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Ecosystem-Based Fishery Management of Antarctic Krill (Euphausia superba) to Support Baleen Whales and other Predators Production Adapted for Potential Climate Change Effects

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Abstract

Antarctic krill is an important component of the zooplankton production in the Southern Ocean and is a major food source for baleen whales. The role of commercial fishing and predation by whales on Krill abundance has been investigated here using the innovative ecosystem-based fishery management, EBFM which maintains the krill to whale food web ecosystem stability. The literature indicates the Krill fishery may have been overfished, so it was reduced to the current annual upper limit of 0.62 million tonnes for support other predators of krill, such as seals, penguins and flying sea birds. However, recent literature suggests a moderate reduction in krill catch in the Antarctic Peninsula area due to its importance for whale migration to temperate areas. The Peninsula area catch was estimated to be reduced by about 10% due to additional concerns about climate change effects on krill abundance in the Southern Ocean, reducing overall catch to 0.556 million tonnes, moderately higher than the maximum taken in 2022. Hence, the krill biomass fishing was reduced to allow for predation by baleen whales and other predators, giving a full ecosystem-based fishing mortality similar to that previously estimated to maintain krill production in the Southern Ocean.

Introduction

The role of commercial fishing on krill abundance and predation by baleen whales in the Southern Ocean has been investigated [1], [2] but the literature is inconclusive, apparently due to lack of information on the amount of whale predation on krill. To support baleen whale krill consumption, [3] estimated a catch of 5.61 million tonne for the fishery area of 3.7 million Km^2 or 1.516 t/Km^2/year. However, krill were expected to be overfished at that level, so to support other krill predators, such as Penguins, an upper catch limit was set at 0.62 million tonnes. That gave a krill catch an order of magnitude lower at 0.168 t/Km^2/year, whereas the reported highest catch in 2022 was lower at about 0.45mt, or 0.122 t/Km^2/year (see CCAMLR https://fishdocs.ccamlr.org/FishRep_48_KRI_2022.html) and Box 2 in [4]. Although there appears to be no published method, it is understood CCAMLR reduced the total catch to allow for krill consumption by baleen whales and other predators. In this paper, the

Ecopath Model by [5] for the Southern Ocean, with the Ecopath Model krill and predator characteristics obtained from their supplementary Table S1, was used to estimate the EBFM fishing mortalities, krill catches and krill production consumption by predators.

As the effects on krill due to fishing are considered important for support of baleen whales, a dominant consumer of krill, the aim of this paper is to examine the current krill fishery catch in terms of the innovative approach of using ecosystem-based fishery management, EBFM. The EBFM to support the whale krill predator's production by [6] was modified for the amount of krill consumption by baleen whales and the other main predators of seals, penguins and flying seabirds. The EBFM was also reduced for the suggested reduction in krill fishing in the Antarctic Peninsula area by [8]. The reduction was considered appropriate after review of the potential climate change effects on the Southern Ocean. Hence, the approach used here was to estimate a modified EBFM to support functioning of the Antarctic Krill in fishery in the Southern Ocean ecosystem. That was undertaken by estimating the krill EBFM fishing mortality from the Ecopath Model results in [5].

Methods

Trophic Transfer Efficiency

Marine ecosystem stability is maintained by applying an EBFM fishing mortality to the main prey species and at the same time supporting the biological production, P, of the dominant predator [6]. That was based upon mimicking natural fish population processes that maintain the biological production transfer from prey to predator production between trophic levels, originally developed by [9]. The necessary data to estimate the transfer is provided in Ecopath Models [10]. The Ecopath model gives the biomass and production to biomass ratio, P/B, allowing estimation of the biological production of the species being fished and the predator species, P, by multiplying the biomass by P/B, so P = B x (P/B), where the P/B ratio is the rate of biomass regeneration [11]. That is the basis for estimating the Trophic Transfer Efficiency, TTE, from the prey trophic level, TL, to the dominant predator in the next higher TL, provided in Ecopath Models. The TTE is estimated by the ratio of predator biological production to the prey production. The TL for a fish species is shown in EcoBase - Ecopath with Ecosim https://ecobase.ecopath.org/. The average TTE of biological production from prey to predator is estimated from the TL by [6]:

$$TTE = 0.54 \times TL_{pred}^{-1.26} \qquad (1).$$

Ecosystem-based fishery management for ecosystem stability

The aim is to estimate the EBFM fishing mortality of the prey, this case Krill, by first estimating the proportion of TTE allocated to maintain the dominant predator production so it is not affected by the fishery catch of its main prey. That proportion was estimated by $\sqrt{(TTE_{pred})}$ using the TL for baleen whales in equation 1.

The krill EBFM F_{MSY} was estimated by the method in [6], defined as MSY divided by fishery biomass. A precautionary factor is applied to adjust for uncertain recruitment allocated to the fishery [12]. By supporting the main predator production, the EBFM F_{MSY} represents ecosystem stability of the krill to whale trophic transfer. Hence, the krill EBFM F_{MSY} is estimated by the method in [6] with the biological production allocated to the krill fishery reduced by 1 - $\sqrt{(TTE_{pred})}$ to support the baleen whale predator production:

$$\text{EBFM } F_{MSY} \text{ (/year)} = 0.67 \times 0.5 \times (1 - \sqrt{(TTE_{pred})} \qquad (2).$$

The precautionary factor, Pa, of 2/3 (taken as 0.67), is typically applied to TL3 fisheries of small pelagic fish [7], [13] and [14]. As the TTE equation 1 also applies to zooplankton in TL2, the Pa factor was assumed to apply to a Krill fishery, a large zooplankton in TL2. The factor 0.5 was applied because the optimum F_{MSY} occurs at half the carrying capacity of the [15] surplus production model. Therefore, the equivalent ecosystem-based krill catch was estimated by multiplying EBFM F_{MSY} by the krill biomass in the Ecopath Model.

Full ecosystem-based fishery management for predator and prey production

The Full EBFM by [6] supports the biological production of predators as well as the prey production. The Full EBFM F_{MSY} is expected to have a low fishing mortality of about 0.1 [15][16]. Accordingly, it is expected to support krill for effects of all the main predators and allow krill in the Antarctic fishery area to be sustained. The krill Full EBFM F_{MSY} was estimated by equation 3 by modification of the ecosystem stability EBFM F_{MSY} from Equation 2 with the TTE transfer to the krill prey:

Full EBFM F_{MSY} (/year) = $\sqrt{(0.54 \text{ x } TL_{prey}^{-1.26})}$ x EBFM F_{MSY} (3).

Note that the TL is for the krill prey being consumed by the predator in equation 2.

Consumption of krill biomass by whales and other predators

The Ecopath Model by [5] shows the krill diet by predators in the Diet Matrix from their supplementary Table S4. The total consumption of krill biomass by the whales and other predators was estimated using the Ecopath Model results for the predator consumption to biomass ratio, Q/B, giving the total prey biomass consumption by the procedure of [10] as $Q_{prey} = B_{Pred}$ x $(Q/B)_{Pred}$. Note that most of the consumption is lost by respiration and excretion to detritus [17], giving the TTE of about 10%. To make Q_{prey} specific for krill consumption, it is multiplied by the proportion of krill in the predator Diet Matrix from the Ecopath Model, giving $Q_{krill} = B_{Pred}$ x $(Q/B)_{Pred}$ x $Diet_{krill}$, which is called here the krill $Crop_{krill}$. As baleen whales feed on krill during the Antarctic summer of three months [18], $Crop_{krill}$ is estimated for whales by multiplying by feeding time factor, F_{time}, 0.25 (3/12 months). Due to darkness and limited sunlight during the darker six months, feeding time by seals, penguins flying sea-birds was expected to be reduced by about 1.5 months, so $Crop_{krill}$ was reduced by F_{time} 0.875 (10.5/12 months) for those predators. Hence, $Crop_{krill}$ was estimated by equation 4:

$Crop_{krill}$ (t/Km^2/year) = B_{Pred} x $(Q/B)_{Pred}$. x $Diet_{krill}$ x F_{time} (4).

The Full EBFM F_{MSY} was estimated by reducing the krill biomass by the estimated amount of krill consumed by the predators.

It is assumed the Ecopath Model errors measured by [19] (see their Table 2) in the California Current apply to the similarly phytoplankton productive Southern Ocean [5], where the California Current phytoplankton production was measured by [20]. The above equations are expected to give reliable estimates because they provide relatively errors measured by coefficients of variation, CV. The results were relatively low: Euphausiids P/B 0.2 but did not provide the B CV which is expected similar to that for small pelagic fish at typically 0.25. Other CVs are: the humpback whale B 0.15, P/B 0.15, Harbor seals B 0.15, P/B 0.10 and flying seabirds typically B 0.10, P/B 0.15. Although CV values are not provided for penguins or TL, [21] noted changes in Ecopath model values average 0.20, which is assumed to apply for penguins, TL and diet estimates.

Results

Summary of krill results for krill EBFM FMSY, Full EBFM FMSY and catches, predator cropping, fishing mortality and krill fishery catch

Table 1. Estimated krill EBFM F_{MSY} and Full EBFM F_{MSY} and predator krill crop rate compared with the fishery catch rate. Units: biomass tww/Km^2, F_{MSY}/year, krill cropping and fishery catch tww/Km^2/year.

Krill Predators	Predator[a] TL	Average TTE	Predator Biomass B	Predator Biomass P/B	Predator Q/B	Krill EBFM F_{MSY}	Krill Full EBFM F_{MSY}	Predator Diet	Predator Krill Cropping $Crop_{krill}$ and Fishery Catch
Baleen Whales	3.54	0.110	2.16	0.03	3.75	0.224	0.094	0.80	1.620
Seals	4.33	0.085	0.25	0.40	15.0	0.237	0.099	0.35	1.148
Penguins	4.1	0.091	0.30	0.75	75.0	0.234	0.098	0.50	9.84
Flying Sea Birds	4.2	0.089	0.08	0.75	100.0	0.235	0.098	0.40	0.975
Krill Fishery[b]	2.44	0.1755	25.0	2.5	33.0	0.195	0.114	0.46	0.168

a) Data from [5], Table S4: Krill TL 2.44, TTE 0.1755 by equation 1, B 25.0 t/Km^2, P/B 2.5.(/year). Krill phytoplankton and zooplankton prey weighted average TL 1.43, dominant prey phytoplankton diet 0.5 and micro-zooplankton diet 0.35, weighted average 0.46,

b) Krill fishery fishing average mortality is estimated by dividing catch by the krill biomass 0.0067/year (0.168 (t/Km^2/year)/ krill biomass 25 (tKm^2).

The estimated Krill EBFM F_{MSY} and Full EBFM F_{MSY} for baleen whales and other predators, as well as the predator diet and krill cropping compared with the fishery catch is shown in Table 1.

Table 1 shows the estimated TTE for predators ranged from 0.085 for seals to 0.110 for baleen whales. The Krill EBFM F_{MSY} for ecosystem stability of whales and other predators averaged 0.233, and the Full Krill EBFM F_{MSY} averaged 0.097/year. The total predator cropping of krill 13.583 t/Km^2/year, mostly by penguins, is equivalent to 54% of the krill biomass. That is similar to the average of 46% predation loss for marine fisheries estimated by [22], higher than the average of 30% for five small pelagic TL3 predation mortalities, M2, by [23] (see their Table 2) and similar to the 58% for Horse Mackerel, Mackerel and other small pelagic fish. Hence, the Krill predation was subtracted from the fishery biomass to estimate the ecosystem-based fishing mortality in the next Section 3.2. Note that the krill consumption is about 50 mt/year in the fishery area, 9-fold higher than the 5.61 mt/year catch estimated by [3], indicating the possible reason for reduction in the fishing limit by a similar proportion to 0.62 mt/year. Consequently, the commercial fishery catch at the upper limit of 0.168 t/Km^2/year is equivalent to a fishing mortality of 0.0067/year (see note b in Table 1, 0.168/krill biomass 25), an order of magnitude lower than the average Full EBFM F_{MSY}. Given that finding, the expected fishing mortality by applying the Full Krill EBFM F_{MSY} to the krill biomass with reduction by predator consumption is examined below.

Equivalent krill fishery biomass after allowing for predator consumption

The Antarctic krill had a high biomass of 25 t/Km^2 at the time of Ecopath Modelling, giving a total biomass in the fishery area of 92.5 m. tonnes (25 x 3.7 mKm^2) and high biological production of 62.5 t/Km^2/year (P = B 25 x P/B 2.5). The findings by [17] Christensen and Pauly (1995) show predator predation reduces the fishery biological production because P equals biomass accumulation plus predation plus catch plus other mortality and losses, so the total predation was subtracted from the biomass to estimate the ecosystem-based catch. That gives a remaining biomass 11.417 (25.0 -13.583) t/Km^2/year and subtracting the existing fishery catch of 0.168, gives an available biomass 11.249 t/Km^2/year. Applying to the average krill Full EBFM F_{MSY} of 0.097/year in Table 1 gives an estimated catch 1.091 t/Km^2/year, a total krill fishery catch of about 4.04 million tonne in the fishery area, which is similar to that estimated by [3] at 5.61 mt/year, but about 28% lower.

Discussion

The reduction in krill biomass by predation mortality for estimation of ecosystem-based fishery management is consistent with the investigation by [24] who proposed ecosystem-based fisheries management make adjustments for significant levels of predation mortality. They noted biological preference points, such as recruitment included in estimation of MSY and $F_{MSY,}$ were to minimise effects of overfishing. The literature found similar high predation effects on the krill fishery [2, 3, 25]. A moderate reduction in catch as a precautionary measure to maintain krill and related predator biological production in the Antarctic fishery areas was prompted by near-term potential climate change effects on phytoplankton and krill production. Further monitoring and research could be undertaken to see if temperature related climate change effects could be offset to maintain production in the Southern Ocean.

The difference with krill catch by [2], or the above estimated Full EBFM F_{MSY}, and the current much lower catch limit could be considered to provide a buffer for near-term climate change, proposed as 25 years until net zero carbon emissions is reached [26]. That is an important consideration due to the amount of literature that suggests climate change effects may cause reduction in Antarctic krill abundance, so a brief review of the fundamental processes that climate change may have on phytoplankton and krill (*Euphausia superba*) abundance in the Southern Ocean was undertaken. The review is for current and near future, not to the end of century effects because of proposed global action to reduce CO_2 emissions to carbon-neutral [26], meaning net removal by land and aquatic environments to equal annual emissions. For example, uptake by the oceans, particularly in the North Atlantic and the Southern Ocean, is about 25% per year by phytoplankton production [27]. The relevant climate change literature findings are briefly summarised in the next section.

Summary of potential near-term Antarctic Ocean climate change effects

Information on climate change effects in the Arctic Ocean are used to provide some perspective on likely effects in the Antarctic Ocean.

Effects of increased water temperature on phytoplankton growth

Phytoplankton diatoms in the Southern Ocean are indicated as the main food for Antarctic krill [28], so significant changes could affect krill production. However, they found the net effect of temperature related climate change is uncertain, but suggested deep water circulation changes may eventually affect nutrient inputs and alter food web flows and biogeochemistry. The early study by [29] see Figure 2 on low temperature effects on diatom growth showed a mounded curvilinear relationship for the diatom *Detonula confervacea*. The curve is indicated as beginning at about 2.2^{o}C, peaking at about 11.9^{o}C doublings/day and decreased at higher temperatures. That species has been reported as occurring in the

Arctic Ocean in Baffin Bay, further south in Davis Strait and in the Bay of Fundy (see World Register of Marine Species https://www.marinespecies.org/aphia.php?p=taxdetails&id=149286, so a similar response to water temperatures may occur for diatoms in the Southern Ocean. At the Antarctic Peninsula, [30] measured the grow rates in container bags of the diatoms *Thalassiosira* sp., *Nitzschla* sp., and *Chaetoceros* sp. at the typical water temperature of 1.5°C, having an average growth rate of 0.39/day, which was suggested by published models to be about 30**%** of the rate at 20°C. On the other hand, *in situ* measurements showed no net growth, apparently due to losses such as sinking and predation [31]. However, [32] found climate change reduced cloud cover over the northern Antarctic Peninsula. The increased exposure to sunlight increased water temperature and stratification, and hence phytoplankton growth rates and abundance in the upper euphotic zone.

The current water temperatures in the Southern Ocean are reported by [33] as ranging from -2.62°C to 5.2°C. As the lower -2.62°C temperature is about 4.8°C lower than the minimum 2.2°C in the diatom curve in the Arctic Ocean by [29], and assuming a similar response curve for diatoms in the Southern Ocean, a peak production at around 7.1°C (Arctic peak 11.9 – 4.8) may occur. That suggests a further temperature increase by climate change to higher than only about 1.9°C (7.1 - Southern Ocean upper temperature 5.2°C) could cause a reduction in phytoplankton production. Although the recent water temperature increase in the Southern Ocean in 2023 has not been published, the sea ice area decreased by about 20% in 2023 since the area in 1979 [34], their Figure 3b, indicating a significant temperature increase. Furthermore, [35] measured a 1.4°C increase in the Arctic Ocean due to global temperature increases. By comparison, [36] reported the overall Southern Ocean temperature trend in the upper 800m as +0.29 ± 0.09 °C per decade from 1993 to 2017, giving a 0.7°C increase in 2017, or 0.9°C extrapolated to 2024. If the dominant diatoms of *Rhizosolenia* sp. and *Thalassiothrix* sp in the Southern Ocean [28] have a similar curvilinear relationship with temperature as shown by [29], the reduction of phytoplankton production, and associated krill production in the near future is a possibility. However, [32] found a recent increase in production with climate change. Hence, further research on the effects of water temperature on phytoplankton growth rates in the Southern Ocean is suggested.

In the summary of climate change effects on phytoplankton in the Southern Ocean, [28] noted the oceans have taken up 25 to 30% of annual atmospheric CO_2, with about 40% in the Southern Ocean and sea ice uptake about 58% of that uptake. However, sea ice extent around the West Antarctic Peninsula was indicated as declined by up to 40% over the past 26 years. Importantly, [37] noted ice sheet tipping points at about +1.5 to 2.0°C, similar to the above suggested increase that may adversely affect phytoplankton production. Conversely, spring melt water in the Southern Ocean with released high iron, which was indicated by [28] to contribute 40-50% of the productivity in the entire ocean. Furthermore, [38], see their Figure 2 found increased phytoplankton production from 1998 to 2018 in the Arctic Ocean due to increased water temperature, reduced sea ice area causing greater exposure to light, and likely increase in nutrients from deep ocean waters. Therefore, the various interrelationships of climate change effects on phytoplankton indicate ongoing monitoring and assessments need to be undertaken.

Water temperature effects on krill growth rates

The natural temperature range of krill was suggested to lie between -1.8 and 5.5 ◦C by [39]. They found smaller size and higher oxygen demand at > 3.5◦C. The findings where similar to those by [40] who noted from the literature that the krill growth optimum temperature was 0.5 ◦C to 1◦C and growth rates decreased between 3◦C and 4 ◦C and found effects on lengths at ≥ 3.5◦C, potentially affecting the South

Georgia krill fishery. However, according to the rate of overall temperature increase by [36], a constant increase of 3.5^{o}C in the Southern Ocean may not occur in the near term, consistent with their rate of water temperature increase.

Suggested reduction in upper krill catch limit as precaution for potential climate change effects

A reduction in krill fishing intensity in the Antarctic Peninsula area was suggested by [8] to protect the krill egg and larvae recruitment to krill production because the area has a high proportion of the current krill catch. That was supported by [41] who suggested the area be made into a marine protected area. The study by [42] suggested krill fishing by new countries and climate change caused decreasing recruitment of krill near the Antarctic Peninsula by reduction in sea ice coverage, and a larger average body length being fished. It was also suggested the existing level of fishing is poorly quantified and controlled. Earlier, [43] suggested krill fishing should be stopped in existing protection zones of the South Georgia and Antarctic Peninsula fishery areas due to the high proportion of krill consumed by predators, particularly land based seabirds. For those reasons, a reduction of the current krill catch in the Peninsula area is suggested, which may also give some precaution for near-term climate change effects on the whole krill fishing area.

The Antarctic Peninsula fishing area 48.1 to the 1000m bathymetry is shown in [8] see their Figure 1. If fishing was stopped in the Peninsula area, the reduction in fishing for the area indicated in [8] was estimated to be about 10.3%. Assuming the Peninsula area has a similar catch per krill biomass as in the whole Antarctic fishing area, the 10.3% reduction is expected to be equivalent to reducing the fishery area upper limit of 0.62 mt/year to 0.556 mt/year (0.62 x [1 – 0.103]), which is still higher than the highest reported catch of 0.45 mt/year in 2021/22. The reduced catch is suggested because climate change effects, particularly for the Southern Ocean, indicated by [27] for the importance to carbon uptake, [44] for expected phytoplankton changes and [37] on marine ecosystem effects cannot be disregarded. Obviously, such a change requires further investigation and research on environmental change effects on larvae recruitment to krill production due to climate change, and the fishery manager and stakeholder approval for the final fishing level decision.

Conclusion

Although the suggested reduction in krill catch may address climate change effects in the near term, if carbon neutral is not achieved in about 25 years, or climate change effects accelerate, it is likely significant changes in the Southern Ocean ecosystem could occur. Hence, the suggested 10.3% reduction in krill catch is a first step in trying to address potential short-term climate change effects.

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