible and more vulnerable to shocks, as the foundational knowledge and experience may be lacking.

The results of this study show that many species are likely to experience variable numbers of challenging days between years and farms. Consequently, for any species, established or emerging, it is important to ensure that sufficient resources are in place for each stage to obtain the necessary knowledge, skills, technology, and infrastructure. However, this may be easier said than done. As with the TRLs (Mankins, 2009), the financial costs and resources involved in achieving each ARL® stage will be highly variable depending on the species. It may not be possible for some species to be commercially cultured, particularly those species at very low ARL® or those that are more capture-based aquaculture at present without a reliable source of juveniles. Some species may require high investments in early stages, whereas others may be able to transfer knowledge from other farmed species or systems. However, as already experienced with the crash of the Atlantic cod aquaculture industry (Puvanendran et al., 2022), bringing a farmed species to commercial market is not an indicator of how well that species will perform in the long-term. Climate change will bring further uncertainties and new challenges on top of current concerns throughout production stages and the wider supply chain (Falconer et al., 2022).

Adaptation to climate change will need knowledge, experience, and innovation. To better describe resilience of commercially farmed species, we included a level termed Adaptation (ARL® 10). ARL® 10 is the Climate Action stage, and this demands strategies that make climate adaptation and mitigation strategies central to all decisions. Climate change should be considered at each ARL® stage, but what sets ARL® 10 apart from the others is that it is a deliberate scaling up of efforts to address the climate emergency by taking action against climate change and its impacts, aligning with Sustainable Development Goal 13, Climate Action (UN, 2023). It is important to note that developing adaptation and mitigation strategies will be a continual process as new challenges will emerge over time and existing problems may amplify, especially under emerging climate change. At present, none of the species are at ARL10, but any species, developing or established, should have ARL® 10 as an overarching goal. Atlantic salmon is closest to ARL®

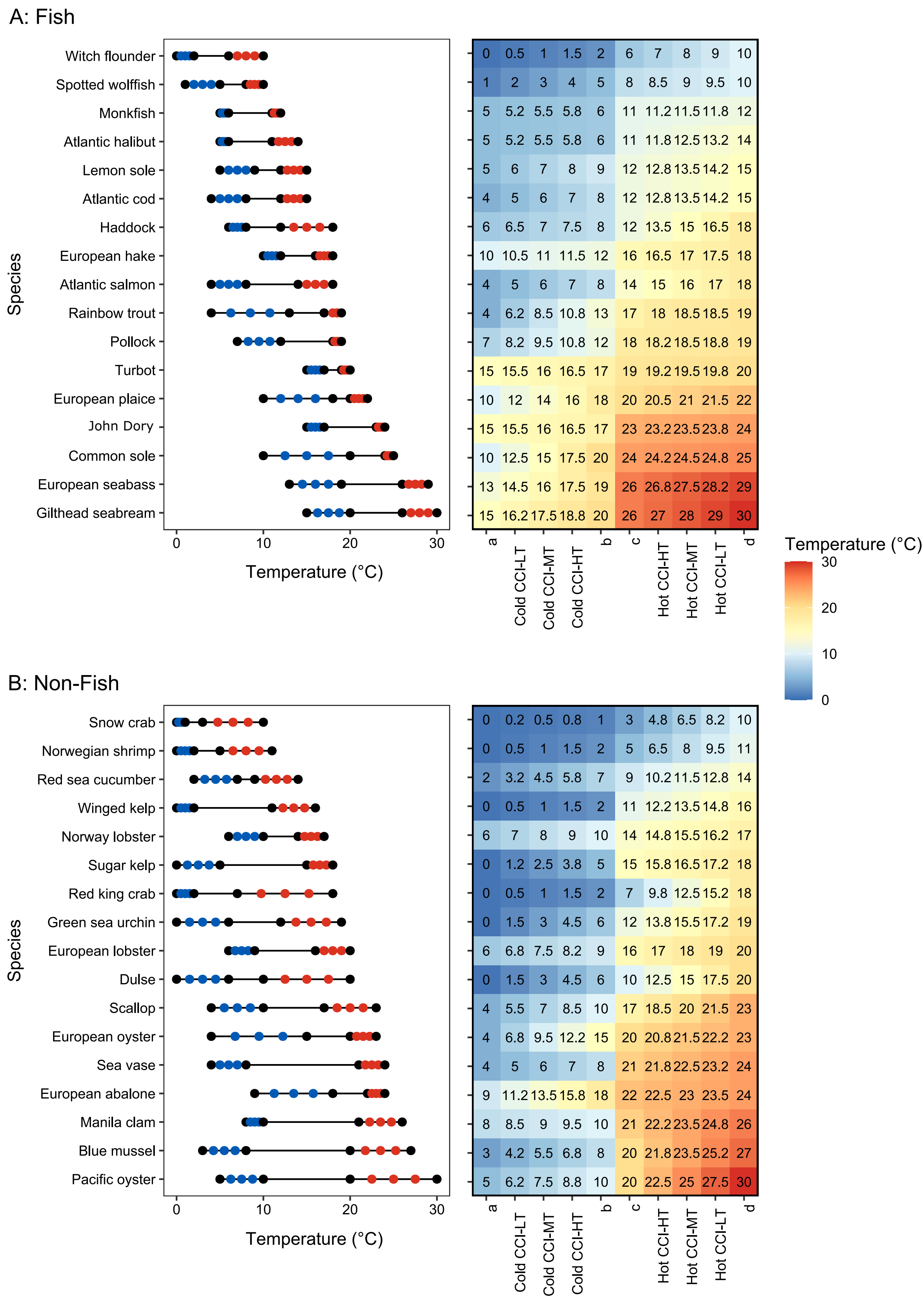

Fig. 5. Species-specific temperature tolerance values (a, b, c, and d from Eq. (1)) using different thresholds (low, moderate, and high resilience) from the challenging condition index (CCI). Species are organized by temperature tolerance based on value for d. The panels on the left show the temperature ranges covered by a, b, c, and d and the different CCI values, (colours refer to Fig. 3). The panels on the right show the values of a, b, c and d, and the different CCIs (colour scale for the tiles represents the coldest temperature in blue to the highest temperature in red, across all of the fish and non-fish species). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

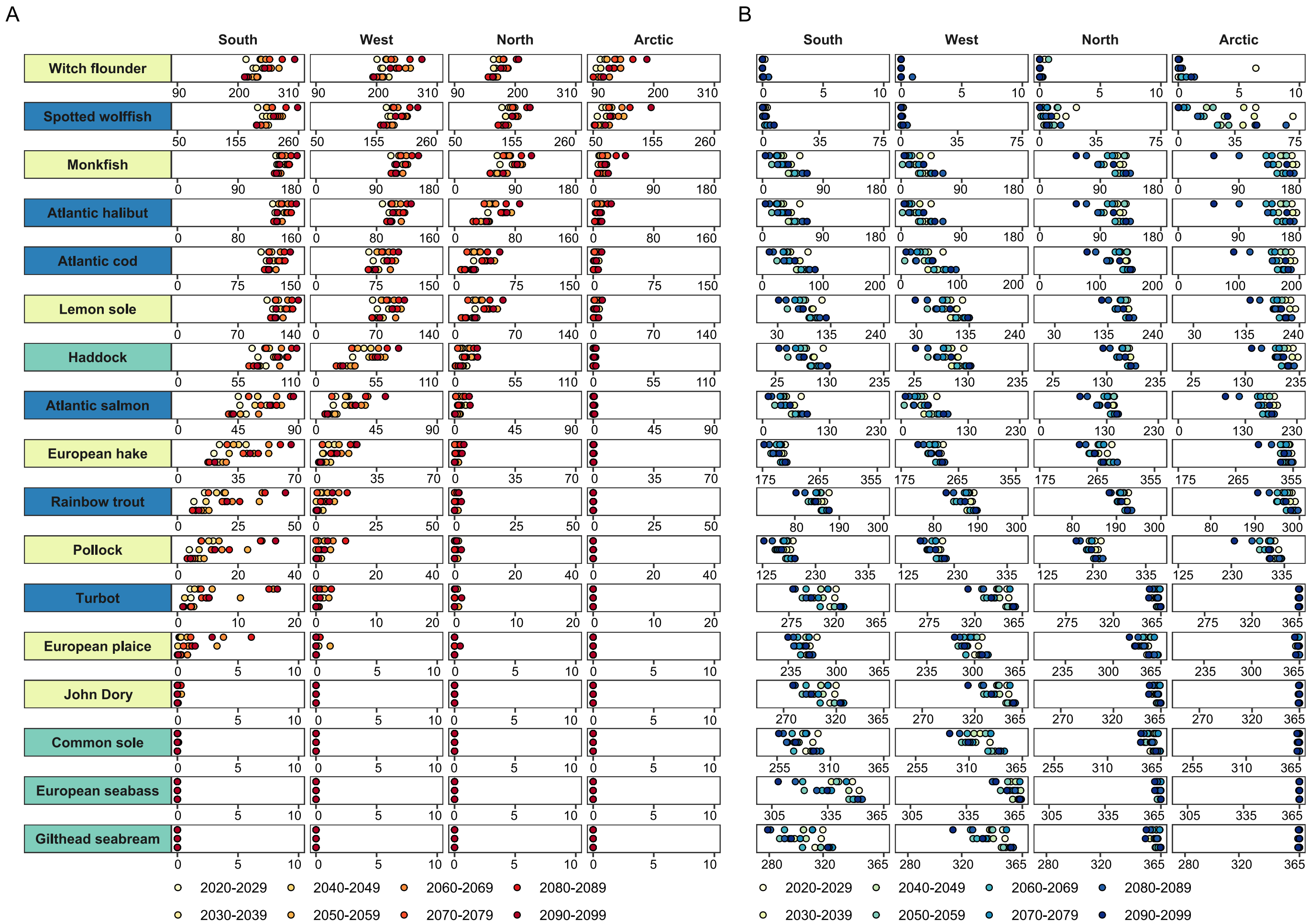

Fig. 6. Decadal average of the annual number of challenging days (using the CCI-MT) for the fish species across all farms in each area for A) Higher temperatures and B) Lower temperatures. In each panel the three rows represent the three different scenarios: SSP1–2.6 (bottom row of points in each panel), SSP2–4.5 (middle row of points in each panel), SSP5–8.5 (upper row of points in each panel). The x axis indicates number of challenging days, and Each panel has a different scale for visualization purposes. The order of the species is the same in A and B. The background colour for the species name represents the ARL® for Norway (see Table 2): Yellow (Research), Green (Development), Blue (Commercialisation). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

10, but was given an ARL® 9 since there are still too many knowledge gaps linked to identification of site-specific impact from climate change and biological thresholds (Falconer et al., 2022) as well as a lack of climate action driven production at present. Emerging focus putting climate action in the centre, including climate change impact and adaptation solutions and reduction of greenhouse gas emissions, may eventually bring salmon aquaculture to ARL® 10. Implementation of strategies to reach ARL® 10 should be the focus in all previous levels when developing species for aquaculture purpose.

4.2. *Species diversification in Norway*

The findings of this study show that there can be considerable differences in number of days that could be considered challenging conditions, particularly in later decades between the scenarios. This uncertainty is a challenge when developing species diversification strategies. Use of multiple climate scenarios is useful in that regard, as decisions on species diversification need to consider the range of potential futures the sector could experience. Use of scenarios also shows what can happen if strict climate mitigation policies are implemented making the future look more like SSP1–2.6 or SSP2–4.5, rather than SSP5–8.5. This information is not only useful for the aquaculture industry, but also the politicians and policymakers that are responsible for setting emission reduction targets.

The results highlight interannual variations in the number of days with challenging conditions. Although climate models do not predict specific years, the variability is an indication of what could be expected and it is useful to know if sites will tend to remain within preferred temperature ranges, or if there will be more fluctuations with challenging conditions. An understanding of the potential range of temperatures at aquaculture sites over multiple years is important as some species are grown over several years, and the optimal temperatures for growth decrease with increasing fish size for species like spotted wolffish, Atlantic cod and Atlantic halibut (Björnsson and Tryggvadóttir, 1996; Björnsson et al., 2007; Foss et al., 2004).

Changing temperature profiles may also influence husbandry practices such as stocking time, or preventative treatment plans (Hernández et al., 2007; Overton et al., 2019). Temperature profiles may further change the water quality conditions and impact the microbial communities in the surroundings (Cavicchioli et al., 2019). Since the farmed species microbiota, immune system and affinity to catch diseases are also affected by these parameters (Sánchez-Cueto et al., 2023; Zanuzzo et al., 2020; Ytteborg et al., 2023), these are compounding factors. This confirms the need to consider the range of temperatures, as well as the total burden of changed parameters and stress that the species will be exposed, rather than just focusing on optimal conditions. Moreover, there are differences in how species respond to cold and hot temperatures (Schou et al., 2022). Cold temperatures may reduce growth rates,

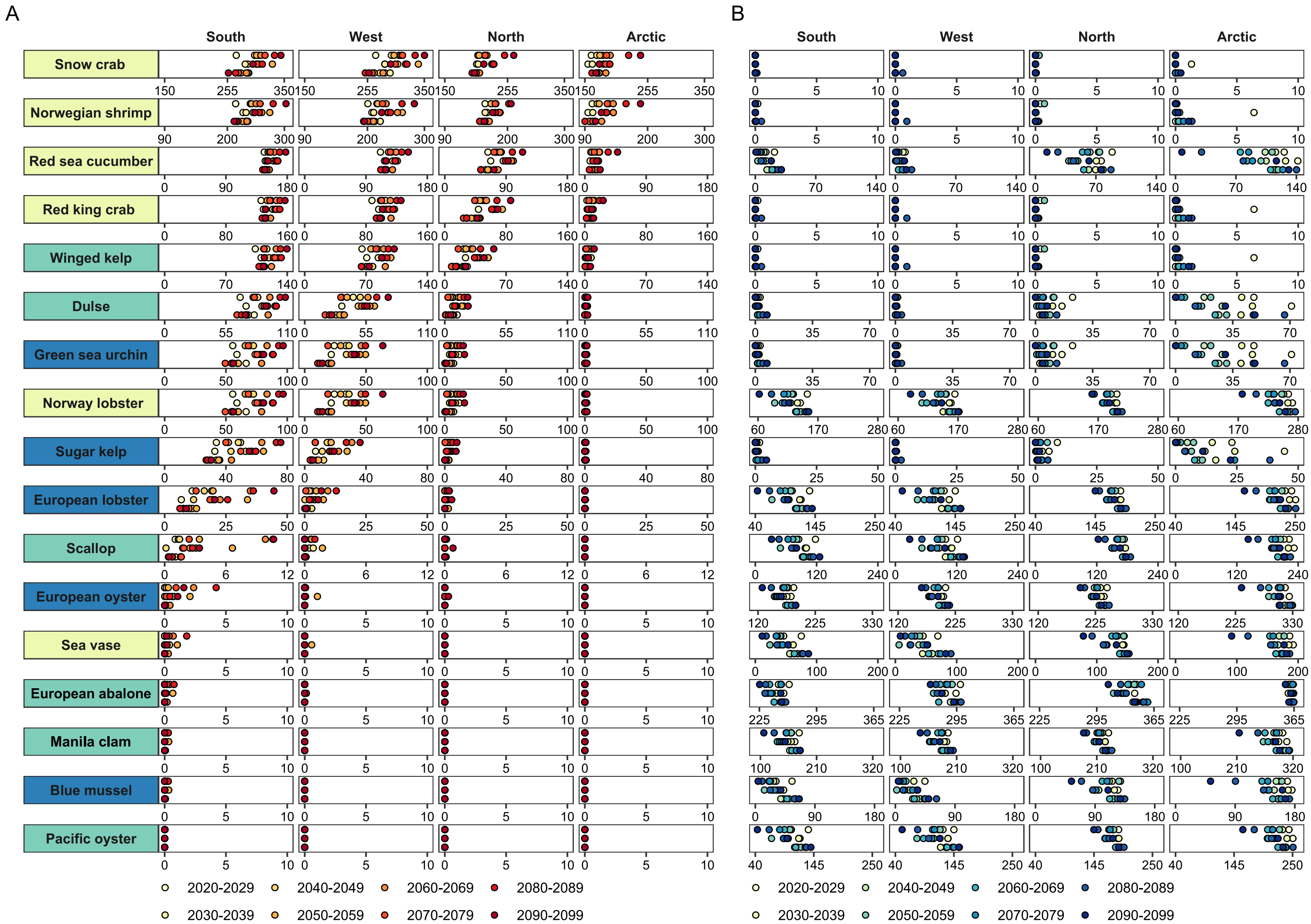

Fig. 7. Decadal average of the annual number of challenging days (using the CCI-MT) for the other species across all farms in each area for A) Higher temperatures and B) Lower temperatures. In each panel the three rows represent the three different scenarios: SSP1–2.6 (bottom row of points in each panel), SSP2–4.5 (middle row of points in each panel), SSP5–8.5 (upper row of points in each panel). The x axis indicates number of challenging days, and Each panel has a different scale for visualization purposes. The order of the species is the same in A and B. The background colour for the species name represents the ARL® for Norway (see Table 2): Yellow (Research), Green (Development), Blue (Commercialisation). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

leading to a longer harvest time, so an understanding of the proportions of the years that are likely to be too hot and too cold is useful from a strategic planning perspective. For example, the results in this study suggest that the challenges due to cold temperatures appear to be a major limiting factor for species such as gilthead seabream, European seabass, John Dory, and European abalone.

The downscaling used in this study is one of the highest resolution climate models available for the entire Norwegian coastline. Use of one realization of three future scenarios regionally downscaled from one climate model is a limitation of this study. Ideally, results would be generated based on two or more regional models forced by at least two Global Climate Models (van der Linden and Mitchell, 2009), however, this is seldom available, as was the case for our study area. Furthermore, it is important to note that climate model outputs may not fully represent the range of conditions that occur at aquaculture farm sites, particularly in coastal areas (Falconer et al., 2020; Falconer et al., 2023). The calibrated temperatures used in this study were more similar to those observed at aquaculture sites but some of the day-to-day variability and extreme temperatures may have been underestimated and there are other uncertainties associated with bias correction (Falconer et al., 2020). Nevertheless, farm-level projections are required to understand the variability between sites and understand potential conditions throughout the production cycle, as many important operational decisions, such as stocking and harvesting, are reliant on an understanding of site-specific environmental conditions at different times of the year (Villanueva et al., 2013). Further research is needed to explore near-coastal temporal variability and how this may change, and what this means for future aquaculture production. There is also an urgent requirement for better in-situ monitoring of important variables such as temperature, with long-term data collection programs to ensure trends and variability can be captured and analysed over time.

This research used temperature projections that represent the conditions approximately at 3–7 m depth and assumed that production would take place in the sea or use the seawater from this depth for production. Some species, particularly those with the higher ARL®, are already grown at these depths in sea-based cages, longlines, baskets, or other forms of sea-based culture system either in Norway or elsewhere. For species with lower ARL®, there may be potential to adapt existing technology, for example lobsters can be raised in sea-based containers (Hinchcliffe et al., 2022), and similar types of containers could be used for other species like Norwegian shrimp. An alternative to sea-based production is land-based or recirculating aquaculture systems (RAS), but there are many challenges with land-based and RAS production, e.g., energy use, social perception, competition for space on land, high costs of production as well as biological challenges for the farmed animals (Badiola et al., 2018; Bjørndal and Tusvik, 2019; Ahmed and Turchini, 2021; Fudge et al., 2023). Submerged aquaculture has also been suggested as a potential route to avoid challenging temperatures in surface

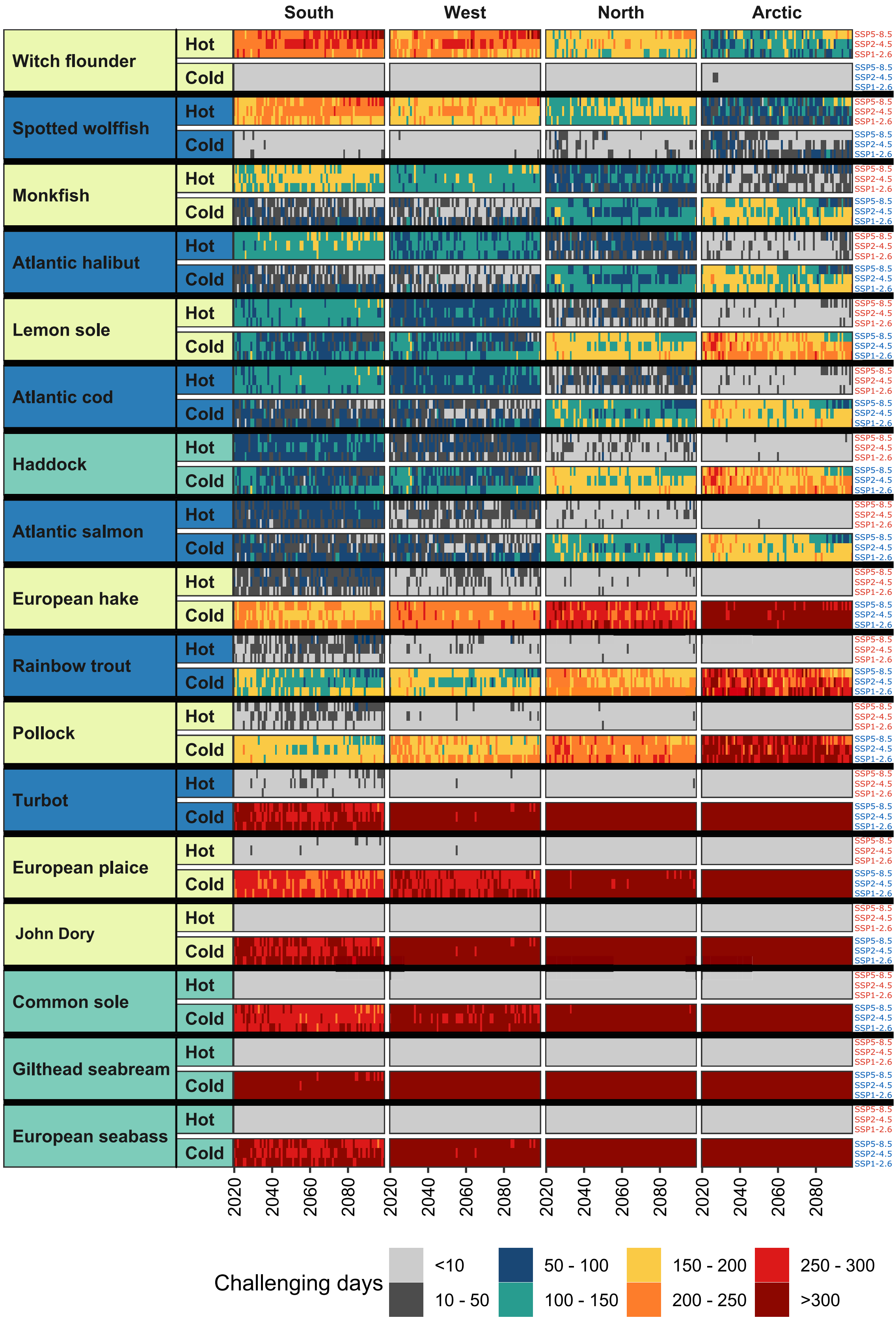

Fig. 8. Mean number of challenging days with moderate resilience (CCI-MT) for cold and hot temperatures for fish species in each area, species (major rows), and scenarios (rows within the hot and cold rows; bottom is SSP1–2.6, middle is SSP2–4.5 and top is SSP5.-4.5). The background colour for each species label indicates the ARL®: yellow (research), green (development) and blue (commercialisation). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

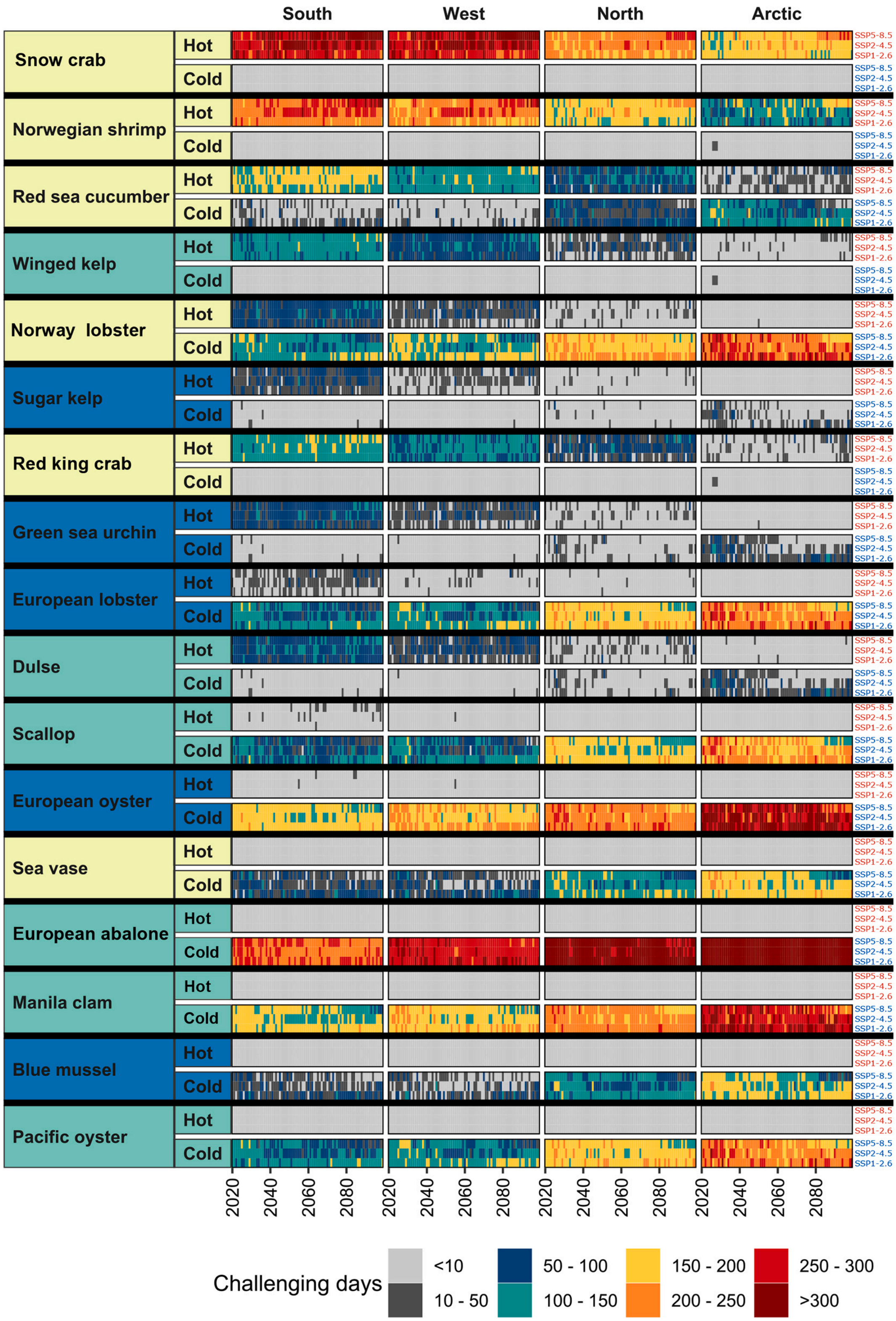

Fig. 9. Mean number of challenging days with moderate resilience (CCI-MT) for cold and hot temperatures for other species in each area, species (major rows), and scenarios (rows within the hot and cold rows; bottom is SSP1–2.6, middle is SSP2–4.5 and top is SSP5.-4.5). The background colour for each species label indicates the ARL®: yellow (research), green (development) and blue (commercialisation). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

waters, but there are few examples of commercial-scale production or trials, and there are many biological, technical, and economic uncertainties associated with submerged production (Sievers et al., 2022). Moreover, the Norwegian coastal waters and fjord systems are very complex, and there is a need for more work on vertical temperature profiles in areas of interest to aquaculture.

Though outside the scope of the present study, it is important to acknowledge that the introduction of new species could negatively

Table 5
Number of mean challenging days in a year per decade and the range is shown in brackets (minimum number of challenging days in a year – highest number of challenging days in a year) for selected species and areas.

Species	Area and Farm	Scenario	Decade							
			2020–2029	2030–2039	2040–2049	2050–2059	2060–2069	2070–2079	2080–2089	2090–2099
Spotted wolffish	Arctic Farm 1	SSP1–2.6	67.1	56.1	67.8	64.4	79.9	57.7	60.5	70.2
			(17–106)	(17–84)	(8–114)	(21–90)	(26–140)	(25–108)	(19–103)	(21–108)
		SSP2–4.5	61.6	75.4	81.5	103.1	92.1	79.6	80.9	79.4
			(10–115)	(36–120)	(33–148)	(56–171)	(36–165)	(49–108)	(17–162)	(33–102)
		SSP5–8.5	68.8	74.9	83.7	79.1	101.7	78	104	145.1
			(20–106)	(9–147)	(54–113)	(12–125)	(71–146)	(18–120)	(84–141)	(117–179)
	Arctic Farm 2	SSP1–2.6	51.4	37.5	57.9	46.3	69.6	34	36.8	65.3
			(0–97)	(0–83)	(0–109)	(0–106)	(0–120)	(1–91)	(0–102)	(0–113)
		SSP2–4.5	40.4	63.6	63	96.1	84.4	81.7	64.6	65
			(0–100)	(0–134)	(3–121)	(48–149)	(29–135)	(23–126)	(0–130)	(0–104)
		SSP5–8.5	54.6	61.6	68.8	75.3	95.9	67.9	124	154.5
			(1–100)	(0–130)	(21–119)	(0–125)	(52–151)	(0–128)	(76–163)	(107–171)
	Arctic Farm 3	SSP1–2.6	73.6	63.8	72.6	67.5	84.5	64.2	62.6	77.9
			(27–102)	(13–108)	(17–121)	(25–99)	(35–135)	(28–107)	(26–99)	(20–117)
		SSP2–4.5	69.4	80.1	96.8	110.4	104.7	88.8	94.2	92.7
			(23–119)	(43–125)	(46–155)	(86–158)	(55–161)	(60–114)	(23–164)	(61–126)
		SSP5–8.5	72.3	79.9	94.6	80.1	102.3	85.6	113.1	151.7
			(29–95)	(15–135)	(62–118)	(16–133)	(63–139)	(30–122)	(76–153)	(115–172)
Red sea cucumber	North Farm 1	SSP1–2.6	88.2	71.7	71.7	73.8	91.3	65	62	83.4
			(68–124)	(0–102)	(1–115)	(25–114)	(59–133)	(1 – 94_	(7–98)	(40–100)
			74	91.6	98.5	103.8	100.9	96.9	95	97.9
		SSP2–4.5	(4–104)	(76–124)	(58–136)	(80–128)	(85–113)	(82–118)	(74–127)	(78–113)
			71.5	85.6	90.8	84.8	90.4	83.5	103.2	115.1
		SSP5–8.5	(35–95)	(35–136)	(63–113)	(33–117)	(67–113)	(56–122)	(72–129)	(75–139)
			87.1	72.8	75.5	80.7	91.8	67.2	65	86.7
		SSP1–2.6	(61–126)	(0–108)	(12–116)	(32–126)	(55–135)	(4–94)	(8–103)	(45–111)
			78.6	96.6	105.4	108.9	108.3	103.9	102.7	101.9
		SSP2–4.5	(22–103)	(74–121)	(64–141)	(90–142)	(87–130)	(87–145)	(76–133)	(83–120)
			73.3	89.4	96.9	86.6	94	85.7	113	125.3
	North Farm 2	SSP5–8.5	(41–101)	(39–150)	(63–122)	(47–127)	(64–117)	(62–117)	(77–144)	(80–165)
			49	35.7	48.7	35.2	51.5	27	31.6	46.1
		SSP1–2.6	(5–112)	(0–86)	(0–119)	(0–86)	(0–97)	(0–55)	(0–89)	(14–74)
			49.6	69.2	80.7	89.3	85.2	74.1	69.9	79.1
		SSP2–4.5	(0–98)	(42–115)	(21–128)	(58–126)	(60–114)	(29–96)	(5–116)	(40–109)
			45.1	57.8	61.2	52.8	59.7	47.6	81.4	102.1
	North Farm 3	SSP5–8.5	(6–73)	(11–128)	(20–91)	(1–105)	(18–102)	(1–118)	(28–128)	(57–136)
			83	80.1	85.6	77.7	101.7	76.4	74.2	81.7
		SSP1–2.6	(51–117)	(23–117)	(57–102)	(53–106)	(78–127)	(33–98)	(23–113)	(60–99)
			76.9	88.5	93.7	103.8	93.2	96.4	100.4	91.6
		SSP2–4.5	(29–112)	(59–120)	(69–112)	(76–125)	(67–111)	(75–117)	(77–116)	(73–110)
			71.3	84.8	89.5	82.8	94	91.2	102.9	108.4
	West Farm 1	SSP5–8.5	(50–89)	(37–113)	(70–104)	(68–95)	(71–107)	(75–101)	(83–139)	(80–137)
			70.6	67.3	72.7	63.9	82.8	53.7	59	64.8
		SSP1–2.6	(37–105)	(11–111)	(36–101)	(45–97	(50–106)	(15–78)	(20–100)	(46–86)
			65.8	78.1	84.1	96.5	86.4	87	93.1	85.2
		SSP2–4.5	(5–97)	(52–103)	(60–101)	(70–119)	(59–109)	(69–112)	(70–110)	(63–108)
			58.8	71.4	79.6	72.5	87.8	75.1	94.8	100.4
	West Farm 2	SSP5–8.5	(41–73)	(33–115)	(53–94)	(53–100)	(66–101)	(57–95)	(69–126)	(65–133)
			76.6	74	74.6	69.6	91.5	66.4	60.9	74.3
		SSP1–2.6	(41–99)	(5–101)	(32–109)	(48–93)	(68–115)	(26–91)	(19–99)	(61–88)
			69.8	85.2	85.9	94.8	86.8	85.3	88	87.3
		SSP2–4.5	(17–93)	(57–121)	(63–101)	(77–116)	(64–101)	(72–104)	(72–110)	(74–106)
			66.2	74.3	81.1	71.2	88.7	78.5	89.1	97.7
Atlantic cod	West Farm 3	SSP5–8.5	(47–87)	(37–109)	(61–109)	(62–87)	(60–108)	(64–96)	(77–107)	(71–125)
			113.1	113.9	109	111.4	119.2	109	109.9	116
		SSP1–2.6	(79–137)	(87–129)	(84–127)	(90–129)	(109–132)	(85–135)	(81–136)	(101–133)
			106.6	115.2	116.2	131.7	123.2	126.2	134.2	114.5
		SSP2–4.5	(81–124)	(81–141)	(89–135)	(110–164)	(101–135)	(107–142)	(116–151)	(94–140)
			103.6	112.8	115.2	112.8	127.2	114.5	132.9	139.3
	South Farm 1	SSP5–8.5	(88–128)	(81–135)	(99–138)	(97–130)	(99–139)	(100–132)	(113–151)	(114–164)
			110.2	108.6	108.5	106.7	119.9	104	102.6	107
		SSP1–2.6	(75–135)	(78–128)	(82–119)	(107–90)	(103–142)	(74–124)	(66–126)	(93–121)
			108.5	110.9	116.1	125.8	120.7	121.5	129.9	109.9
		SSP2–4.5	(76–128)	(87–133)	(85–142)	(110–158)	(98–138)	(111–141)	(111–156)	(88–132)
			97.7	110.6	110.2	106	124.3	107.5	128.8	137.6
	South Farm 2	SSP5–8.5	(74–122)	(81–153)	(94–123)	(88–134)	(97–143)	(96–128)	(106–162)	(100–167)
			119	115.2	119.5	115.3	126.9	117.4	110.9	115.9
		SSP1–2.6	(84–138)	(87–131)	(97–134)	(99–133)	(107–145)	(95–132)	(82–135)	(105–133)
			115.3	117.5	125.4	132.2	128.9	130.2	135.4	117.2
		SSP2–4.5	(79–136)	(87–139)	(100–144)	(117–156)	(116–142)	(117–145)	(124–153)	(94–141)
			109.4	119.5	124.9	120.6	130.8	118.7	135.5	142.2
Winged kelp	South Farm 3	SSP5–8.5	(90–127)	(88–151)	(111–140)	(103–140)	(102–146)	(105–141)	(115–152)	(113–169)

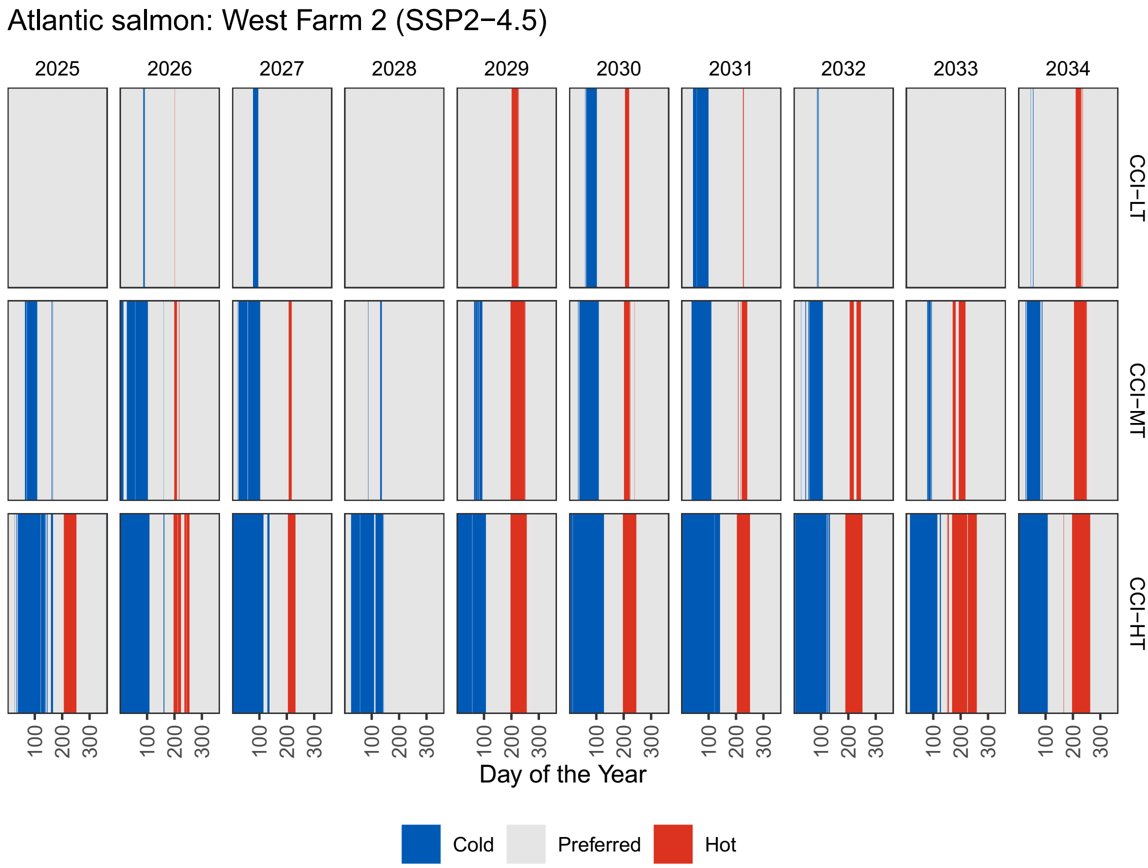

Fig. 10. Daily temperatures for 2025–2034 under SSP2–4.5 reclassified to the three different CCI levels (CCI-LT, CCI-MT and CCI-HT, as shown in Fig. 3) for Atlantic salmon (see thresholds in Fig. 5) for Farm 1 in the West area. Each column represents one year and the rows represent the three CCIs.

impact native species and biodiversity (De Silva et al., 2009). For example, Pacific oyster is considered an invasive species as it was introduced in several European countries as an aquaculture species in the 1960's and then spread rapidly and is replacing native species (Hansen et al., 2023; Martínez-García et al., 2022). If native species are less robust due to warming temperatures, then invasive species may be more suited to settle, leading to changes in ecosystems (Molnar et al., 2008). On the other side, some wild fish stocks are declining, e.g., wolffish is on WWFs list of threatened species (WWF, 2023) and cod catches are reduced (Misund et al., 2016), and aquaculture may be a way to release pressure on wild fish stocks.

This study has deliberately not identified the most suitable candidates for species diversification in Norway. It may be tempting to select the species with the lowest number of challenging days (hot and cold), but species diversification must also consider several other factors, e.g., other climate drivers, biological thresholds, production systems, market potential etc. A range of stakeholders must also be involved in the decisions if species diversification is to be a national strategy. Industry, government, researchers, and policymakers all have roles to play. Therefore, the results from this study should be used to complement discussions on species diversification, alongside other studies such as that produced by Akvaplan-niva (2019).

4.3. Thermal thresholds and the CCI

In agreement with studies in other research areas (Nenzén and Araújo, 2011; Newman et al., 2022), this work has shown that threshold choices strongly influence the results and interpretation of findings. Identification of appropriate temperature ranges and thermal thresholds for each species was a challenge. For some of the species, such as John Dory and monkfish, there was no information on temperature tolerances under aquaculture conditions. For these species, information from wild populations and fisheries studies was used instead. However, as most wild species have the possibility to move away from unfavourable conditions, most temperature studies describe where these animals prefer to live, rather than their critical survivability thresholds that define the temperature tolerance range. Absolute temperature thresholds are difficult to (and likely cannot) be established (Pörtner et al., 2017; Rezende et al., 2014), since there are many factors such as size, developmental stage, and presence or absence of other stressors (Sunday et al., 2019, Zhou et al., 2018). It is also important to recognize that species tolerance range is complicated as there may be ecotypes that have adapted to different temperature conditions. For example, Andersen et al. (2013) reported that the optimal temperature for sugar kelp from southern Norway were found between 10 and 15 °C. However, Forbord et al. (2020) compared a range of sites throughout the country and found that sugar kelp in northern Norway had some of the greatest length and biomass gain, but the temperatures did not exceed 10 °C. Survival at temperatures approaching the lower and upper edges of the tolerance range is also time-dependent, and most species typically tolerate much higher temperatures under acute thermal stress than they do under prolonged conditions, and stable temperatures better than fluctuating temperature (Kır, 2020; Stavrakidis-Zachou et al., 2021b). Therefore, a temperature tolerance range is only an indication of how susceptible species are to thermal changes.

In aquaculture the aim is to optimize production whilst ensuring good health and welfare, rather than just tolerating conditions, so assessing impact of temperature change on aquaculture species needs a different approach to fisheries studies that often use catch-records and species distribution modelling (e.g. Perry et al., 2005; Melo-Merino et al., 2020; Silva et al., 2015). Due to knowledge gaps and uncertainties when it comes to temperature tolerance and stress, we introduced the

CCI. The CCI allowed analysis across the wide range of species used in this study in a comparable way. To support interpretation of the results, three thresholds were included (Low Threshold, Medium Threshold and High Threshold). The range of thresholds were used since multiple stressors and compounding factors might exert additional stress, exacerbating challenging conditions, e.g., deoxygenation, acidification, temperature extremes, changes in salinity, changes in food availability, production procedures and pathogens that may potentially lower the resilience of the species (Gunderson et al., 2016; Sarà et al., 2018; Falconer et al., 2022; Cascarano et al., 2021). The Low Threshold (LT) is nearer the lower/upper thermal limits and the producer has lower flexibility to respond to challenging conditions, especially under multiple stressors like those highlighted, whereas Medium Threshold (MT) and High Threshold (HT) were closer to the preferred range and there may be more flexibility. The values used for a, b, c, and d (species specific thermal thresholds) can be updated as more information becomes available, or producers could perform their own analysis with details on temperature conditions relevant to their production practices. For most of the results, we focused on the CCI-MT, as this was the midway threshold. However, in the example for Atlantic salmon all three CCIs were used and showed that even relatively small differences in thresholds of 1° can lead to considerable differences in the number of challenging days. Using the different CCIs illustrates the importance of more species-specific knowledge on biological limitations and thresholds upon environmental conditions, as well as why results from studies like this should contribute to discussions rather than be used strictly as absolute decisions.

5. Conclusion

The present study is only one part of a complicated jigsaw, and it would be highly misleading to suggest the 'best suited' species based on this work alone. Using climate model projections to examine potential temperatures under different climate scenarios provides an important insight into the range of temperature that coastal aquaculture production areas could experience. This should be included when considering species for diversification. If species diversification is considered a national strategy for the future of Norwegian aquaculture, then there is also a need to consider the ARL®. Any species selected for diversification purposes will have to be able to tolerate a range of temperatures in future years. Those species that have narrower ranges and/or lower adaptive capacity may be more of a risk. Undoubtedly climate change brings uncertainty to the future aquaculture sector, and this means that farming any species will be more difficult, particularly under the higher emissions scenarios (e.g., SSP5–8.5) which will be a considerable departure from conditions experienced now. Trying to develop a long-term sustainable aquaculture sector for the SSP5–8.5 world will be much more difficult than adapting to similar conditions as experienced in the present. Therefore, intensified efforts to counteract or stabilize global warming at 1.5 °C is urgent in a food-production perspective.

CRediT authorship contribution statement

Lynne Falconer: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Lars Olav Sparboe:** Writing – review & editing, Investigation. **Trine Dale:** Writing – review & editing, Investigation. **Solfrid Sætre Hjøllo:** Writing – review & editing, Investigation. **Orestis Stavrakidis-Zachou:** Writing – review & editing, Investigation. **Øivind Bergh:** Writing – review & editing, Investigation. **Philip James:** Writing – review & editing, Investigation. **Nikos Papandroulakis:** Writing – review & editing, Investigation. **Velmurugu Puvanendran:** Writing – review & editing, Investigation. **Sten Ivar Siikavuopio:** Writing – review & editing, Investigation. **Øyvind Johannes Hansen:** Writing – review & editing, Investigation. **Elisabeth Ytteborg:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We thank Joachim Stoss (Sterling White Halibut), Cartron Point Shellfish LTD (New Quay, Burrin, Ireland), Matt Slater (Alfred Wegener Institute, Germany) for their input. We also thank Dr. Robinson Hordoir, Institute of Marine Research for performing the downscaled climate simulations, and the aquaculture companies who provided temperature data. This work was supported by the UK Research and Innovation Future Leaders Fellowship (MR/V021613/1), the Norwegian Research Council (No. 194050, Insight), and ArcticHub (European Unions Horizon 2020 research and innovation programme under grant agreement No 869580).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2024.741350.

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