Projections of Fishery Recovery in Canada

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Summary

This study predicted potential recovery scenarios for 124 depleted and uncertain (conservatively assumed to be depleted) Canadian marine fish and invertebrate stocks tracked by Oceana Canada's annual audit, across six regions and seven major taxonomic groups. We found that positive recovery outcomes resulted under scenarios where there was immediate implementation of rebuilding regulations and management strategies that account for and mitigate the effects of climate change. The number and biomass of healthy stocks that can be expected in five to ten years were found to be influenced by various fishing and climate scenarios, as well as the initial biomass of uncertain stocks as follows:

- The proportion of healthy stocks could potentially increase by 15.4% by 2028, and to nearly half of all populations by 2033 if rebuilding regulations are followed under a high mitigation scenario (SSP1-2.6).
- When fishing is restricted for depleted stocks and there is no assumed risk from climate change, it is estimated that 31.5% to 83.1% of 124 depleted stocks will recover to healthy levels after five years, increasing from 70.2% to 83.1% within ten years.
- During scenarios of high climate mitigation and low fishing pressure, critical zone stocks recover between 21.8% and 54.8% in five years, and 60.5% to 82.3% within ten years.
- The combination of high fishing pressure and a high emissions climate scenario (SSP5-8.5) result in recovery dropping to 8.9% to 20.2% in five years, and 12.9% to 32.3% within ten years.

This report highlights the importance of addressing cumulative human pressures on fish populations and emphasizes the need for governments to implement rebuilding strategies that enable the best conditions for recovery, including determining biomass estimates for uncertain stocks, or assuming conservative biomass estimates to support recovery efforts.

Introduction

Canada's marine fisheries operate within one of the largest Exclusive Economic Zones (EEZ) in the world, covering 5.8 million km^2 (Flanders Marine Institute, 2019) and spanning three oceans and fifteen Marine Ecoregions (Spalding et al., 2007). These waters support a diverse range of fish and invertebrates, many of which are commercially harvested, including the once thriving Atlantic cod fishery, which has been a global symbol of fisheries mismanagement for decades (Castañeda et al., 2020). As of 1987, Canada was the world's largest seafood exporter, and it remains among the top ten seafood exporting nations today. However, mismanagement and overfishing have taken a toll on the fisheries, with repercussions felt from coast to coast. By 2012, Canada's marine fish stocks ranked among the worst in the world compared with similar industrialized nations (Hutchings et al, 2012) and most indicators of good fisheries management have stagnated for the past seven years (Oceana Canada, 2023).

Now, for the first time in over 150 years, Canada is legally required to rebuild its fish stocks and, when successful, will realize the benefits from this important investment in marine conservation. This report aims to provide new realistic projections for this new chapter in Canada's fishing future to better understand what is at stake for Canada's seafood production and marine biodiversity.

New rebuilding laws and policies

The federal government has invested in improving fisheries management through new policies and updated laws, but the latest Fishery Audit (Oceana Canada, 2023) shows that this has not resulted in meaningful changes on the water. Today, 28 stocks are critically depleted, meaning that biomass is below the threshold, or Limit Reference Point (LRP), where serious harm is occurring to the population and harvest rates should be reduced to the lowest possible level. An additional 35 stocks are categorized in the cautious zone, characterized by biomass levels below the healthy threshold but above critical levels. Harvesting rates in this zone should be curtailed to prevent severe depletion and encourage rebuilding to reach the healthy zone. Less than a third of stocks can be confidently considered healthy and nearly forty per cent of all marine fish and invertebrate populations are classified as uncertain due to insufficient reference points and stock status information. Most of the long-standing critically depleted stocks are found in Atlantic Canada, including major forage fish stocks that serve as key linchpins in the ecosystem. Many groundfish and flatfish have not recovered from widespread collapses in the 1990s and continue to be exploited and managed without rebuilding plans. Meanwhile, Canada's seafood economy has shifted to a heavy reliance on a few species of shellfish (dominated by lobster, crab, shrimp and scallops), some of which are also in decline and face mounting threats from climate change.

The updated *Fisheries Act* and rebuilding regulations can – and must – mark a turning point. In 2019, the federal government amended the *Fisheries Act* to require rebuilding plans for critically depleted stocks prescribed in regulation (Public Works and Government Services Canada, 2022). In April 2022, new regulations were published that specify the legal requirements for those rebuilding plans, including targets and timelines, and prescribed a first batch of 30 major stocks, nearly half of which are critically depleted (DFO, 2022a). According to policy, stocks in the cautious zone are required to be managed at levels that support growth toward the healthy zone (DFO, 2022b). In the near future, a second batch of more than 60 stocks will be prescribed (Government of Canada, 2022). Over time, this will result in a greater number of healthy stocks and should prevent stocks in the cautious zone from slipping into critical territory. The next few years will mark a critical period to implement policies and regulations for all depleted stocks if we are to achieve meaningful success in rebuilding ocean abundance.

Rebuilding in the face of climate change

Climate change and ocean acidification are affecting fisheries around the world, raising water temperatures and changing water chemistry, impacting biological processes, altering migratory patterns and disrupting habitats. The impact of climate change will only intensify in the future, potentially leading to a decrease in global fisheries catches (Cheung et al., 2022; Srinivasan et al., 2010), and can delay rebuilding efforts if not addressed (Britten et al, 2017). The Paris Agreement, adopted in 2015, aims to keep global warming well below 2 degrees Celsius above pre-industrial levels, with an aspirational goal of limiting it to 1.5 degrees Celsius. However, there is a 66% chance that we will surpass the 1.5-degree threshold between now and 2027 (World Meteorological Organization, 2023). Canada's current approach to fisheries management fails to adequately consider the effects of climate change (Pepin et al., 2022). Although there is an abundance of knowledge about how climate change affects marine populations, that information is often missing from DFO's science and advisory documents (Boyce et al., 2021). In fact, the science and management documents for nearly three-quarters (72 per cent) of fish stocks do not formally consider climate change, despite the availability of scientific evidence (Schijns and Rangeley, 2022).

Meanwhile, important scientific tools have yet to be consistently applied across all fisheries. These include vulnerability assessments (Boyce et al, 2022a) and risk- and ecosystem-based approaches (Duplisea et al., 2020). Nation-wide initiatives for a Climate Adaptation Framework for Fisheries (Boyce et al., 2023) and a National Climate Change Adaptation Strategy (Government of Canada, 2023) are also underway. Using vulnerability assessments to support climate change adaptation is a critical component of marine management that is not widely applied. Recently, Boyce et al. (2022a) developed a Climate Risk Index for Biodiversity (CRIB) framework to assess over 25,000 marine species and evaluate the vulnerability and risk for 2,045 marine species, including 90 fish stocks, in the northwest Atlantic Ocean under high emission and high mitigation climate scenarios (Boyce et al., 2022b). Climate vulnerability refers to the intrinsic susceptibility of a fish population to the impacts of climate change based on 12 indicators that capture the sensitivity of the species to changes in temperature or ocean chemistry, its ability to adapt to changing conditions, and the exposure of the population to hazardous conditions (Boyce et al., 2022a). Conversely, climate risk is highly relevant to fisheries and refers to the likelihood and potential magnitude of negative impacts facing a fish population in the future based on emission scenarios. Risk assessments with spatial and temporal dimensions help identify the species, location, and timelines necessary to prioritize resources that enable climate-resilient management measures (Holsman et al., 2019).

The longer it takes for fisheries management to adapt to climate change conditions, the greater the risks that climate change poses to fisheries. The best approach to resolving persistent gaps in knowledge and application is to employ precaution rather than reactive measures, while developing robust and informed interventions. The effects of climate change should be incorporated into fisheries management decisions by integrating environmental variability into assessments (Britten et al., 2017) and advice based on risk and uncertainty (Duplisea et al., 2020).

Exploring the potential for rebuilding fish populations

By rebuilding fisheries, we can help restore the ecosystem functions, enhance food security, and support the livelihoods of millions of people who depend on fishing for their income and cultural identity (Costello et al., 2016). Rebuilding requires science-based management, strong governance, and collaboration among all stakeholders, including the fishing industry, Indigenous peoples, policymakers, scientists, and community members. It also requires adapting to changing ocean conditions while reducing greenhouse gas emissions that drive climate change (Cheung et al., 2022). Rebuilding plans work as evidenced by other nations, including the USA, where 45 stocks have rebuilding plans and 47 stocks have been rebuilt since the passage of the Magnuson-Stevens Fishery Conservation and Management Act in 2000 (NOAA, 2022).

Fish population recovery projections are important because they provide valuable information to decision-makers and affected communities on the status and potential of fish populations. Recovery projections can estimate the time needed to rebuild a depleted fish stock to a sustainable level, based on models that incorporate data on the biology, ecology, and fishery dynamics of the species. This information can help guide the development of management plans that balance conservation goals with economic, ecological, and social objectives. By using recovery projections, decision-makers can make informed choices that ensure the long-term viability of fisheries and the preservation of marine biodiversity.

Methodology

To investigate the potential for fish population recovery, we used available research on species' intrinsic population growth rate, density-dependent interactions, risk, and vulnerability to climate change for 185 Canadian marine fish and invertebrate stocks (174 Audit index[1] stocks) to inform scenarios for depleted (cautious and critical zone) stocks under varying fishing and environmental conditions.

Stock selection

A list of 230 stocks (194 index stocks) in Oceana Canada's Fishery Audit was reviewed for stocks that met the input criteria for this analysis. For a stock to be included in the analysis, it was required to have current biomass relative to upper or limit reference points from the latest Audit (Oceana Canada, 2023), intrinsic population growth rate, *r*, or resilience category in case of missing *r* from FishBase (Froese and Pauly, 2023) or literature. All included stocks also required a climate risk score from Boyce et al. (2022a) or a climate vulnerability score (Froese and Pauly, 2023; Hare et al., 2016) at the species-level. Climate vulnerability was only used if there was not climate risk score for that species. Stocks missing any of these data were ineligible for initial analyses. There were 185 stocks eligible for analysis, but since we are estimating potential recovery, we did not present the growth potential for 55 healthy stocks because of their positive

[1] The Audit index stock list (194 stocks) was created for the 2017 Fishery Audit and has been maintained over time to assess Canada's fisheries management performance using indicators developed from globally accepted best practices. It is based on marine fish and invertebrate stocks included in Oceana Canada's report Canada's Marine Fisheries: Status, Recovery Potential and Pathways to Success, combined with those included in the first public release of the DFO's Sustainability Survey for Fisheries (SSF) and any stocks with newly available information from government reports that year. Oceana Canada continues its efforts to build a comprehensive stock list by adding to the dataset any additional stocks found during this update using newly available information from DFO reports, work plans, or new additions to the SSF. This resulted in a dataset that grew from 194 stocks in 2017 to 230 stocks in 2023.

status and assumed future state[2]. Therefore, 130 stocks with uncertain, critical, or cautious stock status are used in this analysis.

Biomass

Each stock's current biomass was calculated relative to a provisional Limit Reference Point (LRP), and then converted to a biomass proportional to carrying capacity, K (K is always equal to 1). The LRP was assumed to be equivalent to 40% of B_{MSY}, and B_{MSY} was assumed to be 50% of unfished levels of abundance, or carrying capacity K (Schaefer, 1954). Therefore, the LRP was assumed as equivalent to 0.2K (Equation 1). When biomass relative to the upper or limit reference point was unavailable, uncertain stocks were run with the assumption of being both critical and cautious, with current biomass in the mid-critical and mid-cautious zones.

$$Biomass\ Relative\ to\ LRP * \frac{0.4BMSY}{LRP} * \frac{0.5K}{BMSY} = Relative\ Biomass * 0.4 * 0.5\ K \tag{1}$$

Climate Risk/Climate Vulnerability

A climate risk factor was assigned to each of the stocks present in the analysis, according to scores from Boyce et al. (2022a). The absolute Risk Index score captures the magnitude and likelihood of adverse effects for these species within their distributions used in the analysis. Each species corresponds to a single risk score regardless of differences in the geographic distribution of stocks. Emission scenarios impact species' risk by altering their predicted exposure to hazardous climate change. In this study, we explore three scenarios: one that assumes there is no climate risk to the population, a high mitigation scenario (SSP1-2.6), and a high GHG emissions scenario (SSP5-8.5), which accounts for potential negative effects on fish growth. Each stock has a climate risk score (Boyce et al., 2022a) based on two contrasting emission and socio-economic scenarios (Gütschow et al., 2021):

SSP1-2.6 – a high mitigation scenario; reduced global CO_2 emissions, trending towards sustainable development, and temperature increase stabilizes around 1.8°C.

SSP5-8.5 – a high emissions scenario; doubled global CO_2 emissions, intense fossil fuel exploitation/energy intensive lifestyles, and temperature increase stabilizes around 4.4°C.

While Canadian fisheries management currently lacks a national indicator for climate vulnerability on a single-stock basis, a wide range of studies and methods are available in peer-reviewed literature to support vulnerability indicators. Climate vulnerability scores were derived from FishBase (Froese and Pauly, 2023) based on Jones and Cheung (2018) and NOAA's Climate

[2] Since the model follows the DFO provisional harvest rules, it is assumed that stocks are not being overfished, and therefore only increasing in biomass, plateau, or fluctuate near B_{MSY} when in the healthy zone, depending on the range of intrinsic population growth rates, climate risk and fishing level.

Vulnerability Assessments published by Hare et al. (2016) for the same species in neighbouring regions.

Intrinsic rate of population increase

The intrinsic rate of population increase, *r*, was extracted from FishBase (Froese and Pauly, 2023) with upper and lower confidence levels. If *r* was not available, then a category corresponding to the resilience of a species was used to inform an *r* range (Froese et al., 2017). In one case, upper and lower bounds for *r* were based on available literature for the specific stock.

Model

The model is based on a mechanistic Schaefer logistic growth equation (Schaefer, 1954) with additional parameters to account for population depensation (Froese et al., 2017) and climate risk (Equation 2).

$$B_{t+1} = B_t + r * p * q * B_t\left(1 - \frac{B_t}{K}\right) - C_t \tag{2}$$

Where:

p is population depensation
q is the climate risk factor
r is the intrinsic population growth
K is the carrying capacity
B_t is biomass proportional to K at time *t*
B_{t+1} is biomass proportional to K at time *t+1*
C_t is the amount of biomass removal due to fishing at time *t*

Since intrinsic population growth rate, *r*, has both upper (r_U) and lower (r_L) confidence levels, both upper and lower increases in proportional biomass were calculated, and then averaged for the starting biomass of the next time step (Equations 3,4).

Lower Bound

$$B_{t+1,L} = B_t + r_L * p * q * B_t\left(1 - \frac{B_t}{K}\right) - C_{t,U} \tag{3}$$

Upper Bound

$$B_{t+1,U} = B_t + r_U * p * q * B_t\left(1 - \frac{B_t}{K}\right) - C_{t,L} \quad (4)$$

Input data assumptions

The following are assumptions used to account for negative effects on population growth and recruitment from depensation and climate effects in Equations 3 and 4.

$$\begin{cases} p = \frac{4B_t}{K} & if\ \frac{B_t}{K} \le 0.25 \\ p = 1 & if\ \frac{B_t}{K} > 0.25 \end{cases}$$

Population depensation accounts for the reduction of recruitment at a small stock size

$$\begin{cases} q = 1.0 & if\ no\ climate\ risk\ or\ vulnerability\ factor\ used,\ or\ is\ low \\ q = 0.8 & if\ climate\ risk\ or\ vulnerability\ is\ medium \\ q = 0.6 & if\ climate\ risk\ is\ high\ or\ vulnerability \end{cases}$$

The climate risk factor accounts for a constant negative effect on population growth.

The biomass removed from fishing mortality, C_t , varies by biomass relative to K, $^{B_t}/_{K}$, as well as fishing scenario. The DFO Provisional Harvest Rules (PHR) (DFO, 2009a) were used to calculate guidelines for biomass removal C_t.

DFO Provisional Harvest Rules:

$$\begin{cases} C_t < F_{MSY} \approx \frac{r * K}{4} & if\ 0.40 < \frac{B_t}{K} \le 0.50, Healthy \\ C_t < F_{MSY} * \left(\frac{B_t - 0.4B_{MSY}}{0.8B_{MSY} - 0.4B_{MSY}}\right) \approx \frac{r * K}{4} * \left(\frac{B_t - 0.2K}{0.4K - 0.2K}\right) & if\ 0.20 < \frac{B_t}{K} \le 0.40, Cautious \\ C_t = 0 & if\ \frac{B_t}{K} \le 0.20, Critical \end{cases}$$

Minimum and maximum C_t were calculated for the Cautious zone and Healthy zone using the equations provided by DFO's Provisional Harvest Rules.

<u>Cautious zone</u>

Lower C_t bound If $B_t = 0.25$ then $C_t < r/16$
Upper C_t bound if $B_t = 0.40$ then $C_t < r/4$

<u>Healthy zone</u>

$C_t < r/4$

For those stocks with biomass starting in the Critical zone an equilibrium point was calculated which would keep that stock at the same level, low fishing and high fishing scenarios were then taken to be proportional to these values.

Figure 1 shows how the biomass is processed in the mechanistic growth model depending on starting biomass within critical, cautious, and healthy stock status zones.

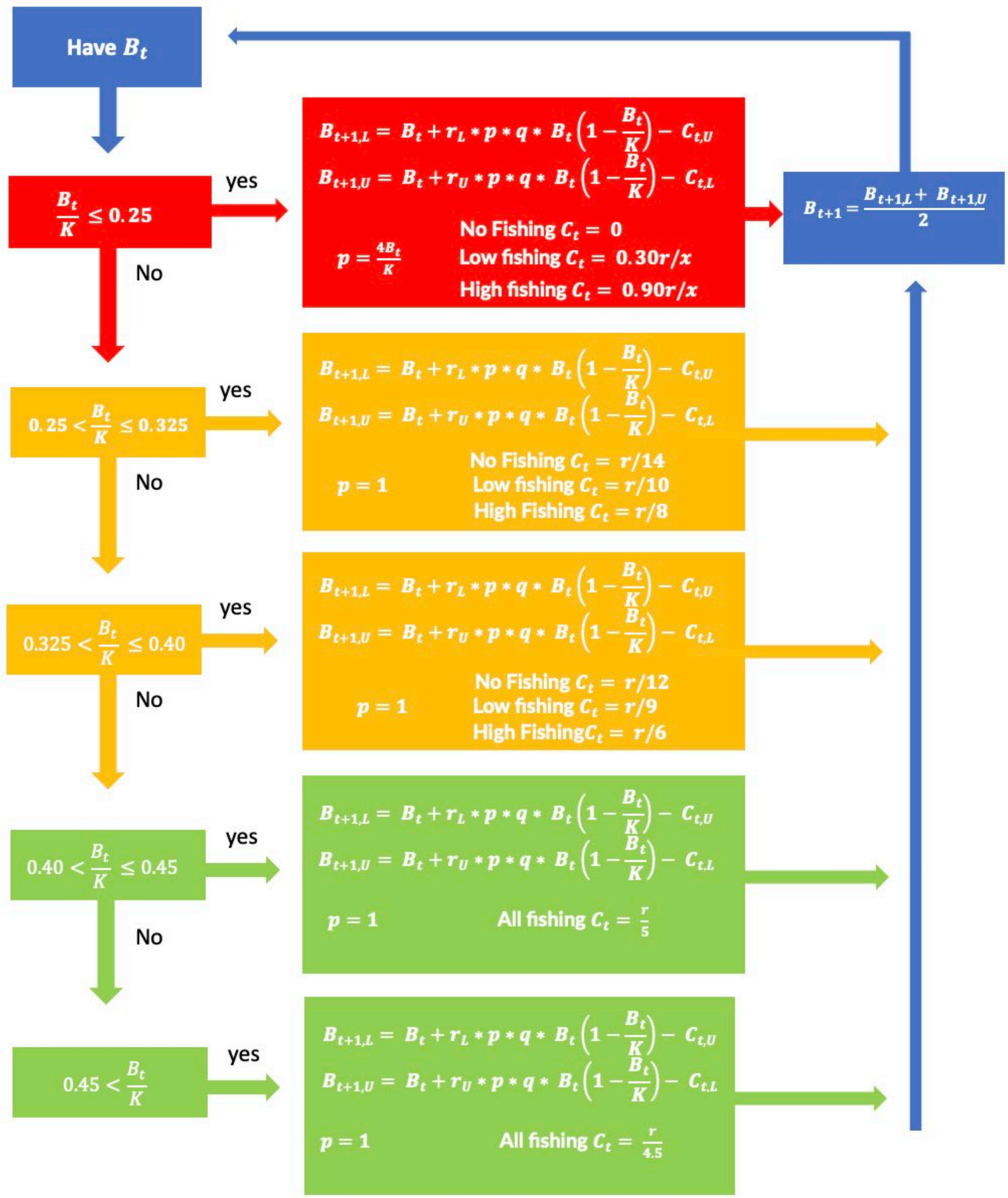

Figure 1. The process of calculating the biomass over time through the mechanistic model. Red squares represent biomass in the critical zone, yellow represents biomass in the cautious zone and green represents biomass in the healthy zone. All biomass is expressed as proportional to carrying capacity.

Results

The following Tables show the number of years until stocks in the critical zone (B_t > 0.2K) reach the cautious (years to LRP) and healthy zones (years to USR) (Table 1, 2), the number of years until stocks cautious zone reach the healthy zone (years to USR) (Table 3, 4), the number of years until stocks in the uncertain status zone reach the healthy zone (years to USR) with the biomass assumed to be mid-critical (Table 5, 6) or mid-cautious (Table 7, 8) status zone. Nine scenarios with three fishing and three climate conditions were explored. There is both an upper and lower limit provided by the algorithm (Figure 1) but the number of years to the specified reference points (LRP and USR) is expressed as the year when the mean biomass, B_t, reaches the respective reference point, not the upper or lower bounds.

Growth of Critical Zone Stocks

Of the 185 stocks that were processed, 28 (25 Oceana Fishery Audit index stocks) had a starting biomass in the critical zone. Table 1 shows the number of stocks that would grow above their respective LRP (B_t = 0.2K) and USR (B_t = 0.4K), under three fishing scenarios (none, low, and high), and climate scenarios (no climate risk, SSP1-2.6, SSP5-8.5), while Table 2 shows the proportion of stocks recovering to cautious and healthy zones within five and ten years in three scenarios.

Table 1. The number of years for stocks with a starting biomass in the critical zone to reach their respective LRP and USR. The number in brackets is how many of the total are not Audit index stocks (n=3).

Fishing / Climate Scenario	Stock Count to Cautious (LRP)			Stock Count to Healthy (USR)		
	≤5 years	≤10 years	> 10 years	≤5 years	≤10 years	> 10 years
No Fishing / No climate risk	15 (2)	20 (2)	8 (1)	9	16 (2)	12 (1)
No Fishing / SSP1-2.6 Climate	14 (2)	17 (2)	11 (1)	5	14 (2)	14 (1)
No Fishing / SSP5-8.5 Climate	14 (2)	17 (2)	11 (1)	5	14 (2)	14 (1)
Low Fishing / No climate risk	14 (2)	17 (2)	11 (1)	7	15 (2)	13 (1)
Low Fishing / SSP1-2.6 Climate	11 (2)	16 (2)	12 (1)	3	14 (2)	14 (1)
Low Fishing / SSP5-8.5 Climate	11 (2)	16 (2)	12 (1)	3	14 (2)	14 (1)
High Fishing / No climate risk	6	14 (2)	14 (1)	2	5	23 (3)
High Fishing / SSP1-2.6 Climate	5	9 (1)	19 (2)	0	0	28 (3)
High Fishing / SSP5-8.5 Climate	5	9 (1)	19 (2)	0	0	28 (3)

Table 2. The percentage of Audit index critical stocks (n=25) that are expected to recover to their LRP and USR within 5- and 10-year periods for the following fishing/climate scenarios: 1. No Fishing / No climate risk, 2. Low Fishing / SSP1-2.6 Climate, and 3. High Fishing / SSP5-8.5 Climate.

Fishing / Climate Scenario	Within 5 years		Within 10 years	
	To Cautious (LRP)	To Healthy (USR)	To Cautious (LRP)	To Healthy (USR)
No Fishing / No climate risk	52%	36%	72%	56%
Low Fishing / SSP1-2.6 Climate	36%	12%	56%	48%
High Fishing / SSP5-8.5 Climate	20%	0%	32%	0%

Growth of Cautious Zone Stocks

Of the 185 stocks, 34 (31 of which were Oceana Audit index stocks) had a starting biomass in the cautious zone ($0.2K<B_t \leq 0.4K$). Table 3 shows the number of stocks that would rebuild above their respective USR ($B_t = 0.4K$), under three fishing scenarios (none, low, and high), and climate scenarios (none, SSP1-2.6, SSP5-8.5), while Table 4 shows the proportion of stocks recovering to the healthy zone within five and ten years in three scenarios.

Table 3. The number of years for stocks with a starting biomass in the cautious zone to reach their respective USR. The number in backets is how many of the total are not Audit index stocks (n=3).

Fishing / Climate Scenario	Stock Count to Healthy (USR)		
	≤ 5 years	≤ 10 years	> 10 years
No Fishing / No climate risk	32(3)	32(3)	2
No Fishing / SSP1-2.6 Climate	27(2)	32(3)	2
No Fishing / SSP5-8.5 Climate	27(2)	32(3)	2
Low Fishing / No climate risk	32(3)	32(3)	2
Low Fishing / SSP1-2.6 Climate	25(1)	32(3)	2
Low Fishing / SSP5-8.5 Climate	25(1)	32(3)	2
High Fishing / No climate risk	27(3)	32(3)	2
High Fishing / SSP1-2.6 Climate	11	16	18(3)
High Fishing / SSP5-8.5 Climate	11	16	18(3)

Table 4. The percentage of Audit index cautious stocks (n=31) that are expected to recover to their LRP and USR within 5- and 10-year periods for the following fishing/climate scenarios: 1. No Fishing / No climate risk, 2. Low Fishing / SSP1-2.6 Climate, and 3. High Fishing / SSP5-8.5 Climate.

Fishing / Climate Scenario	To Healthy (USR)	
	Within 5 years	Within 10 years
No Fishing / No climate risk	93.6%	93.6%
Low Fishing / SSP1-2.6 Climate	77.4%	93.6%
High Fishing / SSP5-8.5 Climate	35.5%	51.6%

Growth of Uncertain Stocks

Of the 185 stocks, 68 (all Oceana Audit index stocks) had uncertain starting biomasses. These stocks were processed twice, once with the biomass assumed to be mid-critical status zone ($B_t = 0.1K$), and once with the biomass assumed to be mid-cautious status zone ($B_t = 0.3K$). Table 5 shows the number of stocks that would grow above their respective LRP ($B_t = 0.2K$) and USR ($B_t = 0.4K$), under three fishing scenarios (none, low, and high), and climate scenarios (none, SSP1-2.6, SSP5-8.5), from the critical zone. Table 6 shows the proportion of stock recovery for three scenarios with assumed starting biomass in the critical zone. Table 7 shows the number of stocks that would rebuild above their respective USR ($B_t = 0.4K$), under three fishing scenarios (none, low, and high), and climate scenarios (none, SSP1-2.6, SSP5-8.5) from the cautious zone. Table 8 shows the proportion of stock recovery for three scenarios with assumed starting biomass in the cautious zone.

Table 5. The number of years for Uncertain stocks, assumed to have a starting biomass in the mid-critical zone, to reach their LRP and USR values. All Uncertain stocks included in the analysis are Audit index stocks.

Fishing / Climate Scenario	Stock Count to Cautious (LRP)			Stock Count to Healthy (USR)		
	≤ 5 years	≤ 10 years	> 10 years	≤ 5 years	≤ 10 years	> 10 years
No Fishing / No climate risk	44	65	3	1	44	24
No Fishing / SSP1-2.6 Climate	44	64	4	0	42	26
No Fishing / SSP5-8.5 Climate	44	64	4	0	42	26
Low Fishing / No climate risk	44	64	4	1	44	24
Low Fishing / SSP1-2.6 Climate	34	58	10	0	34	34
Low Fishing / SSP5-8.5 Climate	34	58	10	0	34	34
High Fishing / No climate risk	0	41	27	0	1	67
High Fishing / SSP1-2.6 Climate	0	30	38	0	0	68
High Fishing / SSP5-8.5 Climate	0	30	38	0	0	68

Table 6. The percentage of Audit index uncertain stocks that are assumed to be critical (n=68) that are expected to recover to their LRP and USR within 5- and 10-year periods for the following fishing/climate scenarios: 1. No Fishing / No climate risk, 2. Low Fishing / SSP1-2.6 Climate, and 3. High Fishing / SSP5-8.5 Climate.

Fishing / Climate Scenario	Within 5 years		Within 10 years	
	To Cautious (LRP)	To Healthy (USR)	To Cautious (LRP)	To Healthy (USR)
No Fishing / No climate risk	64.7%	1.5%	95.6%	64.7%
Low Fishing / SSP1-2.6 Climate	50%	0%	85.3%	50%
High Fishing / SSP5-8.5 Climate	0%	0%	44.1%	0%

Table 7. The number of years for uncertain stocks, assumed to have a starting biomass in the mid-cautious zone, to reach their USR. All Uncertain stocks included in the analysis are Audit index stocks.

Fishing / Climate Scenario	Stock Count to Healthy (USR)		
	≤ 5 years	≤ 10 years	> 10 years
No Fishing / No climate risk	65	65	3
No Fishing / SSP1-2.6 Climate	56	59	9
No Fishing / SSP5-8.5 Climate	56	59	9
Low Fishing / No climate risk	65	65	3
Low Fishing / SSP1-2.6 Climate	41	61	7
Low Fishing / SSP5-8.5 Climate	41	61	7
High Fishing / No climate risk	62	65	3
High Fishing / SSP1-2.6 Climate	14	24	44
High Fishing / SSP5-8.5 Climate	14	24	44

Table 8. The percentage of Audit index uncertain stocks that are assumed to be cautious (n=68) that are expected to recover to their LRP and USR within 5- and 10-year periods for the following fishing/climate scenarios: 1. No Fishing / No climate risk, 2. Low Fishing / SSP1-2.6 Climate, and 3. High Fishing / SSP5-8.5 Climate.

Fishing / Climate Scenario	To Healthy (USR)	
	Within 5 years	Within 10 years
No Fishing / No climate risk	95.6%	95.6%
Low Fishing / SSP1-2.6 Climate	60.3%	89.7%
High Fishing / SSP5-8.5 Climate	20.6%	35.3%

Regional and Taxonomic Summaries

The time it takes to rebuild overfished stocks will vary depending on the species, driven by their biomass, growth rates, and level of fishing and climate-induced mortality. Pelagic forage species and invertebrates are projected to rebuild sooner than slower-growing groundfish and flatfish (Figure 2). Rockfish and redfish exhibit a high potential to recover to healthy levels in as few as five years without fishing or climate impacts. In the stronger management scenarios of no/low fishing and no/mitigated climate effects, the National Capital region, responsible for managing stocks including redfish, mackerel, and Northern shrimp, has the highest potential for short-term recovery, followed by the Pacific and Maritimes regions (Figure 3). All scenarios indicate that Quebec, Newfoundland and Labrador, and the Gulf regions will experience stock recovery, but will continue to manage critically depleted stocks in ten years.

Based on the analysis, positive biomass trajectories are projected for stocks when managed consistently within regulatory requirements, while closing key data gaps on how climate affects fish populations. Under high fishing pressure on depleted populations, stocks are likely to continue to persist at low levels, whereas under measures directing fishing to the lowest possible levels, many stocks are expected to recover. Out of a total of 56 stocks that were classified as critical or cautious, under conditions of low fishing and any climate scenario, approximately 27 to 36 stocks have the potential to recover within 5 years, and about 35 to 36 stocks could recover within 10 years (Figure 4). On the other hand, in scenarios of high fishing and any climate condition, around 11 to 26 stocks could potentially recover within 5 years, and approximately 16 to 34 stocks could recover within 10 years. If the rebuilding regulations are followed and fishing is kept to the lowest level (F=0) in the critical zone, climate change effects are considered and emissions are mitigated, the number of healthy stocks could increase by 15.4% in 2028, and nearly half of all populations could be healthy by 2033 (Figure 5).

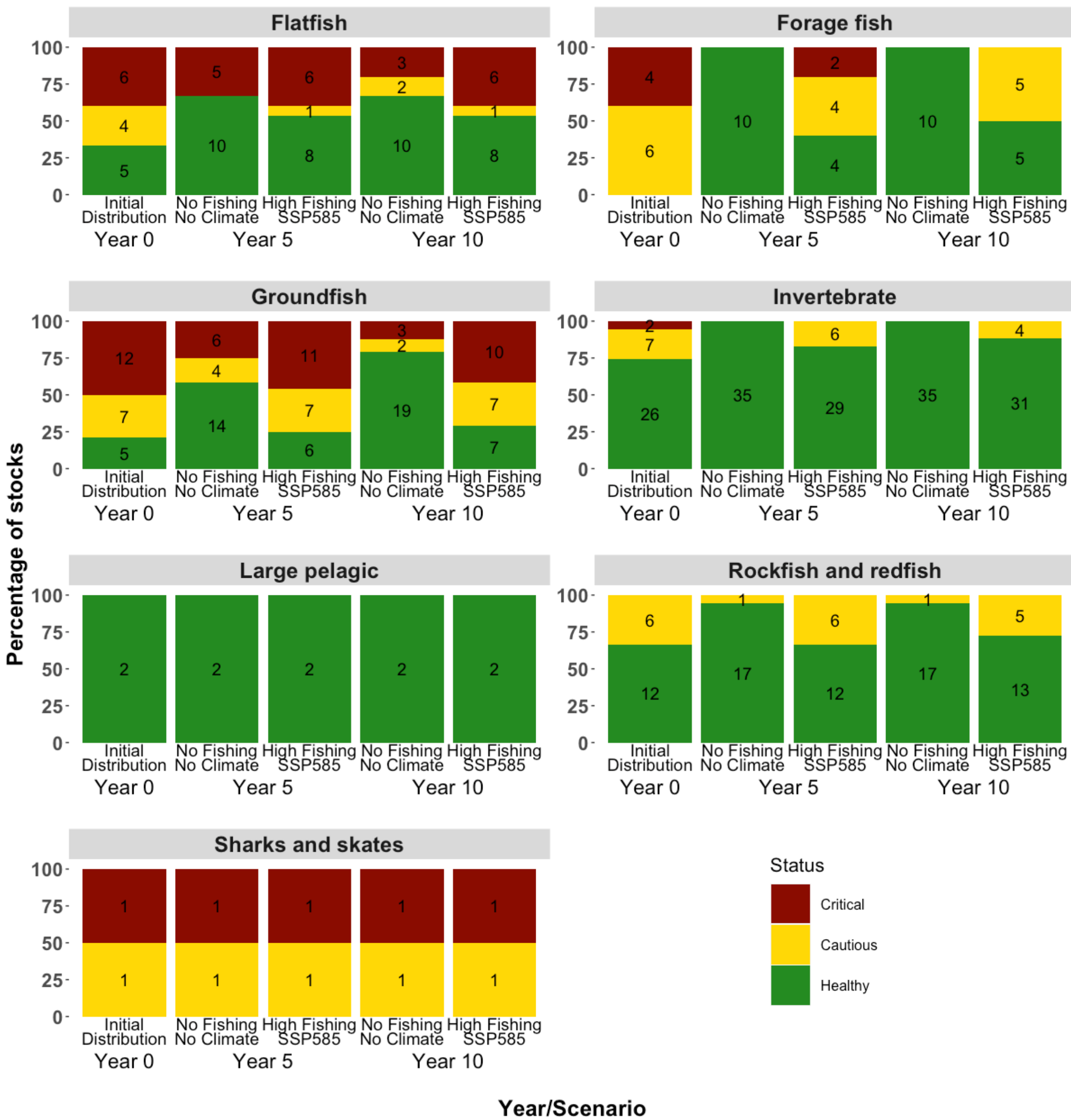

Figure 2. Recovery potential of 106 Audit index stocks (excluding uncertain stocks) by taxonomic group after 5 and 10 years under the two extreme scenarios, No Fishing / No climate risk Change impacts, and High Fishing / SSP 5-8.5 high emission climate impact scenario. The totals represent Audit index stocks that have known status in the critical, cautious, and healthy zones. Uncertain and non-index stocks were not included.

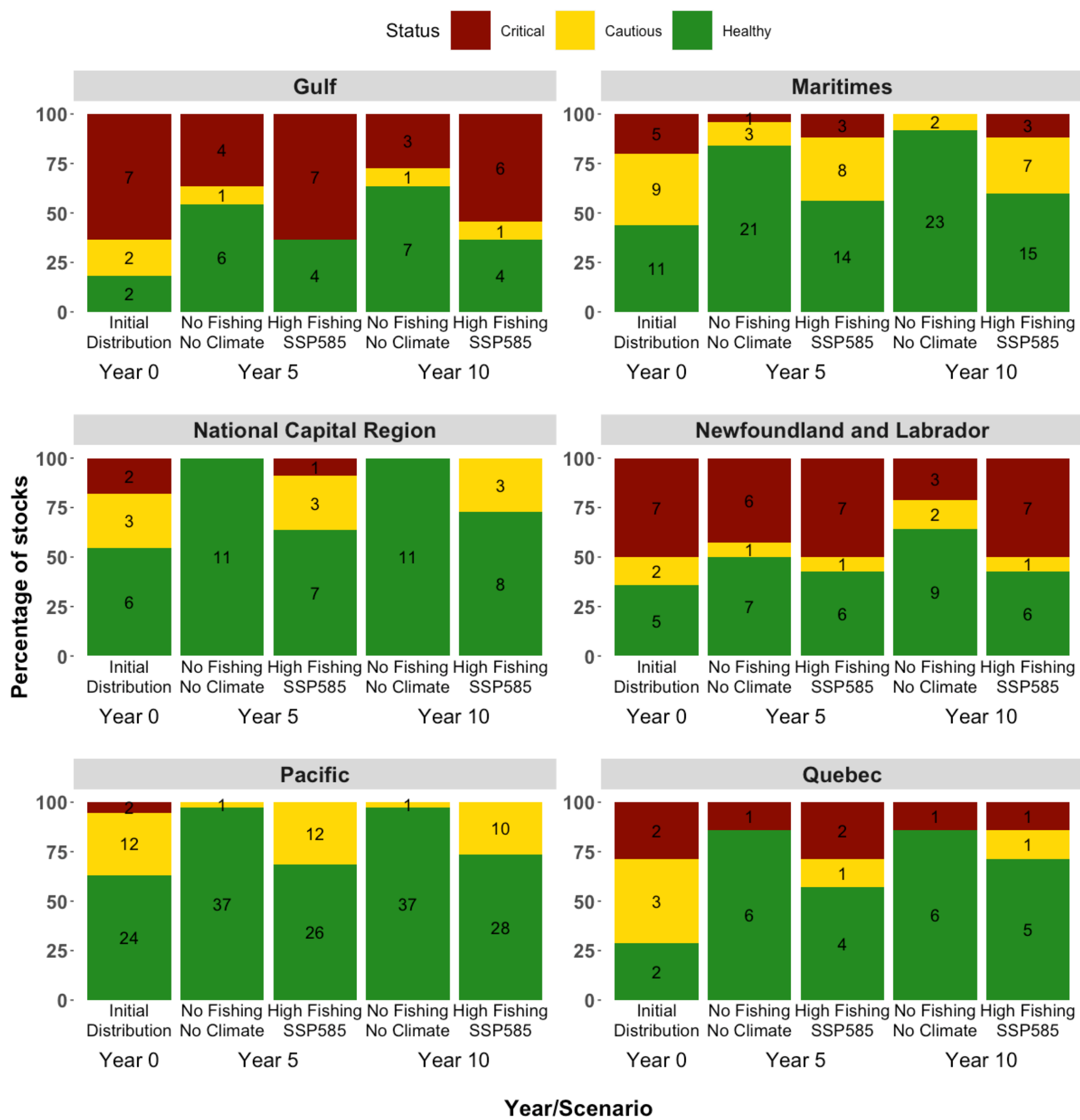

Figure 3. Recovery potential of 106 Audit index stocks (excluding uncertain stocks) by region after 5 and 10 years under the two extreme scenarios, No Fishing / No climate risk, and High Fishing / SSP 5-8.5 climate scenario. The totals represent Audit index stocks that have known status in the critical, cautious, and healthy zones. Uncertain and non-index stocks were not included.

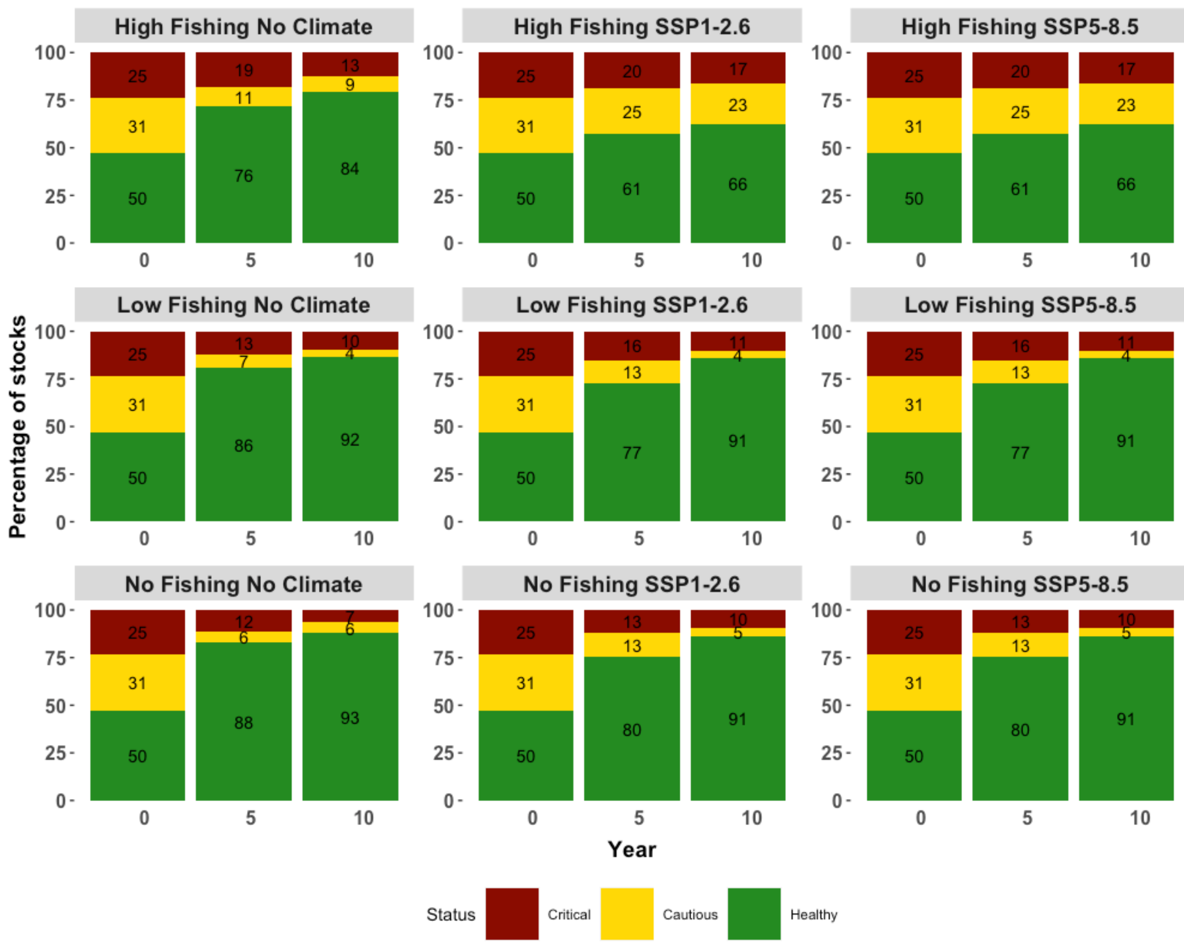

Figure 4. Recovery potential of 106 Audit index stocks (excluding uncertain stocks) included in the analysis for each of the climate and fishing scenarios. The totals represent Audit index stocks that have known status in the critical, cautious, and healthy zones. Uncertain and non-index stocks were not included.

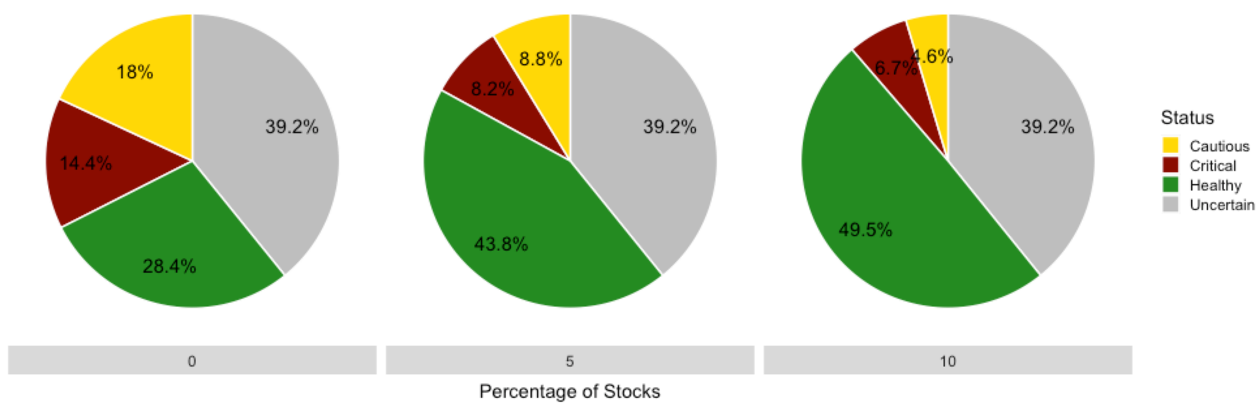

Figure 5. Recovery potential of 194 Audit index stocks after 5- and 10-year periods with no fishing in the critical zone, and a high mitigation climate scenario. Of the 56 depleted Audit index stocks (critical and cautious) 88.9% were processed, the remaining 11.1% of depleted stocks were assumed to remain critical or cautious. All Uncertain and Healthy stocks are assumed to have an unchanged status as well.

Discussion

The findings of these exploratory analyses demonstrate that fisheries recovery potential would be greatly improved if sustainable harvest rules are followed, and climate-adaptive management plans are implemented based on the best available data. We found that high fishing exploitation and high emissions scenarios prolonged the recovery period for all depleted fish. High levels of fishing exploitation when stocks are in the critical zone had the greatest negative impact on recovery timelines and further extended under climate scenarios of high GHG emissions. Conversely, not considering species vulnerability to climate change would lead to overly optimistic recovery timelines. Additionally, the initial biomass of uncertain stocks had a direct impact on how long recovery takes. This underscores the importance of having accurate biomass estimates for these uncertain stocks. Collectively, these crucial insights underscore the complex interplay of factors that should guide effective management strategies.

Specific recovery strategies must be ecosystem-based and guided by responsible catch limits, reference points, with short and long-term management objectives. Although we estimated recovery according to biologically-based reference points centered around Maximum Sustainable Yield (MSY), it is appropriate to pursue higher levels of biomass or objectives related to age and size distribution for species to effectively carry out their functional roles within the ecosystem. Prioritizing forage fish is essential because their life history allows for faster rebuilding with lower catch limits, and their recovery is exceedingly threatened by changing climate conditions. As critical links in marine ecosystems, forage fish serve as prey for larger fish, seabirds, and marine mammals and if populations are restored, it can lead to cascading benefits throughout the entire ecosystem. It is important to design ecosystem-based recovery strategies, informed by policy (DFO, 2009b) and compatible with Indigenous Knowledge Systems, to support long-term socio-ecological benefits.

With international commitments to climate initiatives and a National Climate Change Adaptation Strategy under development, Canada is well positioned to utilize climate-adaptive tools and frameworks in its fisheries. The impact that high emission scenarios have on slowing the recovery potential of most stocks in this analysis underscores the importance that recovery plans take climate change into account and make plans for adaptation. Priority should be given to rebuilding critically depleted populations vulnerable to climate change effects and stocks that are important for ecological, socioeconomic, and cultural values. The upcoming Climate Adaptation Framework for Fisheries (CAFF) evaluates the climate vulnerability of fisheries along three axes – ecological, infrastructure, and management – to understand barriers to adaptation and produce outputs to support climate adaptation (Boyce et al., 2023). The framework includes tools such as the Climate Risk Index for Biodiversity (CRIB) to evaluate global climate vulnerability of marine species, the Coastal Infrastructure Vulnerability Index (CIVI) to assess economic vulnerability of fisheries, and a survey to assess how climate variability and change are considered in fisheries management. The CAFF must be used by policymakers, strategic planners, fisheries scientists, and the fish industry to identify vulnerabilities and opportunities for adaptation.

Improving our understanding of fisheries recovery calls for a collaborative and comprehensive strategy. This means fostering genuine partnerships among Indigenous Peoples, commercial fishing industries, governments, and community groups. By working together, we can promote responsible fishing practices, share vital knowledge, and protect marine ecosystems responsibly. It's crucial to center Indigenous priorities in rebuilding efforts, respecting their inherent rights and Knowledge Systems while advancing reconciliation goals. A recent example is the draft Haida Gwaii Pacific herring rebuilding plan (CHN et al., 2023), a successful outcome of such collaboration, addressing ecological, cultural, economic, and governance aspects. Further investments in research, technology, and innovation are needed to improve data collection, modeling, and forecasting of fish populations and ecosystems. As these demands expand, resource allocation becomes imperative for a maturing management framework. Additionally, cultivating capacity is essential to implement and assess fisheries recovery measures, ensuring the engagement of all stakeholders. By adopting these approaches, Canada can achieve thriving fisheries while safeguarding the marine environment for the future.

Rebuilding timelines

Our analysis provides a simplistic way to estimate timelines – an essential element required in a rebuilding plan to help measure the effectiveness of management measures. When rebuilding a stock to its rebuilding target, the timeline (Tmin) must be based on the minimum number of years required to rebuild the stock in the absence of all fishing (F=0) under current productivity conditions. Rebuilding targets are set based on a high likelihood of success, meaning that there is a probability greater than 75% that the stock state will be above the LRP. The finalized timeline can be set at a maximum of two to three times Tmin, to consider tradeoffs between a high likelihood of rebuilding success and socio-economic and cultural impacts (DFO, 2022a).

The results provide an estimate of the time it may take stocks to recover under favorable circumstances without fishing and assuming no climate risk compared to scenarios under high fishing pressure and accounting for climate risk. While we do not account for probabilities, we do explore different productivity conditions to account for climate risk and depensation. For example, we find that the Atlantic mackerel stock could be rebuilt to levels above the LRP in less than five years (Table 1) without fishing and medium climate risk. According to the latest assessment, there is a 68% probability that the stock will be above the LRP in two years and a 75% probability that it will achieve this goal within six to seven years (DFO, 2023). Thus, to assess the effectiveness of fisheries management strategies in achieving rebuilding objectives, it is essential to utilize robust models tailored to specific stock dynamics, incorporating probabilities, tradeoffs, and environmental factors.

Our analysis also shows that certain fisheries, particularly forage fish, are especially vulnerable to climate change, and there is a significant data gap that needs to be addressed to support effective management. All the stocks assessed scored medium or high climate risk, and critical stocks experienced slower recovery under climate risk scenarios without fishing, and increasingly longer when the stock experiences cumulative pressures from high fishing and climate risk. This suggests that there is a need for management measures to both improve fisheries status in a changing environment and mitigate climate change effects (Cheung et al., 2022; Gaines et al., 2018).

Limitations and areas of future research

One of the primary limitations of fisheries recovery projections is the lack of robust and reliable data on fish populations, fishing effort, and environmental conditions. Without dependable information, it is difficult to make accurate predictions about future trends. There were several stocks ineligible for the analyses due to a lack of intrinsic population growth, illustrating the need to do more research about the life histories of these species. Since the biomass outputs are strongly influenced by the rate of population increase, this parameter would benefit from further review and expert advice to use the most suitable range. For example, *r* sourced from Fishbase for Atlantic cod differs strongly from available literature for Northern cod (NAFO areas 2J3KL), a specific stock of the same species with a very low *r* range. Therefore, rebuilding timelines for Northern cod (NAFO areas 2J3KL) were longer than other cod stocks with similar starting biomasses like Atlantic cod in NAFO areas 4X5Yb and 3Ps. There are cases where the mechanistic model projected very high relative biomass for Yellowtail flounder, due to very wide growth ranges. Both Pacific rockfish and Atlantic redfish stocks exhibit sporadic recruitment pulses that can result in larger stock sizes (Senay et al., 2021; Starr and Haigh, 2022), but this dynamic is not considered in the analysis. Future analysis may consider standardizing *r* values or incorporating "boom and bust" growth dynamics.

Although scientists have a general understanding of how climate change is affecting the oceans, there is still a lot of uncertainty about how individual fish species will respond. We included vulnerability and climate risk factors based on the assumption that there would be a negative impact on population growth at medium and high scores (Boyce et al., 2022a). Other studies that account for non-stationary growth rates show that recovery probabilities are reduced by 19%, on average, relative to models assuming static productivity (Britten et al., 2017). As well, climate change impacts many fish populations in ways other than growth rate and may vary across spatial and temporal scales. Predicting how these effects will interact is challenging, subject to widespread uncertainty. However, fisheries management decisions are made every season based on imperfect or limited information and so, despite the lack of precision in the data used in this report, the exploration of possible future states can provide valuable management guidance. It is an attempt to provide a compelling rationale for accelerating the development and implementation of rebuilding plans, strengthening science, monitoring and the application of precautionary approaches.

Assuming values for relative biomass removals under high and low fishing scenarios is subject to several limitations and may lead to inaccurate projections. The stocks in this dataset did not have information in their respective stock assessments on how much tonnage removed relates to total biomass. We tested plausible ranges depending on the stock status zone but recognize that the accuracy of these assumptions depends on many factors, including the biology and life history of the fish species, the intensity and frequency of fishing, and the ecological context of the fishery. Therefore, it is important to use caution when making assumptions about relative biomass removals and to account for total fishing removals in stock assessments and fisheries management decisions.

In the Arctic region, five stocks including redfish, Arctic cod, and Greenland halibut are healthy or uncertain status according to the latest Fishery Audit (Oceana Canada, 2023). Unfortunately, these stocks could not be incorporated into the analysis due to missing input data, underscoring the critical need for focused research and management attention in this area. The scarcity of baseline data for Arctic fisheries is glaring, even as it emerges as an expanding frontier due to climate change. Understanding the state of Arctic fisheries is important due to climate-induced environmental shifts, vulnerability of slow-growing species, and the significance of fisheries to Arctic communities' food security and culture. Responsible management based on this understanding helps preserve the unique Arctic ecosystem, ensuring both ecological sustainability and community well-being.

Conclusion

This report emphasizes the importance of a comprehensive approach to support the recovery of Canadian fisheries in the face of climate change, overfishing, and biodiversity loss. To achieve rebuilding targets, federal regulatory frameworks and policies must be implemented immediately, as well as significant investment in capacity and research, fulfilling reconciliation commitments, adopting ecosystem and climate-adaptive approaches, and closing data gaps. Canada can maximize its potential to rebuild wild fish for the benefit of our ocean ecosystems, coastal communities, and seafood industry with the necessary regulatory, policy, and science foundation in place.

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