EVALUATING THE IMPACT OF MULTI-YEAR RESEARCH CATCH LIMITS ON OVERFISHED TOOTHFISH POPULATIONS

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Abstract

In stocks that have been depleted by overfishing, the benefit of additional fisheries removals for research purposes needs to be evaluated against the risk that such catches may contribute to delaying or preventing the recovery of such stocks. Through simulating a Patagonian toothfish (*Dissostichus eleginoides*) stock that has been subjected to varying levels of overfishing and research catches, this study shows that stocks can take decades to recover even in the absence of fishing, and relatively low levels of research catch can significantly delay the recovery of a stock. Scenarios assessed in this study indicate that, where a stock has been depleted to at or below 20% of the median unfished spawning stock biomass, research catches in excess of 0.6% of median unfished total stock biomass should be avoided to ensure that research does not significantly impact on the recovery of depleted stocks in the long term. Research catches may need to be even lower where there is uncertainty regarding the key parameters related to stock productivity, such as growth, maturity, recruitment or natural mortality rates.

Keywords: recovery plans, *Dissostichus* spp., management strategies, research fishing, CCAMLR

Introduction

CCAMLR has closed several fisheries due to concerns that stocks have been depleted by overfishing; they were considered to be below 20% of median spawning stock biomass prior to fishing (SSB_0). For example, very high levels of illegal, unregulated and unreported (IUU) fishing on Ob and Lena Banks (estimated to have caught 7 086 tonnes of Patagonian toothfish (*Dissostichus eleginoides*) between 1996 and 2009 (SC-CAMLR, 2009b)) and declining catches by the authorised fleet in the fishery (Divisions 58.4.4a and 58.4.4b) led to the conclusion that the stock was likely to be depleted, and it was closed in 2002 (CCAMLR, 2002). The relationship of the stock on Ob and Lena Banks to other stocks in the southern Indian Ocean is unknown.

Recently, proposals have been submitted to conduct research fishing on Ob and Lena Banks to provide a source of data on the current status of this stock (Delegation of Japan, 2009). When evaluating strategies for monitoring such depleted stocks, for example through research fishing, SC-CAMLR has agreed that research should be conducted in such a way that it does not impact on the recovery of the stock, while any data collection plan which may involve research fishing, should aim to produce an assessment within a 3–4 year time frame of research commencing (SC-CAMLR, 2009a). Therefore, the level of research catch should maximise the information gained from the research program, while at the same time minimising the risk that these catches hinder the recovery of a stock within a 2–3 decade time frame and thus result in a failure to achieve the objectives of Article II of the CAMLR Convention.

Determining precautionary catch limits for research fishing has been difficult due to a lack of formal evaluation of the impact of research catches on depleted toothfish stocks. However, studies of species within and outside the Convention Area indicate that any source of fishing mortality may

Table 1: Input parameters for simulations of *Dissostichus eleginoides* using the generalised yield model (GYM), based on the parameters from Candy and Constable (2008) and SC-CAMLR (2009c).

Category	Parameter	Values
Age structure	First age class in stock	1 year
	Last age class in stock	35 years
	Oldest age in initial structure	36 years
Initial population structure	Age structure	Random recruitments
	Biomass	5 000 tonnes
Recruitment	Mean R_0	136 000
	CV of lognormal	0.6
	Percentage of SSB_0 after which recruitment declines	0.2
Natural mortality	Mean annual M	0.13
von Bertalanffy growth	t_0	–4.2897
	L_∞	2 870.8 mm
	k	0.02056
Weight-at-age (kg)	Weight-length parameter – A	2.59×10^{-9}
	Weight-length parameter – B	3.2064
Maturity	L_{a50}	14 years
	Range: 0 to full maturity	10–18 years
Fishery parameters	Age first selected	5
	Age fully selected	11
	Season	1 Jan–30 Dec
	Catch during fish-down phase	0–945 tonnes yr^{-1} (see Table 2)
	Catch during research phase	0–90 tonnes yr^{-1} (see Table 2)
Simulation specifications	Number of runs in simulation	1 001
Individual trial specifications	Years to remove initial age structure	1
	Years prior to fishing	5
	Reference start date in year	1/1
	Increments in year	365
	Years to project stock in simulation	75
	Reasonable upper bound for annual F	5.0
	Tolerance for finding F in each year	0.000001

significantly delay recovery of depleted fish stocks (Hammer et al., 2010; Murawski, 2010; Wiedenmann and Mangel, 2006).

This paper extends the work conducted by de la Mare and Constable (1990) on developing strategies for managing depleted fish stocks by CCAMLR. By simulating a toothfish population that has been overfished, i.e. fished at a level higher than would satisfy the CCAMLR decision rules, and depleted to a level where the productivity of the stock is compromised (see Constable et al. (2000) for a description of the CCAMLR decision rules and their relationship to Article II of the Convention), this study explores the impact of varying levels of depletion and research catches, and assumptions about stock productivity, on the status and recovery of the stock.

Methods

Modelling framework

The generalised yield model (GYM; Constable and de la Mare, 1996) was used to simulate a range of scenarios for a Patagonian toothfish stock. In the first instance, growth, mortality and reproductive parameters and the coefficient of variation (CV) of recruitment were derived from estimates for the toothfish stock in Division 58.5.2 (Candy and Constable, 2008; SC-CAMLR, 2009c) and are shown in Table 1. The unfished median biomass (B_0) was set at 5 000 tonnes, to be within the range of total aggregate catches taken from the toothfish stock on Ob and Lena Banks (SC-CAMLR, 2009b). Annual recruitment was selected at random from a lognormal distribution with a CV of 0.6 and mean recruitment set to achieve a median status (ratio of median spawning stock biomass, SSB, at

Table 2: Input parameters for simulations of *Dissostichus eleginoides* using the generalised yield model (GYM) to assess the impact of varying levels of overfishing and subsequent research (scenarios 1–6). Scenarios were also parameterised to test the sensitivity of the results of a reference scenario (scenario 3 with a research catch of 30 tonnes per year for 5 years) to assumptions about selectivity (scenarios 7 to 9), size-at-maturity (scenarios 9 and 10), growth rate (scenarios 12 and 13), recruitment variability (scenarios 14 and 15), stock recruitment relationship (scenario 16) and natural mortality rate (scenarios 17 and 18).

Scenario	Overfishing rate (tonnes yr^{-1})	SSB_0 after overfishing	Research catch (tonnes yr^{-1})	Parameter set
1	945	10%	0, 15, 30, 45, 60, 75, 90	As per Table 1
2	893	15%	"	"
3	841	20%	"	"
4	782	25%	"	"
5	730	30%	"	"
6	677	35%	"	"
7	As per scenario 3	20%	30	As per Table 1 except age fully selected = 9
8	"	"	"	As per Table 1 except age fully selected = 13
9	"	"	"	As per Table 1 except during the research phase fish are first selected at 1, fully selected between 3 and 5 and not selected above age 7, as in a trawl survey
10	"	"	"	As per Table 1 except L_{a50} = 8 years; range: 0 to full maturity = 9–15 years
11	"	"	"	As per Table 1 except L_{a50} = 8 years; range: 0 to full maturity = 13–19 years
12	"	"	"	As per Table 1 except k = 0.0216
13	"	"	"	As per Table 1 except k =0.0195
14	"	"	"	As per Table 1 except CV of lognormal recruitment = 0.4
15	"	"	"	As per Table 1 except CV of lognormal recruitment = 1.0
16	"	"	"	As per Table 1 expect recruitment declines when SSB is below 40% SSB_0
17				As per Table 1 expect recruitment is unaffected by a decline in SSB_0 at any level
18	"	"	"	As per Table 1 except M = 0.12
19	"	"	"	As per Table 1 except M = 0.14

the end of the projection period to the median unfished spawning stock biomass, SSB_0) of 1.0 over a 75-year projection time frame in the absence of fishing. With the biological parameters chosen, SSB_0 was 3 530 tonnes or ~71% of B_0 in the simulated population.

Ten years into the projection period, intense overfishing, characteristic of IUU activity in some areas of the Indian Ocean sector of the Southern Ocean (Lack, 2008), was simulated by a constant catch removal each year for 5 years (subsequently called 'historical overfishing'). These catch levels were varied to reduce *SSB* to 10%, 15%, 20%, 25%, 30% and 35% of SSB_0 at the end of the 5-year period. The annual catches taken in each scenario are shown in Table 2. Fishing selectivity for scenarios 1 to 6 was modelled as a linear increase from 0% selectivity for 5-year-old fish up to 100% selectivity for >11-year-old fish, approximating longline selectivity (Candy and Constable, 2008).

Impacts of research fishing

To simulate a multi-year research fishing program, constant catches (from 15 tonnes yr^{-1} to 90 tonnes yr^{-1} in 15-tonne intervals) were removed from the stock over a 5-year period in each of scenarios 1 to 6 shown in Table 2, starting in the year immediately after historical overfishing had ceased.

The GYM was parameterised to record the *SSB*, total biomass and vulnerable biomass in each year, and 1 001 simulations where run in each scenario combination of overfishing and research fishing.

To evaluate the impact of the different levels of research fishing on the recovery of the stock, the ratio of the stock when it had been subjected to the various levels of research fishing to the median stock status under a no research fishing scenario was calculated. The length of time it would take for the stock to recover completely under each scenario was also estimated. Following the rationale that research fishing should not impact on the stock in the short term or impact on its long-term recovery, the results of the scenarios were used to reflect on the following criteria for evaluating levels of catch:

(i) What is the maximum research catch that ensures a greater than 50% probability that the stock status will be at a higher level when the research concluded than when the research commenced (i.e. so that the research does not make the current situation worse)?

(ii) What is the maximum research catch that results in a greater than 50% chance after 20 years that the stock has recovered to 95% of the median level without fishing (i.e. so that the research has negligible impact on the recovery trajectory of the stock in the long term)?

Sensitivity testing of model assumptions

Key parameters used to assess the impact of research fishing as described above, including growth rates, maturation, recruitment variability and stock recruitment relationships, are likely to differ between toothfish stocks. Similarly, gear selectivity may differ between IUU and research fishing. Therefore, a series of additional scenarios were run to test the impact of modifying the assumed values for key parameters from a reference scenario (scenario 3) (Table 2). The effect of decreasing or increasing the age at which fish were fully selected by 2 years was tested in scenarios 7 and 8 respectively. Scenario 9 was parameterised to test the effect of overfishing occurring with longline selectivity, while research fishing selects mainly juveniles, similar to a research survey (Candy and Constable, 2008). The effect of fish maturing 2 years younger or older was tested in scenarios 10 and 11. The impact of 5% higher or lower growth rate (k) was tested in scenarios 12 and 13. Scenarios 14 and 15 tested the effect of varying the CV of the lognormal recruitment distribution. The impact of assumptions of stock-recruitment (S-R) relationships on population dynamics after historical overfishing was also investigated, with a ‘strong’ S-R relationship where mean recruitment declined when *SSB* was below 0.4 SSB_0 (scenario 16), and no S-R relationship (scenarios 17). Finally, the impact of natural mortality being 0.1 higher or lower than the assumed value of 0.13 was tested in scenarios 18 and 19.

Results

In the absence of fishing, the simulated population was stable throughout the projection period. Under all scenarios where the population was fished, the median spawning stock biomass recovered to some extent. Without any research catch it took up to 27 years for the fish stocks to recover to a median of 50% SSB_0 (the long-term target for CCAMLR toothfish fisheries) in the most heavily overfished scenarios (Table 3).

None of the scenarios, including those with no research catches, satisfied criterion (i) of having a greater than 50% probability that the stock status was higher after the research concluded compared to when research fishing began. In all scenarios, stock status continued to decline for several years after overfishing had ceased (Figure 1). This ongoing decline was due to the effects of natural mortality on mature fish that was not being compensated for by the sufficient addition of newly matured fish to the *SSB*. After several years, the median stock status first stabilised, then increased as small fish that had escaped historical overfishing recruited to the spawning stock.

There was an approximately linear response between stock status 20 years after historical overfishing ceased and the level of research catch for all *SSB* levels of overfishing (Figure 2). The higher the level of historical overfishing, the greater the impact that any research fishing had on the recovery of the stock, both in absolute terms as well as relative to the estimated median biomass if no research fishing occurred. For example, a stock at 35% SSB_0 at the cessation of overfishing was estimated to sustain around twice the rate of research catch of a stock at 15% SSB_0 that would satisfy criterion (ii). However, under all scenarios shown in Figure 2,

Table 3: Effect of different levels of research catch on the number of years, after overfishing commenced, for a simulated *Dissostichus eleginoides* stock to recover to a median status of 50% SSB_0. Parameters used in the scenarios are described in Tables 1 and 2. Scenarios where recovery time is greater than 20 years are shaded light grey and those where recovery is greater than 30 years are shaded dark grey. * = the reference scenario for results from scenarios 7 to 18 (Table 2).

Scenario	Status after overfishing (% SSB_0)	Years to recover to 50% SSB_0						
		Research catch (tonnes yr^{-1})						
		0	15	30	45	60	75	90
1	10	27	28	29	30	31	32	34
2	15	21	22	24	25	26	27	28
3	20	17	17	19*	20	21	22	23
4	25	15	16	16	17	17	18	19
5	30	14	14	15	15	16	16	17
6	35	13	13	14	14	15	15	16

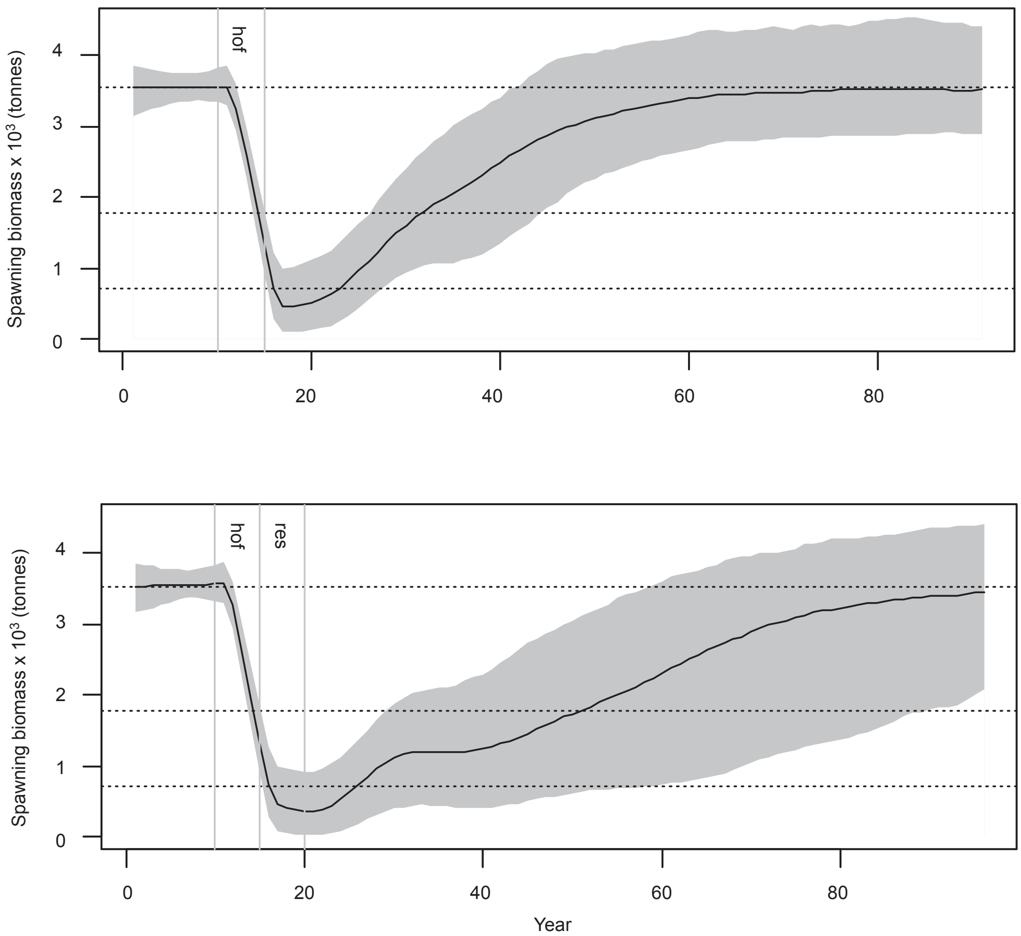

Figure 1: Median spawning stock biomass (black lines) and 95th percentile range (grey area) for 1 001 simulated *Dissostichus eleginoides* stocks, that have been historically overfished over 5 years (interval labelled hof) down to a median 20% of SSB_0 and are then unfished thereafter (upper panel), or are subsequently fished at 90 tonnes for 5 years (interval labelled res) as part of a research plan (lower panel) (100%, 50% and 20% SSB_0 reference lines are shown).

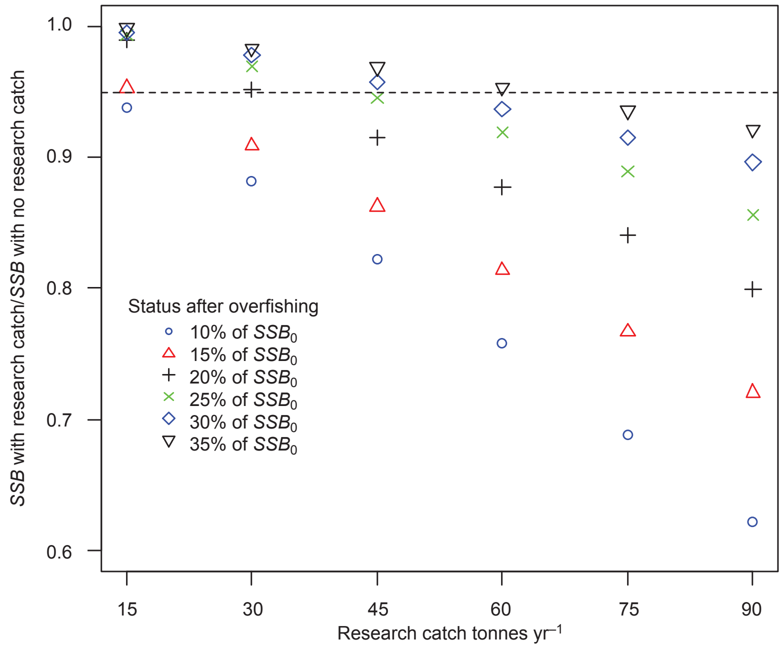

Figure 2: Impact of a 5-year research fishery on recovery 20 years after historical overfishing ceased, relative to a scenario where no research fishing occurred. Scenarios above the dotted line would satisfy criterion (ii) that research catches allow recovery to 0.95 of a scenario were no research fishing occurred after historical overfishing.

a research catch at much greater than 60 tonnes (equivalent to 1.2% of the simulated initial biomass of 5 000 tonnes yr^{-1} for 5 years) would result in a failure to satisfy criterion (ii), and in the most overfished scenario, an apparently small research catch of 15 tonnes retarded the recovery of the stock.

The results of scenarios 7 to 18 indicate that multi-decadal recovery times estimated above were generally robust to many of the assumptions regarding fishery and biological parameters used in the reference scenario (Table 4), with most cases showing recovery rates within ±3 years of that estimated in the reference scenario, and no scenarios recovering in less than a decade. However, in scenario 16, where mean recruitment begins to decline once the stock is below 40% SSB_0, stocks took 9 years longer to recover than in the reference scenario. Similarly, where the rate of natural mortality was varied, the estimated time to recover varied from 4 years earlier for $M = 0.12$ to 7 years longer for a higher $M = 0.14$.

Discussion

Many nototheniid stocks within the CCAMLR area that had been subjected to overfishing in the past have yet to recover several decades after fishing has ceased (Jones and Kock, 2009). Even in depleted fish stocks that have recovered worldwide, recovery generally takes decades and frequently depends on exceptional recruitment events, suggesting that overfishing contributes to reduced or more variable recruitment rates (Caddy and Agnew, 2004; Murawski, 2010; Wakeford et al., 2007). An S-R relationship remains to be estimated from empirical data for any toothfish stock, and so this remains a key source of uncertainty in applying the results of this study to assist management of overfished toothfish stocks. The importance of the potential impact of overfishing on recruitment rates is confirmed by the result of this study, with the level of depletion that results in a decline in recruitment having the largest impact on the rate of recovery of a stock of any of the single parameters varied in sensitivity testing. Hence, while many of the scenarios in this study indicate long time frames, of the order of 15–25 years for recovery of an overfished toothfish stock, actual recovery rates may be even longer if the relationship between stock size and recruitment is strong at low stock sizes.

As the results from this study confirm, overfished toothfish stocks are likely to take long periods of time before they recover sufficiently to support commercial fishing even when unfished.

Table 4: Effect of key parameter assumptions on the number of years, after overfishing commenced, for a simulated *Dissostichus eleginoides* stock to recover to a median status of 50% SSB_0. Scenario parameters are as described in Tables 1 and 2. Changes are relative to the result for scenario 3 (Table 1) with a research catch of 30 tonnes yr^{-1}, which had a status of 20% SSB_0 after overfishing and recovered to a median status of 50% SSB_0 after 19 years from the commencement of overfishing.

Scenario	Change in status after overfishing (% SSB_0)	Change in years to recover to 50% SSB_0
1	0	–3
2	0	1
3	0	–2
4	0	–2
5	0	1
6	4	–2
7	–4	3
8	0	–2
9	0	0
10	0	–2
11	0	9
12	5	–4
13	–6	7

Therefore, allowing any additional fishing pressure, such as through a research fishing program, needs to be very carefully evaluated. As shown above, catches that may appear minor, an order of magnitude smaller than the IUU catches the stock was subjected to during overfishing, can still significantly retard recovery. Furthermore, any other sources of fishing mortality, such as ongoing IUU fishing, will also hamper recovery, and should be taken into account in any assessment of the additional risk that research fishing may pose.

These results may seem to present a conundrum – for many toothfish stocks that may have been overfished, such as at Ob and Lena Banks, assessments do not exist that provide a robust way to provide an estimate of B_0 or SSB_0, and so a precautionary research catch limit may not be able to be determined in a straightforward way. However, methods do exist whereby a minimum biomass estimate could be achieved for such stocks. This includes combining depletion analyses and catch histories with plausible population parameters for a stock, as shown in McKinlay et al. (2008) and Welsford et al. (2009) for BANZARE Bank (Division 58.4.3b). Further, where feasible, robust estimates of standing stock biomass across large areas can be estimated from research trawl catches with much lower removals than have been proposed for longline-only research programs. For example, the random stratified trawl survey conducted each year in Division 58.5.2 captured less than 20 tonnes of toothfish in 2009 across 160 hauls (Nowara, 2009), representing less than 0.02% of the estimated SSB_0 of that stock (SC-CAMLR, 2009c), yet still provide robust estimates of juvenile and pre-adult stock biomass for the area. Such biomass estimates can be included in a population model, such as the GYM, to determine scenarios of unfished stock biomass, and the level of likely risk from a proposed research program, as in this study for a hypothetical stock. Ageing all the fish retained would also enable estimates of critical parameters for estimating stock productivity, such as growth rates, age-at-maturity and year-class strengths, as well as gear selectivity-at-age, which would enable more accurate parameterisation of scenarios evaluating rates of recovery for stocks of toothfish that have been overfished.

Studies that have evaluated recovery plans for other depleted fish stocks (Hammer et al., 2010; Wiedenmann and Mangel, 2006) indicate that some of the elements that are the best predictors of successful recovery plans are already implemented by CCAMLR. Targeted fisheries are closed to dramatically reduce the fishing pressure once overfishing is detected, and a 35-year projection period for assessments of long-lived species such as *Dissostichus* spp. is used to acknowledge the particular life-history characteristics that will influence the prognosis for recovery. Assessments of many of the largest toothfish stocks around South Georgia (Subarea 48.3), the Ross Sea (Subarea 88.1) and Heard Island and McDonald Islands (Division 58.5.2) explicitly include uncertainty in key parameters in projections used to evaluate the likely future state of stocks and sustainable levels of catch (Candy and Constable, 2008; Dunn and Hanchet, 2009; Hillary et al., 2006). However, further research is required to determine robust indicators of stock status and recovery rates of overfished stocks to enable evaluation of the effectiveness of the management strategies currently employed by CCAMLR, particularly for stocks where data collection plans to date have not been effective in generating robust assessments. When evaluating the additional risk that research fishing poses to these stocks against the benefit that such research may provide in terms of determining the actual trajectory of a stock, results of simulations such as in this study should be considered before additional stress is placed on a stock.

Conclusions

The results of this study show that toothfish stocks that have been severely overfished will take many years to recover to the CCAMLR target levels of 50% SSB_0, even when no fishing occurs for more than a decade afterwards. Any fishing on these stocks, even for the purposes of collecting scientific data, poses a risk to the recovery of these stocks within a time frame of 2–3 decades. Where recruitment levels may also have been impacted, recovery may take even longer. Therefore, commencing a research fishing program immediately after a period of severe overfishing substantially increases the risk that CCAMLR would not achieve its objectives for such stocks.

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