Supplemental Information: Whale recovery and the emerging human-wildlife conflict over Antarctic krill

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Supplementary Note 1

Estimating baleen whale krill consumption

To evaluate annual krill consumption by humpback (*M. novaeangliae*), fin (*B. physalus*), and blue whales (*B. musculus*), we used estimates from the published literature on daily prey consumption (P_C), and number of days feeding in the Southern Ocean each year (D_F).

- D_F, estimates from[1,2]:
  - 100 days (range 90-120)

- P_C, in tonnes – median estimate and range (25th-75th percentile) by species – from[3]:
  - *M. novaeangliae* = 3.15 (range 1.81-4.93)
  - *B. physalus* = 2.06 (range 1.25-3.12); estimated using Southern Ocean krill swarm densities and feeding rates from individuals studied in the Eastern North Pacific due to lack of Southern Ocean data for these species.
  - *B. musculus* = 4.19 (range 2.68-6.04); estimated using Southern Ocean krill swarm densities and feeding rates from individuals studied in the Eastern North Pacific due to lack of Southern Ocean data for these species.

To generate a lower bound for individuals in each species, we multiplied the lower estimate of total days feeding (90 days) by the 25th percentile of daily prey consumption. To generate an upper bound, we multiplied the upper estimates of total days feeding (120 days) by the 75th percentile of daily prey consumption.

We then estimated population size before and after whaling for CCAMLR Subareas 48.1-48.4.

- Modern (21st-century) population size estimates (N_M) taken from literature values on *M. novaeangliae*[4], *B. physalus*[5], and *B. musculus*[6,7]. These studies cover similar, but smaller, regions to Subareas 48.1-48.4; thus, these population estimates are likely conservative when considering the region as a whole.

- Historic (pre-whaling) population size estimates (N_H) were estimated using modeled outputs for the Atlantic/Indian sector of ref [8]. However, numbers presented in ref.[8] are females only; therefore, we multiplied by two to give the full population size. Next, we divided by four as CCAMLR Subareas 48.1-48.4 together are approximately one-quarter of the Atlantic/Indian sector of the Southern Ocean from ref.[8]. Conventionally, it is not correct to simply divide a survey area by a factor to derive a population estimate; thus, these should be considered conservative, first-order approximations. This produced population size estimates of:
  - *M. novaeangliae*: (51,945 * 2) / 4 = 25,973
  - *B. physalus*: (209,490 * 2) / 4 = 104,745
  - *B. musculus*: (100,690 * 2) / 4 = 50,345

Finally, to generate estimates on annual krill consumption, for each species we multiplied:

- $D_F \times P_C \times N_M$ for modern whale populations
- $D_F \times P_C \times N_H$ for historic whale populations

Supplementary Note 2

The precautionary principle and ecosystem-based management

Following a precautionary, ecosystem-based approach, CCAMLR is mandated to ensure that "the risk of changes in the marine ecosystem which are not potentially reversible over two or three decades" must be minimized[9]. Further, it requires that fishing efforts are capped at a level that "ensures the greatest net annual increment" such that the ability of the species to reproduce above replacement levels is not damaged. Lastly, it states that the ecological relationships between "harvested, dependent, and related populations" cannot be damaged by fishing[9]. Taken together, these objectives dictate the use of a precautionary approach to minimize risks associated with fishing, particularly when the risks could be significant and are challenging to quantify[10].

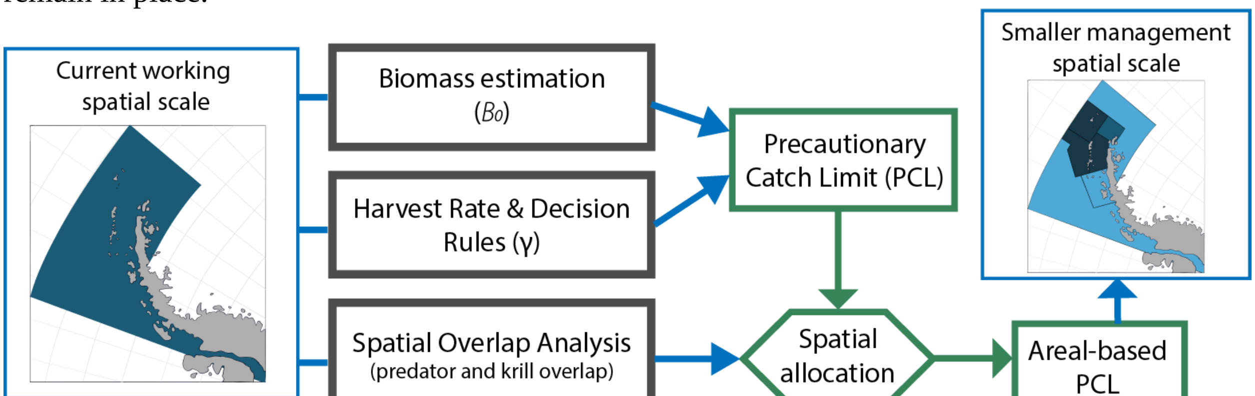
The precautionary approach applied to the krill fishery is designed to set Precautionary Catch Limits (PCLs) that support krill predators while maintaining krill biomass. PCLs are calculated by multiplying the estimated unexploited biomass (B_0) by an estimation of a precautionary harvest rate (γ). The specific conservation criteria, called decision rules, are used to select a value for γ that, when multiplied by B_0, set a PCL that ensures the fishery does not irreversibly remove more krill from the ecosystem than can be replaced in 20 years (see Supplementary Figure 1). The decision rules are where predators are factored in.

The decision rules value for γ includes a recruitment criterion; specifically, "the probability of the spawning [krill] biomass dropping below 20% of its median pre-exploitation level over a 20-year harvesting period is 10%" (Rule 1) and a predator criterion (Rule 2; i.e., the "escapement level"); specifically "the median escapement at the end of a 20 year period is 75% of the median pre-exploitation level [of the krill stock estimated in 2000]"[11,12]. The third and final rule ensures that the more precautionary approach is always taken[12]. The predator criterion is a catch-all that encompasses the needs of species that predate on krill without needing to list specific animals and the variability in their seasonal, spatial, or geographical needs explicitly. The decision rules help set a precautionary exploitation rate such that when the PCLs are calculated based on the estimated B_0, predators needs are factored into the equation via the "escapement level". It can be noted that while this is what CCAMLR deems "precautionary", it is a basic estimation that does not account for spatial or temporal variability in either criterion.

PCLs are set for large scale Statistical Areas within the Convention Area. These areas, and their PCLs, are then further subdivided into subareas (see Supplementary Figure 1). For the krill fishery in Area 48, the spatial division of PCLs within the four subareas employs and an allocation of the PCL called trigger limits. While initially trigger limits were set as an interim solution, they have remained in force since PCLs were first set for the area. The trigger level is a second, more conservative approach to the management of the krill fishery that sets the total allowable catch within Area 48, to 0.62 million tonnes divided between Subareas 48.1-48.4. Currently the trigger level states that subareas 48.1, 48.2, 48.3, and 48.4 are allocated 25%, 45%, 45%, and 15% of the 0.62 million tonnes that can be caught, respectively, as long as the total catch within the areas stays below the trigger limit[13]. There is recognition within the conservation measure that, "neither the precautionary catch limit nor the trigger level is sufficient to prevent concentrated fishing in sensitive areas and acknowledges that advances are urgently needed". While a strategy to develop an improved science-based management approach for krill has been underway for years, as it stands today, the subdivided trigger limit remains the effective catch limit for krill in Area 48. Notably, CM 51-07 expired in 2021 but has been granted two additional 1-year extensions by the Commission to enable further progress on the revision of the krill fishery management approach.

If CM 51-07 expires that could allow all 620,000 t to be taken in just one or two subareas; this is a pressing concern. For further details on the management of the krill fishery and its history, see[10,14–17].

While the trigger limit sets PCLs for the subareas, further spatial and temporal divisions of PCLs for critical areas like 48.1 are vital. In 2019, CCAMLR endorsed a revised, science-based management approach for krill, comprising (i) a stock assessment to estimate precautionary harvest rate; (ii) a regular update of biomass estimate, initially at the Subarea scale, but potentially at multiple scales; and (iii) a spatial overlap analysis, to inform a more effective spatial allocation of catch. Since then, progress has been made towards the revised management plan, however, its adoption has yet to be agreed upon by all CCAMLR Members. In 2022, the Scientific Committee recommended seven smaller krill fishery management units within Subarea 48.1 to allocate catch to[16,17]. Consensus has yet to be reached for these newly suggested catch limits within these fine-scale management regions, and until then the current management practices described above will remain in place.



Supplementary Figure 1 | Krill fishery management approach. The three components and workflow of the revised krill management approach. Adapted with permission from SC-CAMLR-40, Annex 8, Figure 1[16].

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