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Managing the Antartic Krill Fisheries

An Empirical Analysis of Regulatory Regimes and its Effects on Krill and Predator Species for a Sustainable Industry

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Executive Summary

Antarctica's Southern Ocean hosts a large range of important species that have been the subject of marine exploitation for about two hundred of years. Historically, whales and seals have been overexploited and this has led to increasing efforts to establish further fishing regulations and conservation measures by organizations such as the International Whaling Commission (IWC) and the Commission for Conservation of Antarctic Marine Living Resources (CCAMLR). This ecosystem hosts a complex food web that heavily relies on the world's most abundant species in biomass, Antarctic krill (*Euphasia superbia*). This species is of concern because of its central role in the food web as a primary prey species for the majority of predator species that are of conservation importance. The Antarctic krill population faces future challenges such as potential increases in fishing and receding sea ice due to climate change. Changes to CCAMLR's current krill management regime are necessary to ensure the sustainable management of krill in the future. This thesis aims to evaluate to what extent current CCAMLR enacted krill catch limits function in various catch scenarios where fishing demand is variable and krill recruitment may be decreasing due to climatic factors. Further, what changes to the fishing regime can be made to strategize for an economically viable fishing management regime that safe-guards significant predator species in a future with variable catches and a warmer climate where sea-ice continues to recede? We utilize the Mori and Butterworth model to simulate krill dynamics within study area A which is composed of CCAMLR's statistical area 48 and 58. We use a reliance weighted index to further understand the effect of various scenarios on predator populations. Our study finds that fixed catch limits below 4.7 million tonnes in a fixed catch limit scenario, or variable catch limits that are between 10% and 15% of total stock size, achieves an equilibrium state for krill and all predator species involved when the recruitment rate is at 0.4 and when recruitment suffers a 20% reduction in a simulated sea-ice reduction scenario. The variable catch limit is more equipped to deal with sea-ice reduction scenarios, but it is laborious to implement for CCAMLR. Further research regarding updates to the Mori and Butterworth model, predator inter-species dynamics, recruitment in relation to climate change are required to derive further understanding of this complex system.

Introduction

The Southern Ocean contains unique species and extreme environmental conditions that have supported the exploitation of marine resources since the 1800s (Basberg (1), 2008, pp.31). Management of Antarctic fisheries is crucially important to avoid repeating the severe historical exploitation of Antarctic prey and predator species, such as whales, that have to date taken decades to recover. While sealing was the primary economic activity in Antarctica in the 19th century, the whaling industry was the first major exploitative industry (Basberg (1), 2008, pp. 31). The earliest recorded Norwegian expeditions to Antarctica took place in 1892 in pursuit of whales. The whale population suffered greatly, quickly becoming near depleted despite international efforts to regulate catches throughout the 20th century. An eventual ban was placed on whaling of humpback and blue whales in 1962. However, overexploitation of the whale stocks removed any chance of profitability before consensus on regulations could be reached and function as intended (Basberg (1), 2008, pp. 42). In the 21st century, krill among other species are widely fished. Krill predator species such as whales and seals are of special conservation concern and closely monitored especially by the Commission for Conservation of Antarctic Marine Living Resources (CCAMLR).

Antarctic krill, *Euphausia superba,* (hereby referred to as "krill") are pelagic crustaceans that play a central role in the Southern Ocean's food web. This species is the most abundant on Earth by biomass (Annasawmy et al., 2022; Atkinson et al., 2022; Atkinson et al., 2019; Quetin & Ross, 1991). Current estimates of krill biomass are 400 million metric tons (Annasawmy et al., 2022; Meyer et al., 2020). Management of krill fisheries are important because of krill's role as a primary food source for predator species that are of special conservation concern such as petrels, albatrosses, penguin species, demersal fish species, species of Antarctic seals, humpback whales, minke whales, blue whales, and squid (Annasawmy et al., 2022; Quetin & Ross, 1991). Krill fisheries management systems are determined and controlled by Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Current management of krill fisheries is based on fixed catch limits that are applied to large spatial units (>0.6 million km^2) (Cavanagh et al., 2021). These measures are based on a series of interim measures pending development of a larger management strategy that aims to protect predator species and the greater ecosystem (Cavanagh et al., 2021). However, management of the krill fisheries lag behind other modern fisheries because catch limits have not been set to change depending on stock size or changes in krill distribution in over 20 years (Cavanagh et al., 2021).

Krill populations face two major future challenges. First, there is increasing pressure on the krill population due to potential upswings in fishing. Catches have been growing steadily, reaching a high point of 450 000 tonnes in 2020. Estimates from CCAMLR indicate that potential catch could reach up to >8 million tonnes per year, which could support 1.5% of the human population with a source of omega 3 (Cavanagh et al., 2021). Second, climate change is expected to create long-lasting changes in environmental factors such as continued sea-ice recession which may result in lower levels of successful krill recruitment. According to Atkinson et al. 2019, the Southern Ocean is among the fastest warming regions on the planet and krill distribution has contracted over the last 90 years.

Additionally, recent studies conclude that low exploitation rates (catch per unit biomass), existing industry compliance with regulations, and circumpolar catches below 70% of combined catch limits in the Scotia Sea region are not sufficient to protect krill predators from the additive effects of fishing and climate change (Cavanagh et al., 2021).

Meyer et al., 2020, examined the management benefits that can be achieved by considering important aspects of krill ecology further into management decisions. A key research priority produced by this paper was the importance of the development of future-proof fisheries management to combat climate change. Specifically, the authors highlight the need to construct catch limits that are appropriate to handle future climatic extremes and accompanying effects on krill populations, which are expected to increase in frequency in the future. Our research aims to expand on this priority proposed by Meyer and colleagues. This thesis utilizes the predator-prey dynamic model presented by Mori and Butterworth (2006) to analyze the current CCAMLR established management regime's functioning under three potential krill catch scenarios that simulate the effects of increased demand and climate change: status quo, high krill catch and variable catch.

The research question is as follows:

As the Southern Ocean warms, with expected long-lasting effects on the krill recruitment and dynamics, stagnant CCAMLR fishing regimes are in place. To what extent can current krill catch limits function in various catch scenarios where fishing demand is variable and krill recruitment may be decreasing due to climatic factors? Further, what changes to the fishing regime can be made to strategize for an economically viable fishing management regime that safe-guards significant predator species in a future with variable catches and a warmer climate?

By addressing this research question, we hope to further examine the extent to which more flexible catch limit scenarios can expose the weaknesses in the current regime and suggest additions to strengthen the scheme with alternative solutions.

In this thesis, chapter one will cover a historical overview of marine exploitation in the Antarctic and the development of the krill industry. Chapter two will cover the ecology of the study species, Antarctic krill. Chapter three will cover the potential and confirmed effects of climate change on krill populations. Chapter four will describe the economic theory of fisheries and fisheries regulation. Chapter five will review our methodology including model choice. Chapter six will discuss the results of our analysis followed by chapters seven, which explores the discussions and conclusions.

1. Historical overview

In comparison to the rest of the world, the history of human activity in Antarctica is very short. It is a remote and inhospitable place, but expeditions have been sent there for exploration or harvesting of marine living resources since the 1800s. Sealing was the primary economic activity for a while but the first major industry to reach the region was whaling. The first expeditions sent to Antarctica to look for whales left in 1892 (Basberg (1), 2008, pp. 31). One British expedition and one Norwegian. Neither caught any whales on this expedition but the Norwegian ship found and harpooned one (Headland, 2009, pp. 223).

1.1. Whaling in Antarctica

The captain of the Norwegian ship, Carl Anton Larsen would return to the Antarctic and play a major role in the development of the industry. In 1904, he established the first whaling station on South Georgia, financed by Argentine investors. In 1905, another entrepreneur by the name of Christian Christensen brought a factory ship to the Falklands and the South Shetland Islands, a method that would later prove quite successful. The area around the tip of the Antarctic peninsula and north towards the Falklands became the most significant hunting ground for whalers in the Southern Ocean. South Georgia and South Shetlands housed multiple shore stations and factory ships, mostly run, and staffed by Norwegians. It is during this period where we see the first attempts at regulation in Antarctica. The Falklands and South Georgia were under British rule and the governor of the Falklands made it his priority to establish a regulatory regime and placed limits on the number of shore stations and hunting vessels. No limits were however placed on the number of whales hunted and it did not take long for the industry to take its toll on the whale population (Basberg (1), 2008, pp. 32). The governor, William Lamond Allardyce, did seem concerned with the sustainability of the industry. The economy of the Falklands colony was not particularly strong, and he saw whaling as a potential way to increase its revenue. He was aware of the dangers overexploitation could lead to and his regulations were aimed at securing an industry that could last. In addition to regulating the number of stations and ships in operation, he mandated full utilization to limit waste and implemented protection of mothers and calves. The limitations of equipment and licenses paired with full utilization served as a soft catch limitation in that it limited catches to what the whalers could catch and fully process with their equipment (Basberg, 2019, pp. 263). This management system did probably slow the overexploitation down by quite a bit and it is conceivable that the stocks would have depleted a lot earlier without them. However, it was not equipped to adapt to technological development that led to each vessel and station being able to process increasing numbers of whales (Basberg, 2019, pp. 265).

In the years following the first World War, the hunting grounds were largely depleted. This did not dissuade the whalers who simply left the area for new hunting grounds. C. A. Larsen once more lead the way by deploying a factory ship to the Ross Sea that did not require a shore station to process the whales. This had the advantage of not having to acquire concessions or licenses to hunt and many other whalers did the same (Basberg (1), 2008, pp. 36). The unregulated whaling across the Antarctic did not go unnoticed among the whaling nations. In the late 20s, multiple meetings and initiatives involving many nations took place with the aim of creating international agreements. These agreements implemented many of the same regulations as Allardyce had done, such as full utilization, protection of calves and the requirement for licenses, but much like Allardyce they did not implement a catch quota system (Basberg, 2019, pp. 266). In the early 1930s, around 40 factory ships, 6 shore stations and 200 hunting vessels caught around 40 000 whales in Antarctic waters. Whaling effort took a dip in the following years but quickly ramped up again and reached a new peak in 1937-38 when 46 000 whales were caught. (Basberg (1), 2008, pp. 36). Britain and Norway attempted to regulate catches following an economic crisis in the industry after the peak years of 1930-31. They introduced quotas but compliance was poor and new entrants to the fishery undermined the effort (Basberg (1), 2008, pp. 42). These quotas had such a small effect that catches surpassed the 1930-31 catches before the decade was over.

The second World War put a stop to the industry. Most of the whaling fleet was appropriated and used for wartime transport and a large portion was sunk. Following the war, however, was a great increase in demand for whale oil. The industry was given new life and a new entrant rose to meet the demand, the Soviet Union (Basberg (1), 2008, pp. 38). This led to new international efforts to curb the exploitation of whales. In 1946, the International Whaling Commission (IWC) was established. The IWC introduced restrictions on the volume of catches by way of Blue-Whale-Units, where the total number of whales caught would be limited to 16 000 blue whale equivalents. This proved to be insufficient, as the quotas were not species specific, and the volume was too high. It also sparked controversy among the whaling nations who disagreed on how to monitor the restrictions. Some nations abandoned the BWU system around 1960 and in its place came a national quota system which proved even less effective at protecting the whale population. Poor management of the quotas and a lack of individualization led to a race to catch as much as possible before the quota was reached and whaling during the period increased (Basberg, 2019, pp. 266-267). This period was later referred to as the Whaling Olympics and the industry reached yet another peak in 1961-62 with around 50 000 whales caught. This would be the last peak as catches dropped quickly in the following decades and finally ended in 1982 (Headland, 2009, pp. 65). British and Norwegian companies had begun to liquidate their assets in the 50s and 60s and in the 70s only Japan and the Soviet Union still had whaling vessels in the area (Basberg (1), 2008, pp. 38). After the whaling peak in 1962, the hunting of blue whales and humpbacks was banned but the whaling industry ended because of failing catches and profits. Overexploitation had reduced the stocks to the point where it became unprofitable before any regulations could effectively protect them. (Basberg (1), 2008, pp. 42).

All attempts to regulate the whaling industry in Antarctica failed, either because there was no international consensus about sovereignty or regulatory authority in the area, or because they were introduced too late to make a significant difference. In the late 50s, nations with interest in Antarctica started to come together to figure out a way to collectively manage their affairs. In 1958 the Scientific Committee on Antarctic Research (hereafter referred to as "SCAR") was founded (Headland, 2009, pp. 30). Its job was to coordinate scientific research among the different signatory nations. Shortly after, in 1961, the Antarctic Treaty was ratified, establishing a legally binding groundwork for dialogue and cooperation between its signatories. This would pave the way for introducing regulations that interested parties in the area would comply with. Therefore, an opportunity presented itself to be ahead of the development of new industries and make sure they would not negatively impact the Antarctic ecosystem.

1.2. The establishment of CCAMLR

Fishing was also a prospective industry in Antarctic water since the beginning of the 20th century, but it was not nearly as attractive as whaling. Entrepreneurs preferred to invest in the more profitable of the two. When the whaling industry was starting to slow down in the 60s, fishing was given more serious consideration. The first nation to start fishing in the area was the Soviet Union in the late 60s. In the 70s, more nations joined the fishery. It began with Antarctic cod but toothfish and mackerel became much more prevalent. It quickly became apparent that krill would be a very lucrative fishery. It has been used as fish feed and a good source for omega-3 fatty acids and recent developments have found even more uses, such as food supplements, cosmetics, pharmaceuticals, and pet food. The industry grew rapidly and surpassed all other fisheries, reaching a tonnage of 400 – 500 thousand in the 1980s (Basberg (2), 2008, pp. 185).

SCAR developed a program to estimate the size and importance of fish and krill stocks and recognized the importance of protecting krill in Antarctica. Krill is the primary food source for multiple species of predators and is a vital part of the food chain and ecosystem. In 1978 to 1980, members of the Antarctic Treaty system convened and decided to form a convention to protect the ecosystem in the ocean around Antarctica. This led to the establishment of the Convention for the Conservation of Antarctic Marine Living Resources ("CCAMLR") in 1982. CCAMLR was given the authority to create regulations and set catch limits for species within its jurisdiction, and the signatories of the Antarctic Treaty would have to comply and enforce compliance from vessels bearing their flag. Cooperating heavily with SCAR, CCAMLR decided that it would be best to set precautionary catch limits and estimating a species importance to the entire ecosystem before setting catch limits. (Andersen, 2008, pp. 108).

The marine ecosystem around Antarctica reaches somewhat north of the 60° parallel that usually defines the Antarctic, and the area that the Antarctic Treaty encompasses. Therefore, CCAMLR needed to have jurisdiction that encompasses the entire Antarctic Convergence, the system of ocean currents that extend some ten degrees further north, and that reaches areas that are under the national jurisdiction of sovereign nations. South Georgia is located in this latitude – controlled by Britain. France controls the islands of Crozet and Kerguelen, both part of the French Southern and Antarctic Lands, and therefore needed to negotiate a way to respect both the national jurisdiction of France and the regulatory authority of CCAMLR. Negotiations reached a satisfying conclusion which set the precedent for the way all other territories whose boundaries lie within the Convergence (Andersen, 2008, pp. 114).

1.3. The development and regulation of the krill fishery

It did take some time for any actual catch limitations to be set for the krill fishery. In the 1980s, CCAMLR introduce regulations on mesh size and protection of seabirds and mammals. It also prohibited directed fishing of several species which were already being overfished, such as marbled rockcod, prohibited fishing of several species in certain areas and introduced catch limitations for others to prevent having to prohibit the fishery. In some cases it worked and in others they eventually had to prohibit. In many ways, it seems that CCAMLR spent the 1980s playing catch up with fisheries that were already too extensive. In order to protect a species, one must have scientific information about the stock size and ecology and such information can only be gathered by fishing. Fisheries were being overfished before enough information was gathered to realize it was happening. This led to serious discussions about precautionary catch limits, intended as temporary over-conservative limitations in place while enough information was gathered. This did cause controversy as some considered this equivalent to pure conservation but eventually this principle was used for some species, such as toothfish and krill (Andersen, 2008, pp. 114). In 1991, a conservation measure was introduced that placed precautionary catch limitations on krill in the area referred to as statistical area 48 in CCAMLR regulations (CCAMLR, 1991, Conservation Measure 32/X). In 1992 they also placed precautionary limits on the krill fishery in statistical subarea 58.4.2 (CCAMLR, 1992, Conservation measure 45/XI) and in 1996 in statistical subarea 58.2.1 (CCAMLR, 1996, Conservation measure 106/XV) (Figure 1). These areas encompass much of the sea around Antarctica from the tip of South America east to the sea south of Tasmania, excluding areas that are subject to national jurisdiction such as the Falklands (Britain), French Southern and Antarctic Lands and the Heard and McDonalds Islands (Australia).

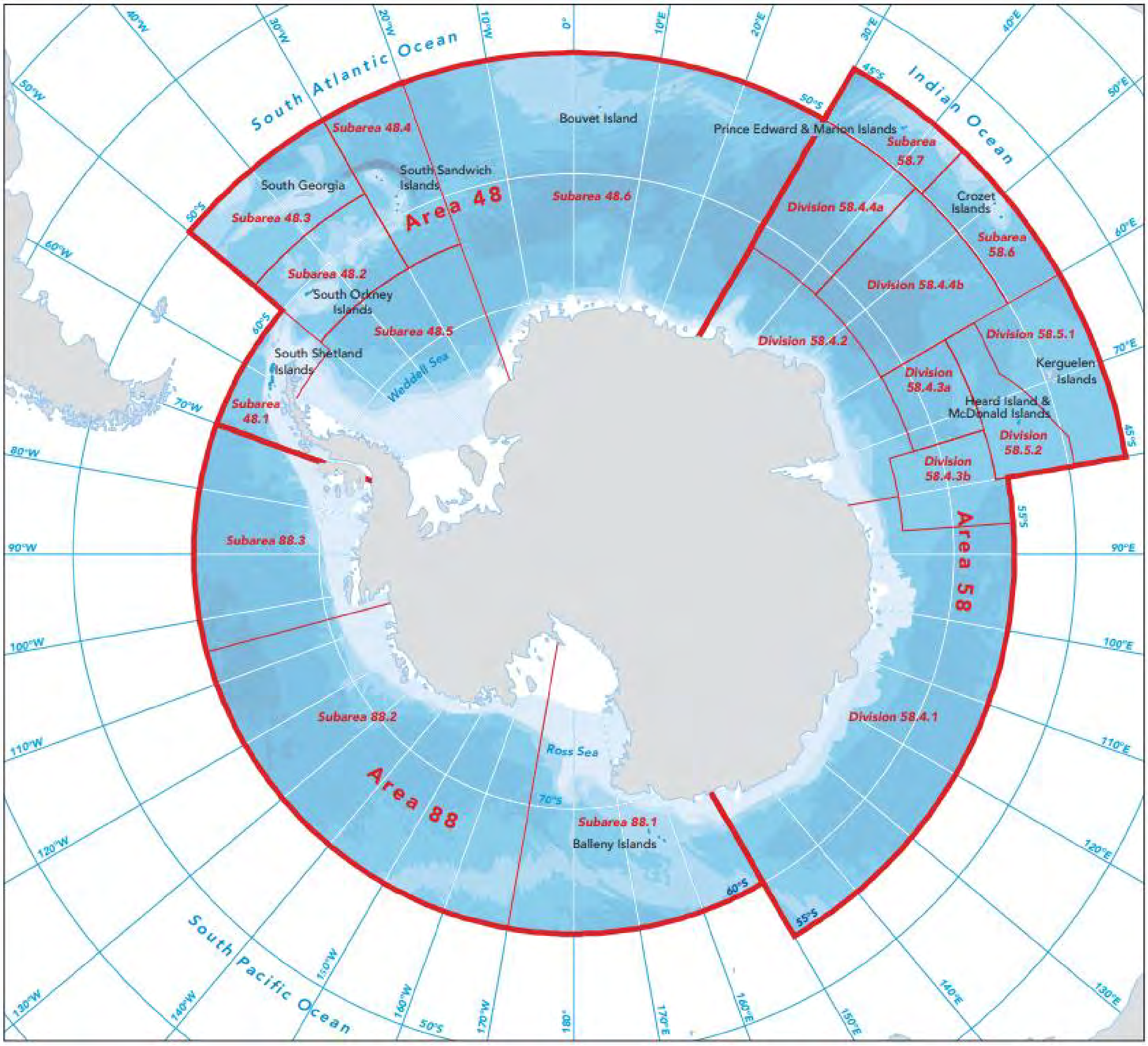

Figure 1. *Map of Antarctica and its statistical areas (Source: https://www.ccamlr.org/en/document/organisation/map-ccamlr-convention-area)*

In the decades leading up to the introduction of the catch limits, the krill fishery grew rapidly (Figure 2). In 1974, when krill was first harvested in Antarctica, about 19 000 tonnes were caught. By 1980, catches had risen to 357 000 tonnes. The fishery took a dip in 1983 and 1984, with only around 100 000 to 150 000 tonnes caught, but by 1987 it had reached new heights with 400 000 tonnes in catches. In the years 1988 to 1991, catches fluctuated at around 350 000 tonnes (Fishsource, 2022).

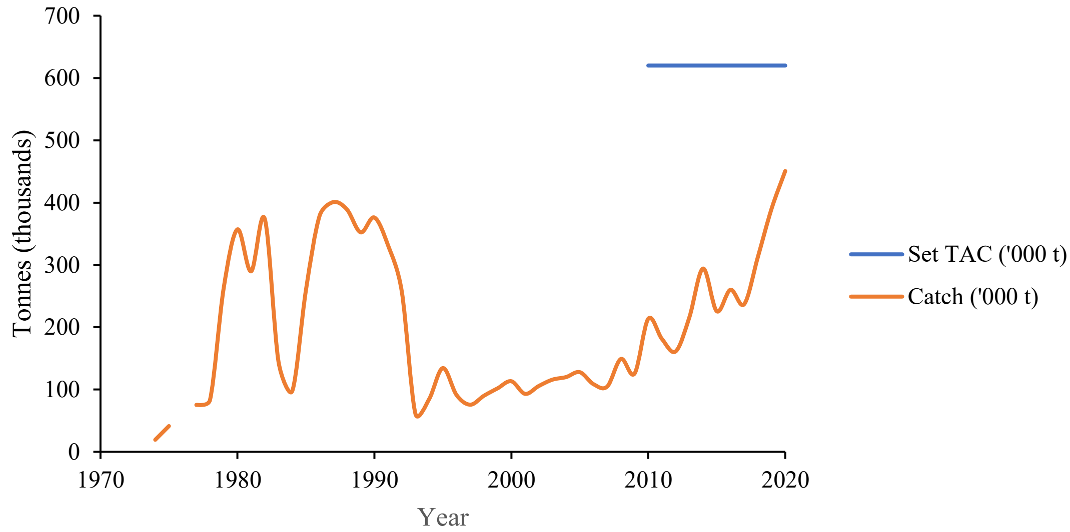

Figure 2. *Historical krill catches in the statistical area 48 (Fishsource, 2022).*

Facing this growing industry and in anticipation for catches to continue rising, CCAMLR stepped in to set a limit to prevent this ecologically important species from being overexploited. When the catch limitation was implemented in 1991, it stipulated that no more than 1.5 million tonnes of krill could be caught in any fishing season in area 48. CCAMLR had been advised by its Scientific Committee to implement a precautionary catch limit to apply to subareas within area 48 that would be decided upon should the total catch in area exceed 620 000 tonnes. This was done in order to have a failsafe in place should catches be too concentrated in one subarea because that could lead to adverse effects on predator populations that hunt in these territories (CCAMLR, 1991, Conservation measure 32/X). This was not considered sufficient to protect the predator populations as the problem could easily become too big to fix before the Committee is able to advise CCAMLR on these divisions and CCAMLR is able to implement the regulations. It was considered important to implement a system that would divide catches between appropriate subareas before the problem arose (Watters et al., 1992).

These concerns did not seem to be necessary however, as immediately following the implementation of conservation measure 32/X, catches decreased significantly. All throughout the 1990s (1993) and 2000s yearly catches were around 100 000 tonnes. They did continue to work on improving the precautionary system, but progress was not fast. In 2000, the conservation measure was updated. The catch limit was raised to 4 million and it was subdivided between subareas 48.1 to 48.4 so that no more than around 1 million tonnes would be caught in each area. The precautionary trigger level remained, now being a trigger for further subdivision to be decided upon if 620 000 tonnes are caught (CCAMLR, 2000, Conservation Measure 32/XIX). Work continued on developing methods to subdivide the catch limit (Hewitt et al, 2004) but due to the low level of catches, there was likely little sense of urgency in the matter. In 2007, the conservation measure was once again renewed. Still, no new methods of subdividing the catch limit had been agreed upon. An amendment was made to the measure, noting the need for further protection, where the trigger level of 620 000 was set as the effective catch limit until a method of subdivision is developed. Furthermore, the total catch limit of 4 million tonnes was lowered to 3.47 million tonnes, even though this catch limit was effectively made irrelevant by the previously mentioned amendment (CCAMLR, 2007, Conservation Measure 51-01). The final change to this conservation measure was made in 2010, when the total catch limit was raised to 5.61 million tonnes. To this day, no further changes have been made to the subdivision of the catch limit and therefore the effective catch limit remains at 620 000 tonnes per year (CCAMLR, 2010, Conservation Measure 51-01). Since 2010, the fishery seems to be growing again. Before then, yearly catches were around 100 000 per year, but since then they have been steadily growing, reaching a new peak in 2020 when catches were as high as 450 000 tonnes. Development of this conservation measure has been slow.

For a long time, people have raised concerns over the insufficiency of the spatial component of the regulations, but no apparent progress has been made for over 20 years. It does however seem that during those 20 years, no further progress was necessary as catches have never reached the precautionary trigger level of 620 000 so perhaps the lack of urgency is justified. It does remain to be seen how fast the fishery will continue to grow and whether the regulatory system is prepared for a larger level of catches.

2. Antarctic krill ecology

Antarctic krill, *Euphausia superba,* are pelagic crustaceans that play a central role in the Southern Ocean's food web and recycling of minerals such as iron, phosphorous, and nitrogen (Annasawmy et al., 2022; Atkinson et al., 2019; Quetin & Ross, 1991). *E. superba* grows 50-60 mm in total length, with swimming abilities similar to anchovies or sardines (Quetin & Ross, 1991). Estimates of krill biomass are 400 million metric tons (Annasawmy et al., 2022; Meyer et al., 2020). However, it is known that environmental factors such as tidal regimes, frontal zones, oxygen concentration, sea ice covers, water circulation, shelf break and bank bathymetry affect krill aggregation structures and densities (Annasawmy et al., 2022). In the last three decades, krill abundance across the Southern Ocean has declined for unknown reasons (Meyer et al., 2009). Krill are considered to be a successful species in part due to these three biological characteristics (Annasawmy et al., 2022; Veytia et al., 2022; Quetin & Ross, 1991).

1. Krill's ability to locate concentrated food sources and efficiently utilize them
2. Growth and reproductive cycles are linked to seasonality of food availability and food habitats
3. Unique physiological mechanisms enabling survival in long stretches of food scarcity in the winter

2.1. Krill feeding

Krill feeding anatomy is complex and consistent of feeding appendages called a "feeding basket" that capture food particles, filter then move food into the mouth (Figure 3; Quetin & Ross, 1991). Six pairs of thoracic appendages and setae move to facilitate feeding. Through the space created by the opening of the thoracic appendages and setae, water and food particles enter the feeding basket for consumption.

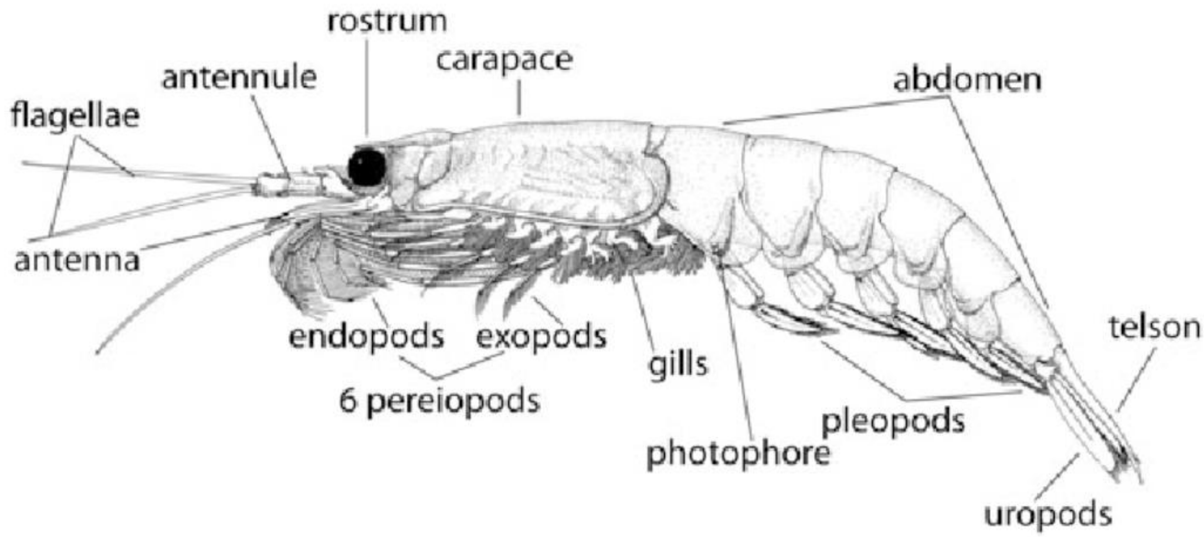

Figure 3. *Depiction of Euphasia superba, reaching lengths of up to 60mm (Siegel, 2016).*

A unique feeding basket provides krill with the ability to obtain and benefit from diversly sized, and originating free floating particles for example: small phytoplankton cells, or microplankton such as tintinnids (Quetin & Ross, 1991). A variety of feeding behaviours also adds to the versatility of krill feeding. Compression filtration is described as the rhythmic-like expansion and contraction of the feeding basket to increase the rate of movement of the free-floating food particles from the ocean water into the mouth of krill (Quetin & Ross, 1991). Raptorial feeding is another commonly used feeding mechanism where krill utilize thoracic appendages to scrape and collect algae from sea ice (Quetin & Ross, 1991).

A variety of swimming behaviours adds to feeding versatility including long-distance swimming, chemosensory abilities, and schooling behaviour. Adult krill are strong swimmers and can travel distances of 10km or greater per day to follow receding ice-edges, phytoplankton blooms and identify areas of high phytoplankton concentrations through chemical stimuli for additional food sources (Quetin & Ross, 1991). Aggregation in swarm or discrete schools is common, with densities of volume between 20 000 and 30 000 m^{-3} (Quetin & Ross, 1991). Typically, schooling behaviour occurs in widths of 200m in one horizontal dimension and several metres in thickness (Quetin & Ross, 1991).

2.2. Growth and reproductive cycles

The success of krill can also be attributed to the coupling of their life-cycle to the extreme polar seasonality (Veytia et al., 2022). The production of krill embryos and larvae occurs when phytoplankton abundance is highest, where summer phytoplankton blooms are abundant. Maturation of the embryos begins in September and October. Following spawning, the embryos sink in the water column to 800 to 1000m deep over 4.5-6 days (Quetin & Ross, 1991). Hatching then occurs and the larvae swim back to the top of the water column to feed. Food availability at this stage is critical as larvae cannot withstand more than 14 days of starvation. Adults release several batches of embryos during the summer to increase chances of success for larvae when food availability is high (Quetin & Ross, 1991). The large batches sizes increase chances of successful larvae feeding and overwintering, resulting in the large biomass of krill annually (Quetin & Ross, 1991).

2.3. Krill overwintering survival strategies

According to Meyer et al 2009, larval and post larval krill have different overwintering strategies. Overwintering larval survival is closely linked to their recruitment into the juvenile population in the next spring (Meyer et al., 2020; Meyer et al., 2009). Recruitment success variability is driven by the preceding winter's environment, typically through sea-ice habitat availability (Meyer et al., 2009).

Adult krill, also known as post larval krill, utilize several overwintering mechanisms that allow for adaptability to intense seasonal conditions (Meyer et al., 2009). Some research indicates that postal larval kill can survive up to 200 days without food by reducing their metabolic rates and increasing reliance on lipid reserves. In autumn and winter, post larval krill reduce metabolic rates by up to 50%. This physiological change is triggered by changes in Antarctic light (Meyer et al., 2009). Post larval krill also rely on alternative food sources such as phytoplankton in times of food scarcity.

Larval or juvenile krill, have lower lipid reserves than post larval krill and are not able to survive long period of famine. Autotrophic materials available in the water column are not sufficient to cover the metabolic demands of larvae, therefore they must rely on the food sources below the sea ice for development and survival (Meyer et al., 2009). At the larval stage, krill are most vulnerable to death due to starvation (Meyer et al., 2009).

2.4. Southern Ocean's complex food web

Antarctic krill are also considered a successful species because it is the most important macrozooplanktonic herbivore in the Southern Ocean, differing from other large ocean ecosystems (Annasawmy et al., 2022; Meyer et al., 2020; Quetin & Ross, 1991). Krill are primarily herbivores when phytoplankton availability is high (Quetin & Ross, 1991).

Many subject matter experts believe that primary production in the Southern Ocean is restricted by wind-induced turbulence and this results in increased productivity in nearshore coastal regions and upwelling areas compared to the open ocean (Meyer et al., 2020; Quetin & Ross, 1991). This creates predictable pulses in primary production that create the intense seasonality in food source availability which results in seasonal growth and reproduction (Meyer et al., 2020; Quetin & Ross, 1991). This may affect the population abundance of primary producers such as diatoms, nanoplankton and phytoplankton, resulting in chain reaction effects on annual krill abundance (Meyer et al., 2020; Quetin & Ross, 1991).

Due to the year-round abundance and dominance of krill, they are a consistent primary food source for a large number of vertebrate carnivorous species. For this reason, Antarctic krill can be considered a keystone species within the Southern Ocean's trophic system (Annasawmy et al., 2022; Meyer et al., 2020; Quetin & Ross, 1991). Several other small and large herbivores exist at the same trophic levels as krill. Predators birds consume krill including petrels, albatrosses, as well as three penguin species, demersal fish (*Nototheniiformes*), pelagic fish species, four species of seals, baleen whales and squid (Figure 4; Annasawmy et al., 2022; Meyer et al., 2020; Quetin & Ross, 1991). Large marine carnivores' diets consist of 33-90% of krill (Quetin & Ross, 1991).

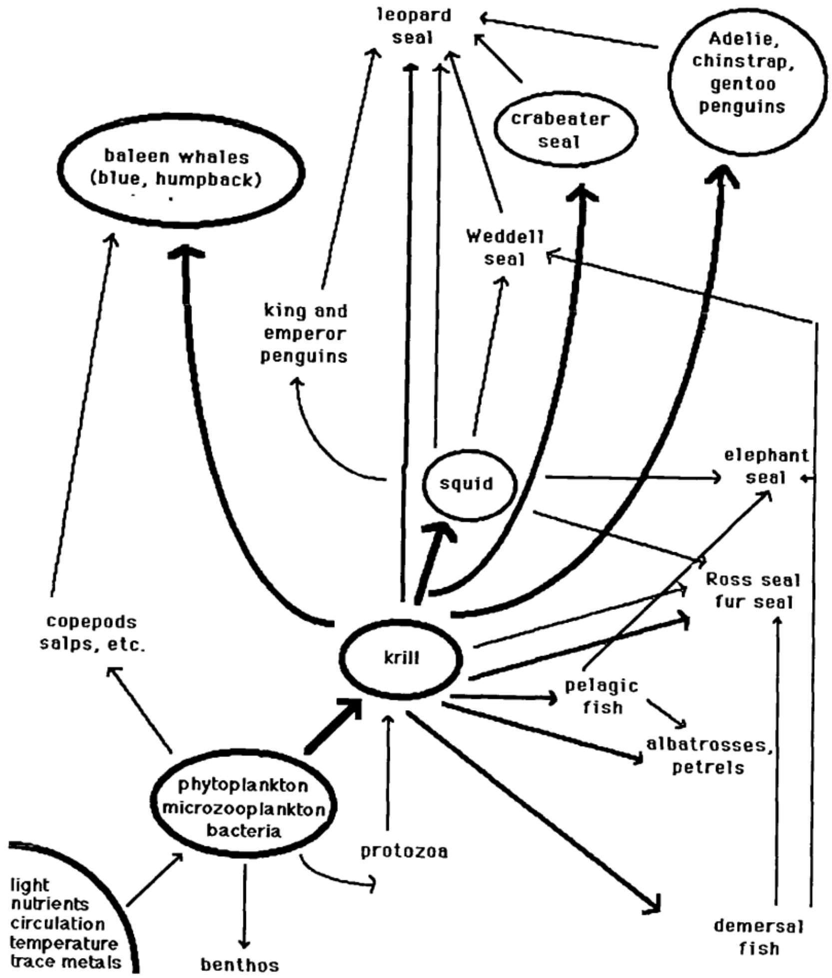

Figure 4. *Southern Ocean's food web.*

Note. Depiction of Southern Ocean's food web where species with thicker arrows and larger circles are more than 90% dependent on krill as prey. Medium lines represent species groups that are more than 33% dependent on krill. Narrow lines represent species groups that are less than 33% dependent on krill as prey (Quetin & Ross, 1991).

2.5. The Habitat of Antarctic krill

Antarctic krill are one of the world's most abundant species by biomass (Veytia et al., 2022). *E. superba* passes majority of its life cycle in the pelagic zone, which consists of the upper 200 m of the Southern Ocean's water column. Krill are circumpolar in distribution, where the highest concentrations are in a few select areas in the Southern Ocean. The largest abundance of krill exists in the waters north and east of the Antarctic Peninsula, which continues east into the Scotia Sea and Weddell Sea gyre (Quetin & Ross, 1991). The majority of krill populations are distributed in the East Wind Drift, which is an area that is closely covered by annual advance and retreats of the sea ice. The East Wind Drift is an area that is created by the east-bound winds drifting over the Antarctic shelf and slope. The West Wind Drifts rotate clockwise to the East Wind Drifts and create a ring along the Southern Ocean between the Antarctic Convergence and East Wind Drifts. A small abundance of krill are found in the West Wind Drifts (Quetin & Ross, 1991).

Antarctic krill endure a habitat with extreme polar seasonality (Veytia et al., 2022). Day length, food availability and ice cover fluctuate greatly within these polar extremes (Quetin & Ross, 1991). In areas of highest krill abundance, day light is constant/near constant throughout December. However, this is a stark contrast to June, where there are a few hours of dusk and/or complete darkness (Quetin & Ross, 1991). Hours of daylight at the surface in turn effects the ambient temperature of the air and water, as well as the maximum energy available for photosynthesis for primary producers such as phytoplankton (Quetin & Ross, 1991).

The decreasing hours of sunlight that accompany winter, aids in the formation of sea ice, which typically covers 20 million km^2 of the sea surface (Quetin & Ross, 1991). Studies have suggested that the abundance of krill is closely linked to edges of sea ice-cover (Quetin & Ross, 1991).

3. Climate change effects on krill

Demand for Antarctic krill is increasing and is projected to continue increasing in the future (Trathan et al., 2022). Estimates from CCAMLR indicate that potential catch could reach up to >8 million tonnes per year, which could support 1.5% of the human population with a source of omega 3. In the future, krill has the potential to contribute to approximately 10% of marine landings, potentially increasing global food security. It is estimated that between 2011-2015, the average catch 216 000 tonnes per year equated to a landing average of catch worth $69 million per year (Cavanagh et al., 2021).

Krill fisheries management systems are, as we have seen, determined and controlled by CCAMLR. This intergovernmental organization utilizes an ecosystem-based approach that incorporates planning for the needs of krill predators (Trathan et al., 2022). Current management of krill fisheries is based on fixed catch limits that are applied to large spatial units (>0.6 million km^2) (Cavanagh et al., 2021). These measures are based on a series of interim measures pending the development of a larger management strategy that aims to protect predator species and the greater ecosystem (Cavanagh et al., 2021). Management of the krill fisheries lag behind other modern fisheries because catch limits have not been set to change depending on stock size or changes in krill distribution (Cavanagh et al., 2021). Recent studies conclude that low exploitation rates (catch per unit biomass), existing industry compliance with regulations, and circumpolar catches below 70% of combined catch limits in the Scotia Sea region are not sufficient to protect krill predators from the additive effects of fishing and climate change (Cavanagh et al., 2021). Finer-scale management that adapts catch limits on a yearly basis with respect to factors such as stock size and distribution should be implemented by CCAMLR to reduce localized effects on krill and dependent predator species (Cavanagh et al., 2021).

3.1. Climate change effect on krill habitat

Globally, the distribution, abundance and diversity of marine species are being altered by climate change (Rogers et al., 2019). Marine and coastal environments are projected to experience changes through changes in rising sea levels, increasing sea temperatures, changes in salinity, pH and oxygen levels, changes in the frequency of rainfall , waves, storms currents and turbidity levels (IPCC 2020; Townhill et al., 2019). The effect on species at a local scale may differ greatly, fundamentally altering the mix of species available in different ecosystems (Rogers et al., 2019). It is expected that effects from climate change will have adverse effects on human communities dependent on fisheries for income and survival (Rogers et al., 2019). Although climate change has a large, expected impact on the fisheries and is expected to be a future challenge for sustainable fishing, little is known about the relative exposure of fishing communities to climate risk (Rogers et al., 2019). It is essential that relative exposure risk is determined because this information is critical to the development of adequate adaptation policies, the prioritization or research initiatives and management efforts, and for developing strategies to reduce community risk (Rogers et al., 2019). Typically, the ecological risk or vulnerability assessments are used to quantify the level of exposure risk specific communities face from factors such as climate change and other stressors. Variables such as species or stock level are used to calculate risk. It is important to note that the fishing exposure risk is highly dependent on the fishing location in the ocean, not only species, or stock targeted (Rogers et al., 2019). In this study we examine Antarctic krill. As previously defined, Antarctic krill are a *c*haracteristic pelagic invertebrate of the Southern Ocean Antarctic (Cavanagh et al., 2021). This species, supports an economically valuable commercial fishery in Southwest Atlantic, where 70% of the population exists and is experiencing rapid warming due to climate change (Meyer et al., 2020). This is an urgent issue because krill populations are adapted to narrow range of temperatures, where those >3 degrees Celsius impede embryonic development and adult growth (Cavanagh et al., 2021).

Currently, the potential impacts of climate change on the krill population are not explicitly included in the krill fisheries management schemes because catch limits do not change on a yearly basis. New developments in field research focusing on environmental changes and long-term trends in environmental factors such as temperature, sea-ice, water temperature and water-column production and climate indices such as ENSO and the SAM, suggest that climate change impacts on krill will be negative (Meyer et al., 2020). Specifically, climate change will negatively impact future krill recruitment. Additional studies have concluded that the distribution of krill is contracting southward in the South-West Atlantic sector and concentrating towards the Antarctic continental shelves due to climate-driven ecosystem change. Under current projections, krill spawning habitat will contract by 80% and will disappear by 2100 (Meyer et al., 2020). Despite over 90 years of research on krill populations, the mechanisms surrounding these changes are unknown (Meyer et al., 2020). As stated by Meyers et al., 2020, additional research in understanding the potential future changes in krill stock is required. Specifically, ecological projections need to take into account the future changes in krill populations and habitat to ensure that catch limits remain appropriate in years of climatic extremes or step-changes (Meyer et al., 2020).

4. Economic theory of fisheries and fisheries regulations

4.1. Stock dynamics and economic incentives

To gain insight into the dynamics of the Antarctic krill fishery and the relationship between the ecosystem, the fishery and CCAMLR's regulatory regime, one must first establish some basic principles of fisheries economics. The economics of fisheries, and any other renewable natural resource, is defined by a few important factors: the relationship between the resource stock size and its renewability, the effect of exploitation on the resource stock size, and the incentives at play for the individuals that participate in the exploitation.

The main advantage of renewable resources is that they can be exploited indefinitely if extraction is equal to or less than the renewal rate of the resource. In the case of fisheries, the renewal rate is dependent on the size of the fish stock and the carrying capacity of its habitat. Because fish stock renews itself through reproduction, if no fish live in the area, no new fish will be born. In some cases, a stock needs to be of a certain minimum size for reproduction to be able to repopulate faster than natural mortality. If the size of the stock is larger than such a minimum, the stock will have a growth rate dependent on the stock size. A larger stock will grow faster because more individuals participate in the reproduction process, leading to a larger number of recruits. At some point, the size of the stock will show diminishing returns in terms of growth. The habitat that the stock requires only contains enough nutrients to sustain a population of a certain size. Overpopulation of the habitat leads to a higher natural mortality or decreased survival of new recruits. The maximum stock size a habitat can support is called "carrying capacity". When the stock size reaches this maximum the growth rate of the stock is equal to the mortality rate and without external influence, the stock reaches equilibrium there. In theory, these dynamics would present a growth function that would be a concave function, rising at first but with diminishing returns until it reaches a point where growth starts to decrease, becoming zero when the stock size reaches the carrying capacity. In simple terms a growth function can be described with a logistic growth function:

$$(1) \qquad G = aS\left(1 - \frac{S}{K}\right)$$

where, G is the growth, S is the stock size, a represent an intrinsic growth rate and K is the carrying capacity of the habitat (Hannesson, 2021, pp. 64 – 69). Displayed in Figure 5 is a graphical representation of the growth function.

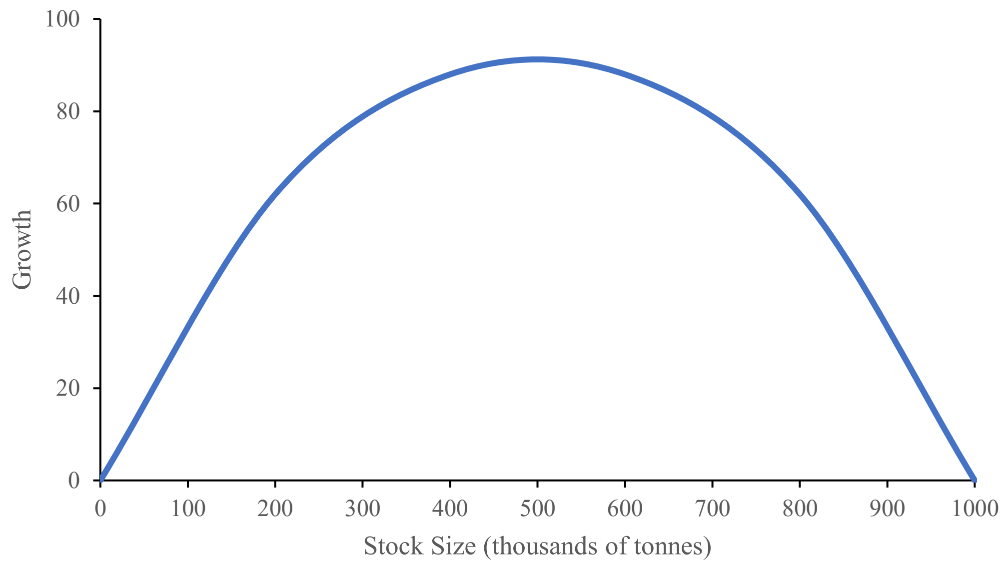

Figure 5. *Logistic growth function.*

This is a very simplistic representation of a real growth function as many more factors influence the growth rate of a fish stock, such as age structure and interaction with predators, but it does provide good insights and has a solid logical foundation. In real life, the growth of a fish stock can also fluctuate due to stochastic factors in their environment, such as climate and weather patterns and changes in ocean currents and temperatures.

The equilibrium stock size, when mortality is equal to recruitment, can be altered by fishing. Consider a fish stock in equilibrium with no fishing. The size of the stock is equal to the carrying capacity and the natural mortality rate is equal to the recruitment rate. A fishing industry is established, and fishermen start harvesting the stock at a constant rate, increasing the mortality rate. The stock becomes smaller and smaller every year until the natural growth rate has risen to a level equal to the mortality rate and the catch rate combined. Then the stock size has reached a new equilibrium where fishermen catch an amount of fish equal to the surplus growth rate of the stock. In this equilibrium, fishermen could continue to catch this amount forever without diminishing the stock. This is referred to as “sustainable yield”. For every value of stock size, there is a value equal to the surplus growth rate which corresponds to a sustainable yield of the fishery. Since the level of fishing effort can influence the equilibrium stock level, one can derive a function that describes the relationship between fishing effort and sustainable yield. The shape of this function is nearly identical to the shape of the growth function, as the sustainable yield is equal to the growth and the fishing effort and stock size have a proportionate relationship. The function is however inverted in a sense, since a high fishing effort leads to a small stock size and vice versa (Hannesson, 2021, pp. 69-71).

Having established both the stock dynamics and the relationship between fishing effort and stock size we can start examining the incentives at play by comparing sustainable yield to the cost of fishing. We can transform the sustainable yield function into a revenue function by multiplying the yield by the price of fish. We will assume for simplicity that the price is an exogenous constant and not affected by the amount of fish supplied to the market. We will also assume for simplicity that the cost of fishing is an exogenous constant and unrelated to the size of the fish stock. These simplifications may not be realistic. If the fishery is significant enough on the world market, prices may well vary with fishing effort, and it is quite possible that it is cheaper to catch fish when it is more abundant in the sea. However, these simplifications do not significantly alter the incentives that lead to equilibrium. Figure 6 illustrates an example of equilibrium in a fishery for a high-cost scenario and a low-cost scenario. The X axis represents the level of fishing effort. The Y axis represents value in the form of arbitrary currency, both the value of the yield and the monetary cost.

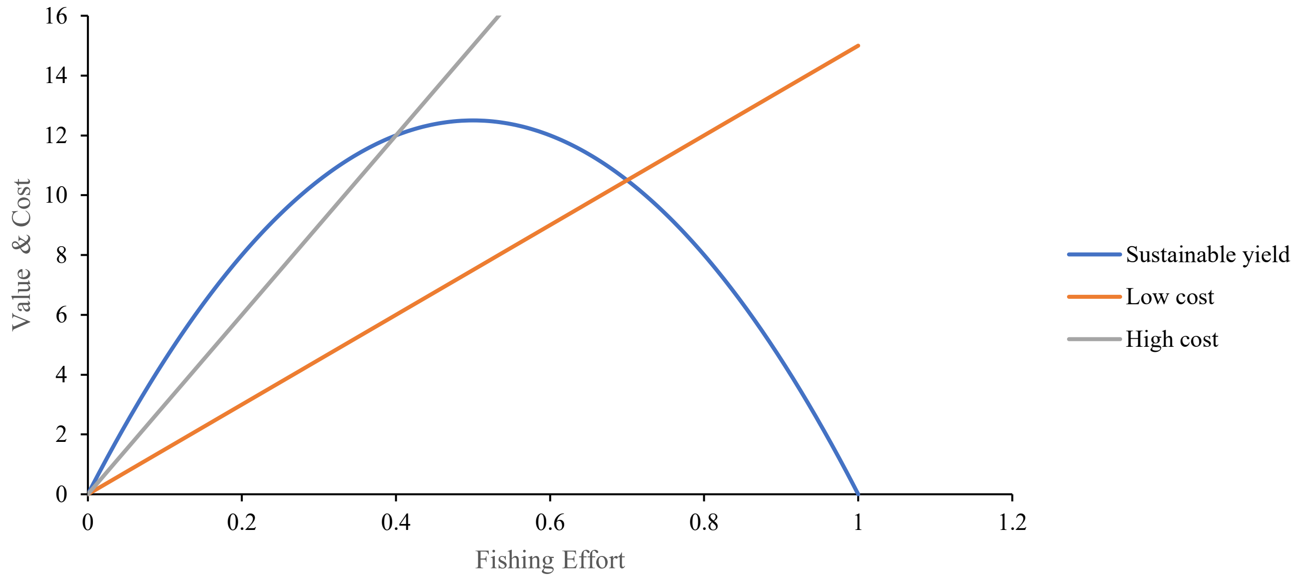

Figure 6. *Equilibrium in a fishery with high and low-cost examples.*

The graph illustrates sustainable yield and the cost of fishing with monetary value on the Y-axis and level of effort on the X-axis. The units are not relevant. It is important to note that a low value on the X-axis corresponds to a large stock, while a high value on the X-axis corresponds to a small stock. In this example, sustainable yield reaches a maximum at an effort level of 0.5. This corresponds to the maximum sustainable yield (MSY) in the fishery. A fishing effort lower or higher than this will produce less in terms of catches. The area of the graph to the left of the maximum is the low-effort side of the sustainable yield curve, where the stock size is larger than what produces maximum sustainable yield. The area to the right of the maximum is the high-effort side of the sustainable yield curve where the stock is smaller than what produces the maximum sustainable yield (Hannesson, 2021, pp. 71-74).

In the low-cost scenario, a free market open access fishery reaches equilibrium in the point where the orange low-cost curve intersects the blue sustainable yield curve. If fishing effort were any lower, there would be surplus profit in the fishery, incentivizing increased fishing. If fishing effort were higher, there would be a net loss in the fishery, incentivizing market exits. One can however see that this equilibrium is not optimal. For any value of sustainable yield, except for its maximum value, there are two values for effort that correspond to it. In the example graph, the low-cost equilibrium is at an effort level of about 0.7, but the same level of sustainable yield could be achieved with an effort level of about 0.3. This means that all the effort between 0.3 and 0.7 is effectively wasted, as the same level of production could be reached at a significantly lower cost. This happens because in a free market, open access fishery, participants in the market face a kind of prisoner's dilemma, where every participant would benefit by having the fishing effort at 0.3 instead of 0.7 but no participant can trust the others to restrain themselves and will therefore risk missing out on revenue by doing so themselves. The individual incentives are not compatible with the incentives of the entire group. This also has an additional risk involved. The reason the fishery achieves the same value of sustainable yield with a higher level of effort, is that the fish stock is significantly smaller, requiring a greater effort to locate and extract fish. This can be a major problem for the conservation and sustainable use of the fishery. If the fishery has a minimum stock size to facilitate reproduction, there is a chance that incentives would lead to a fishing effort too great for the stock to survive. This has happened multiple times in the history of fishing, and multiple times in the history of resource exploitation in the Antarctic.

In the high-cost scenario, the problems are much less serious. The equilibrium is reached when the grey high-cost curve intersects the sustainable yield curve. In this case, the cost of fishing is too high for there to be any risk of overfishing. Without any further regulation, both cases lead to an equilibrium with no economic profit in the fishery. In the high-cost scenario, this might be perfectly acceptable as the cost prevents overfishing and limiting access to the fishery to increase profits might be considered unethical or anti-competitive. In the low-cost scenario, regulation to limit access would benefit both the fishermen and the ecosystem, as profits and efficiency would increase, and the fish stock would be in a much safer position.

If we introduce a stochastic element to the growth function, it may be risky to have a level of effort too great, because random fluctuations in growth could set the stock on a path of extinction and leaving the stock level larger provides a much better buffer for such cases. If recruitment of fish fluctuates in such a way that it is lower than the catch level, or if catches fluctuate by accident so that they exceed recruitment, the stock will decrease. If the equilibrium is on the high-effort side of the sustainable yield curve, the dynamics of the fishery will lead to a smaller and smaller stock because then the smaller the stock is, the lower the recruitment is. If, however, the equilibrium is on the low-effort side of the sustainable yield curve, a smaller stock will have higher recruitment pushing the equilibrium back to its position. In other words, equilibrium is stable on the low-effort side of the curve and unstable on the high-effort side of the curve. It would therefore be much safer to organize the fishery so that it has an equilibrium with a relatively low effort and large stock, like the point C on figure 7 (Hannesson, 2021, pp. 156).

It is also worthwhile to consider that fishermen facing smaller returns might respond by increasing effort to catch more. It is not necessarily intuitive to assume that the best response to diminishing catches is to decrease effort. Fishermen have a vested interest in maintaining effort. They have invested into ships, fishing gear and equipment and reducing the level of effort could be perceived as wasting the investment. When a fishery surpasses the MSY and catches start decreasing, fishermen could decide to increase their effort to make up for lost revenue, leading to a smaller and smaller stock and eventually extinction of the species. This corresponds to what has been dubbed Grahams Law of Overfishing. Furthermore, when a species is fished to extinction, fishermen will move to a new species to maintain a return for their investments, repeating the dynamic that led to the previous extinction sequentially. This has been dubbed the Law of Sequential Depletion (Link, 2010, pp. 10). In any case, it is safer and more efficient to keep the fishery on the low-effort side of the sustainable yield curve.

4.2. Regulation of fisheries

In theory, the economic optimal level of fishing would be the level that maximizes the total profit of the fishery, or the distance between the sustainable yield curve and the cost curve. The profit attained in the fishery can be considered a resource rent, that is a level of profit above the perfectly competitive level that is attained by the utilization of natural resources. The benefits of these rents could then be distributed in accordance with the prevailing values of society. This, however, is dependent on economic efficiency being the primary objective of the industry. In some cases, a ruling regime might prefer maximum employment, food security or environmental conservation as primary objectives, in which case the optimal equilibrium solution would be somewhat different (Árnason, 2009, pp. 743). Maximizing employment could be achieved by allowing the equilibrium solution to be unchanged or by calculating the maximum amount of effort that the fishery could theoretically sustain, this corresponds to the point A (Figure 7). If food security is the priority, setting the limit as equal to the maximum sustainable yield would be the best policy. Profits would not be maximized, but the stock would be relatively safe from collapse, and this would maximize production from the fishery. This corresponds to the point B (Figure 7). With conservation as the goal, the simplest policy would just be to disallow fishing. A more conservative approach would be to allow fishing in a very limited capacity, with equilibrium on the low-effort side of the sustainable yield curve. This would correspond to some point between zero and the point B (Figure 7). Interestingly, the objective of maximizing profit is the one that best aligns with conservation as that also leads to a relatively large stock size (point C).

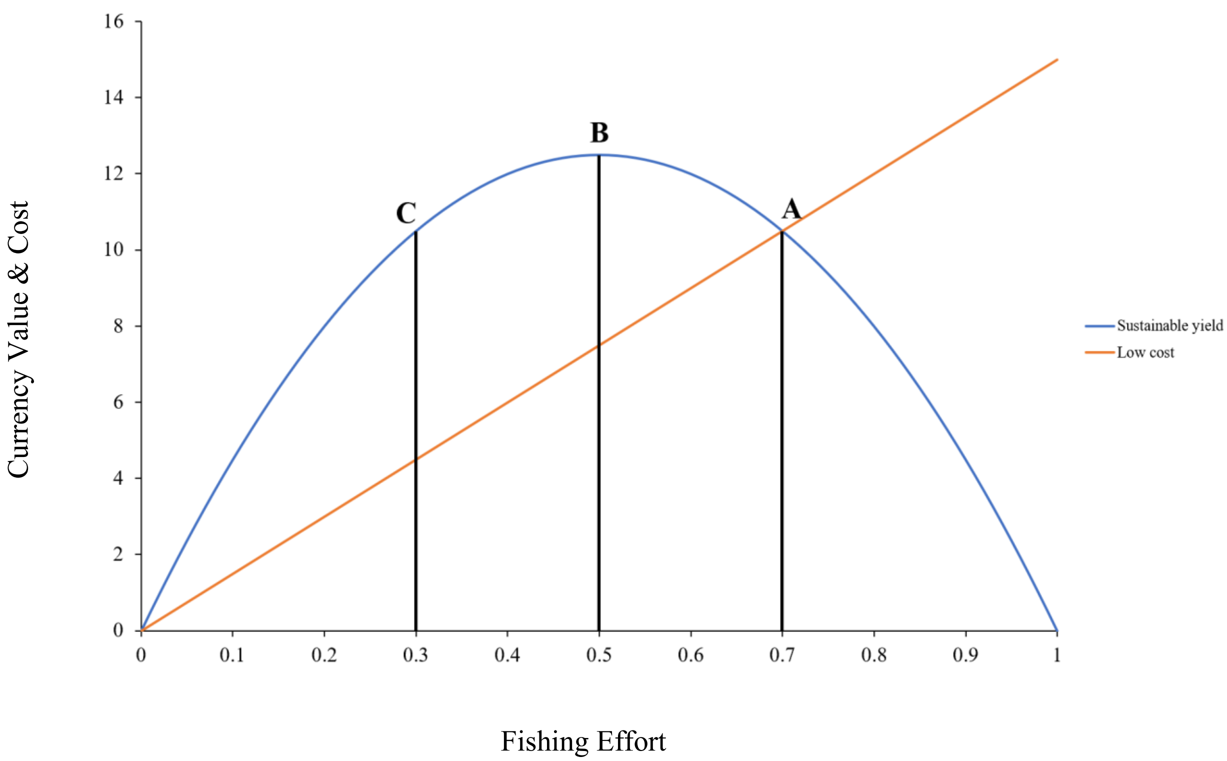

Figure 7. *Equilibrium in a fishery with examples of different regulatory objectives.*

A good regulatory regime for fisheries must accomplish at least two goals: to secure the sustainability of the fishery by preventing overfishing and to ensure economic efficiency. In order to secure both of these objectives, the regime requires three things: a management system, a monitoring system and a judicial system. The management system sets the rules that govern the fisheries, the monitoring system monitors the fish stock and how much is caught to ensure the effectiveness of the management system, and the judicial system ensures that fishermen comply with the management (Árnason, 2009, pp. 744).

The managements system must devise a way to control what level of effort occurs in the fishery. This can be done either by raising the cost of fishing, so that the equilibrium of the fishery is at the preferred level, or by setting a direct limit on fishing. Raising the cost of fishing can be done in many ways. You can set technological constraints by banning the use of some fishing gear or equipment or by requiring expensive monitoring equipment. You can set a requirement for licenses or set some resource rent taxes. Of all of these, taxes tend to be the “cleanest” method. It is simpler to regulate and more difficult to evade, and the resource rent that is taxed is not entirely lost, as the relevant authority can utilize the taxes to provide services. If the equipment that is banned or mandated is not necessary for other reasons, any increase in cost they lead to will be a waste of resource rent (Árnason, 2009, pp. 745-746).

A direct limit on catches is called a total allowable catch (TAC). This is simply a limit on the amount of catch allowed per fishing season. The simplest way to enforce a TAC is by closing the fishery once the limit has been reached and reopening it for the next fishing season. This can however lead to some adverse incentives, as fishermen in the fishery could start racing to catch as much as possible before the limit is reached. This is not optimal. Fishing faster tends to be more costly on average, as the methods are less refined, and inputs are used more intensively. This will also lead to adverse investments, with fishermen investing in equipment they would otherwise not need, and fishing vessels designed for harvest speed. Sometimes the fishing vessels will also be left idle for large parts of the year after the fishery has been closed because they are not suited for other fisheries. Another flaw of this method is that the supply of fish will be very seasonal. Since all the fish is caught in the beginning of the fishing season, there will be an overabundance at first, but a shortage in the later parts of the fishing season. This means a larger part of the catch will be turned into frozen or dried fish that has more shelf life and less will be sold fresh when it fetches the highest price. Any combination of these possible results will lead to an inefficient industry so it would be best to avoid using fishery closure and induce a race. In a way, setting a TAC without preventing a race for the fishery will lead to the cost rising to the point where the equilibrium catch is equal to the TAC (Árnason, 2009, pp. 745).

An effective way to regulate a fishery and ensure that the resource rents are collected, is to introduce property rights over the fishery. This can be done either by giving one firm sole ownership of fishing rights for an entire fishery, or by implementing a TAC with individual quotas, where firms can acquire ownership over a share of the fishery. This way, the firms do not have to race each other for the fish, because every firm has an allocated share of the catch and they can harvest at the speed that best suits them. Then the conservation issue is solved by correctly estimating the stock size and its recruitment rate to correctly set the TAC. This can be quite difficult and costly, so it is recommended to pair this with some resource tax system that can finance marine research. In the case of sole ownership, one can expect the monopolist in charge of the fishery to do the research themselves as it is in their best interest to maintain a sustainable resource stock. These methods have their problems as well. Sole ownership is not likely to be very popular, especially not among existing stakeholders. Establishing it might require driving smaller companies out of the market or forcibly buying them out. Establishing an individual quota system is easier, as current stakeholders can be included by making sure they have access to quotas to continue their business. These quotas can turn into quite valuable assets and giving them out for free can be unpopular among the population that feels others have been given valuable gifts while they were given nothing. On the other hand, requiring existing stakeholders to purchase these quotas can be very unpopular among the stakeholders as not all of them will be able to afford the investment. It is important to think it through when a system like this is implemented (Árnason, 2009, pp. 746-747).

4.3. Ecosystem-based fisheries management

All this theory provides useful insights into the dynamics at play in a fishery, but it makes many simplifying assumptions. One important factor to consider is the role of the species being exploited in the ecosystem. Generally, science and policymaking are focused on single species modelling, with an emphasis on the stock size and recruitment assessments. In Antarctica, however, CCAMLR follows a doctrine of ecosystem-based fisheries management (CCAMLR, 2021, About CCAMLR). What this entails is considering the interspecies effects of fisheries when deciding on catch limitations and fishing gear regulations and assessing the effect of the fishery on the entire ecosystem and not just the stock size of the relevant species. This can be very important when regulating a fishery in a very fragile ecosystem or when environmental conservation is a top priority (Link, 2010, pp. 60-61). Instead of focusing on figuring out how much fish of a certain species should be left in the water each year, this management system aims to specify what species mix is desired in the ecosystem. As one can imagine, this is quite a bit more complicated but is a more rigorous basis for conservation with a lower risk of accidental depletion of a fish stock. Implementing this type of system requires a trade-off, where the regulatory authority must evaluate whether these measures are necessary, feasible or preferable.

Ecosystems are incredibly complicated and numerous factors must be considered. One must acquire extensive knowledge on the geography of the area as well as the species that inhabit it. Commercially exploited species as well as non-commercial but ecologically important species should be categorized, their biological features, processes, and their interactions between each other observed and considered. Identifying which species are keystone species, which are dominant, and which are close to extinction is important. Key features of the geography, such as important sources of nutrients and spawning grounds, should be identified and decisions made on whether they need or warrant specific protection. The ecosystems vulnerability to climate change or natural disasters should be estimated to decide whether special precautions or responses should be implemented. Considering all these factors, substantially more needs to be understood and evaluated to implement an ecosystem-based fisheries management system (Link, 2010, pp. 47-49).

Ecosystem-based fisheries management systems are not a completely different way to regulate fisheries. The same theories and models are used but they are expanded to consider other factors. Models are augmented to include predation, food competition, climate impacts and spatial considerations. How far one is willing to take these augmentations is, again, a matter of trade-offs. One can get better and more accurate estimates of the stock sizes and the effects fishing will have on them by using more complex models with a larger set of variables, but it comes at a cost of increased research expenses and a more complicated regulatory framework. Although the differences between single species-based regulations and ecosystem-based regulations is complicated and it is not necessarily possible to predict exactly what they are, in general, one would assume that an ecosystem-based approach would lead to a lower level of effort, larger fish stocks, higher costs of fishing and higher implementation costs (Link, 2010, pp. 50-51).

4.4. The Antarctic krill fishery in context

In Antarctica, CCAMLR employs a system of total allowable catch with fisheries closure as a way to stop the fishery when the TAC is reached. They also employ many technical limitations meant to preserve the environment, such as mesh size regulation and protection of seabirds and mammals.

Much of their efforts also go into monitoring and research, to prevent illegal fishing, understand the amount caught and to estimate stock sizes (CCAMLR, 2021, Browse Measures and Resolutions). According to the theoretical framework established previously, this should lead to great inefficiencies in the fisheries, with wasted investments, inefficiently fast harvest methods and a volatile supply. In the krill fishery, however, this does not seem to be the case.

The catch limits that are set in the krill fishery are quite large. In area 48, the TAC is set at around 4 million tonnes, distributed among 4 subareas, but effectively the limit is 620 000 tonnes due to the precautionary catch limit (CCAMLR, 2010, Conservation Measure 51-01). This would suggest that the maximum sustainable yield, given environmental and ecological effects, of the catch is somewhere in the neighbourhood of 4 million tonnes a year. Having the effective limit at 620 000 tonnes should lead to a very large and secure stock size. But at no point has the precautionary limit been reached and CCAMLR has never had to close the krill fishery. This leads to the conclusion that using a TAC with fishery closures has not led to the type of race to catch described earlier. In fact, it seems that the catch limit is not in any way binding to the fishery and the sector reaches equilibrium on its own with a very large stock size. This suggests that the cost of harvesting krill in the Antarctic region is high enough to make the catch limitation irrelevant. An evaluation of Aker Biomarine, a Norwegian fishing firm which operates in the Antarctic krill fishery and catches the majority each year, conducted by students at NHH seems to support this conclusion, as the firm has not been able to return profits similar to other seafood companies (Rasmussen & Lindberg, 2020, pp. 110). If that is the case, equilibrium in the Antarctic krill fishery could be described much like the previous high-cost scenario but to the extreme (Figure 8; Figure 9).

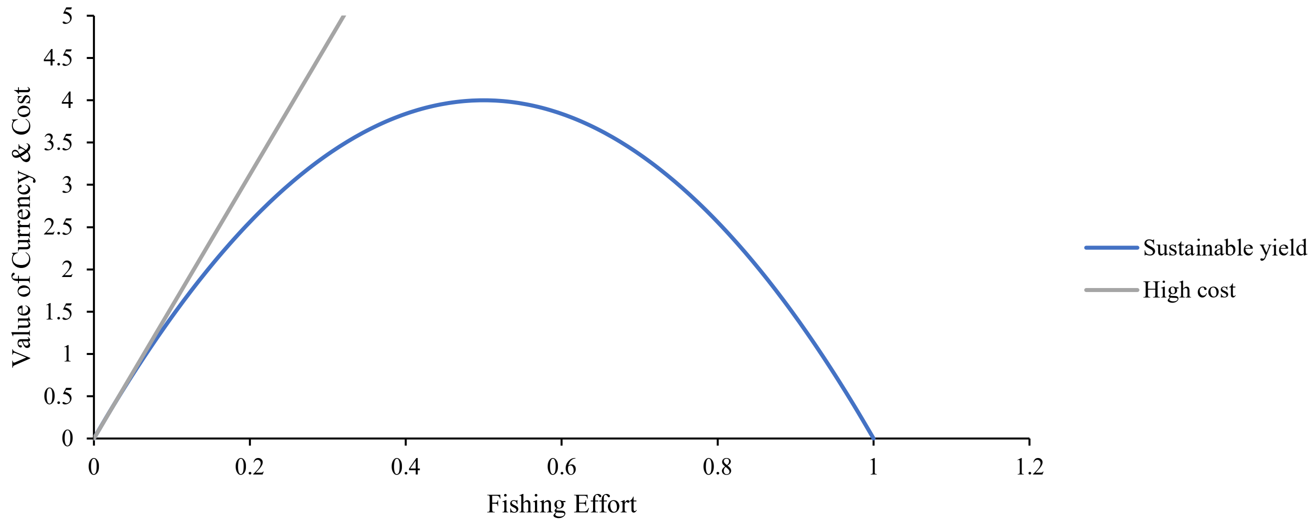

Figure 8. *Theoretical equilibrium in the krill fishery.*

We can see the equilibrium conditions more clearly if we focus on the area where the two lines intersect. Figure 9 displays the equilibrium and compares it to the catch limit.

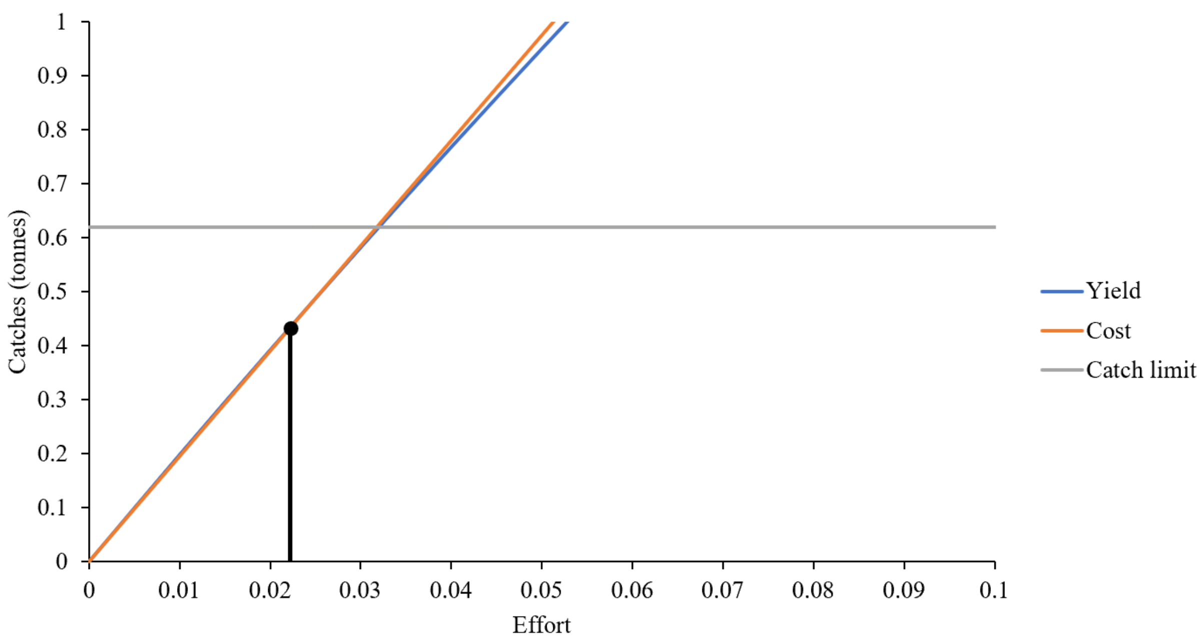

Figure 9. *Theoretical equilibrium compared with catch limit.*

Note. Black dot represents equilibrium point.

Figures 8 and 9 describe an equilibrium condition that fits the observed situation in the krill fishery. Equilibrium is reached at around 400 000 tonnes of catches, which is below the catch limit of 620 000 tonnes and far below the estimated MSY of 4 million tonnes. In this situation, we have an unregulated, open access equilibrium where there is no economic profit in the fishery but there is also no risk to the krill stock. There may be many explanations for this high cost. Many of the companies that operate in the Antarctic are based in faraway counties such as Norway, Britain, or France. The harsh climate may also limit the fishing season to a few months each year and require the ships to be better equipped for cold conditions. The majority of krill catches happen in March through May, while very little is caught in October through December. It is also possible that the regulations on monitoring and licences are quite costly.

5. Methodology and data

5.1. Scenarios

This paper examines three unique scenarios: status quo, high catch, variable catch. Status quo describes krill catch levels in the sub area 48 and 58 that do not rise above the current CCAMLR trigger level of 1 412 000 tonnes. High catch scenarios describe krill catch levels that exceed the current CCAMLR trigger level by a significant degree, reaching the defunct catch limit of 8,3 million tonnes and higher. The variable catch scenario describes yearly krill catches that exhibit large changes in tonnage, due to a catch limit based on a percentage of total stock size. All scenarios incorporate prey-predator dynamics simulated by a predator interaction model designed by Mori and Butterworth (2006). Additionally, the same scenarios are reconsidered for a theoretical development where the recession of sea ice in Antarctic waters reduces the krill stock's ability to replenish itself (Table 1).

Table 1. *Summary of scenarios analyzed.*

	Catch limit	Annual catch ('000 tonnes)
Scenario 1	< 600 000t	600
Scenario 2	8,385mt	8,385
Scenario 2	7mt	7,000
Scenario 2	< 4,7mt	4,700
Scenario 3.1	42%	0
Scenario 3.1	26%	20,000*
Scenario 3.1	19%	17,000*
Scenario 3.1	9.5%	8,900*
Scenario 3.2	27%	0
Scenario 3.2	23%	18,000*
Scenario 3.2	9.5%	8,900*

Note. *Catches are approximations of catches once system reaches equilibrium. Real figures fluctuate between years.

5.2. Data

We utilize historical catch data obtained from the CCAMLR database on krill catch from all nations from 2000 to 2020. In our model we project abundance for krill as well as six predator species that are dependent on krill as a primary prey source including: blue whales, minke whales, humpback whales, fin whales, fur seals, and crabeater seals until year 4000. As the baseline stock data for 2000, we use stock estimates derived in the Mori and Butterworth (2006) article.

5.3. Study Area

The study covers an area, defined as area A in Mori et al (2006), which covers about half of the Southern Ocean, including most of CCALMR statistical areas 48 and 58. It goes east from South America to the ocean south of Australia. This area serves as the primary fishing ground for krill. Some fishing takes place in the ocean south of the Pacific but that is significantly lower in terms of tonnage.

5.4. Mori and Butterworth predator interaction model

In 2006, M. Mori and D. S. Butterworth published the paper “A first step towards modelling the krill-predator dynamics of the Antarctic ecosystem”. The objective of the paper was to determine whether the interaction between krill and its predators can explain population trends in Antarctica. To achieve this objective, they developed a model to simulate the interactive stock dynamics of krill and six native predator species: blue whales, minke whales, humpback whales, fin whales, fur seals and crabeater seals. Using data on historical stock sizes, they estimated the values for parameters and developed a model capable of predicting population developments. In addition, the model was used to estimate equilibrium stock sizes for krill and all the predators in the absence of human involvement. One can assume that this corresponds to the stock sizes as they were before humans started exploiting marine living resources in the area, around 1800. In the paper they use this equilibrium estimate as the stock size for the year 1780 (Mori et al, 2006).

The model is comprised of 7 stock dynamics equations: one for krill and one for each of the predator species. The krill equation is a logistics growth function with additional terms that simulate the mortality caused by predators. The predator equations use a growth function based on growth by consumption of krill with a natural mortality term, a density dependant mortality term, and a catch term. In the paper, they separated the Southern Ocean into two regions, A and P, so many parameters have an indicator, a, to define from which region the estimates are drawn.

Krill stock dynamics:

$$B_{y+1}^{a} = B_{y}^{a} + r^{a}B_{y}^{a}\left(1 + \left(\frac{B_{y}^{a}}{K_{a}}\right)\right) - \sum_{j} \frac{\lambda^{j}\left(B_{y}^{a}\right)^{2}N_{y}^{j,a}}{(B^{j,a})^{2} + \left(B_{y}^{a}\right)^{2}} \qquad (2)$$

Predator stock dynamics:

$$N_{y+1}^{j,a} = N_{y}^{j,a} + \frac{\mu^{j}N_{y}^{j,a}\left(B_{y}^{a}\right)^{2}}{(B^{j,a})^{2} + \left(B_{y}^{a}\right)^{2}} - M^{j}N_{y}^{j,a} - \eta^{j,a}\left(N_{y}^{j,a}\right)^{2} - C_{y}^{j,a} \qquad (3)$$

where,

B_{y}^{a} is the biomass of krill in year y,

r^{a} in the growth rate of krill,

K_{a} in the carrying capacity of krill in the absence of predators,

λ^{j} is the maximum per capita annual consumption of krill by predator j,

$N_{y}^{j,a}$ is the number of predators of species j in the year y,

$B^{j,a}$ is the biomass of krill when the consumption and birth rate of predator j drops to half its maximum,

μ^{j} is the maximum birth rate of predator j, including survival rate of their young,

M^{j} is the natural annual mortality rate of predator j,

$\eta^{j,a}$ is a density-dependence parameter for natural mortality of predator species j,

$C_{y}^{j,a}$ is the number of individual of species j hunted in year y.

They note that while they include a term for catches of the predator species, they omit a similar term for krill. This is because krill catches have historically been very small relative to the stock size. In this study a term, F_{y}^{a}, is added to account for catches of krill (Mori et al, 2006, pp. 225-226).

Summaries of estimated parameters from the paper are presented in Table A1. Parameters were estimated for a reference case as well as different sensitivity scenarios, but here are only the estimates for their reference case. The parameters are named as defined in relation to the model. The index a refers to the fact that each parameter has one value for area A and one for area P. The indices b, m, h, f, s and c refer to the predator species: blue whales, minke whales, humpback whales, fin whales, fur seals and crabeater seals, respectively.

5.5. Stock estimates for use as baseline

In the supplementary material to an article published in 2021 by E. J. Murphy et.al., estimates of abundance for multiple predator species in the Southern Ocean are catalogued. For blue whales, humpbacks, and fin whales the estimates have 2015 as the base year, while minke whales have 1992/3 – 2003/4 as a base year. According to this, the number of blue whales is around 7 000, minke whales around 525 000, humpback whales around 97 000 and fin whales around 17 000. It is important to mention that the figure for Humpbacks is not limited to the Southern Ocean but encompasses the entire southern hemisphere (Murphy et al, 2021, data sheet 1, pp. 11). In an assessment by G. J. G. Hofmeyr for the IUCN Red List of Threatened Species, the total population of Antarctic fur seals was estimated at between 4.5 and 6.2 million around South Georgia. South Georgia is the home of around 95% of all Antarctic fur seals (Hofmeyr, 2008). J. L. Bengtson and B. S. Stewart, in 2018, estimated the abundance of crabeater seals to be between 5 and 10 million, although some estimates can range between 2 and 75 million (Bengtson et al, 2018). Krill biomass estimates are hard to come by. The most recent estimate from CCAMLR indicates about 62 million tonnes in statistical area 48 (Krafft et al, 2021).

Mori and Butterworths model prediction estimates the total equilibrium biomass to be around 145 million tonnes, 92,6 of which would inhabit area A, under circumstances where no exploitation of krill or any predator species has taken place. This would suggest that the current biomass should be quite a bit higher than that since fewer predators are feeding on the stock.

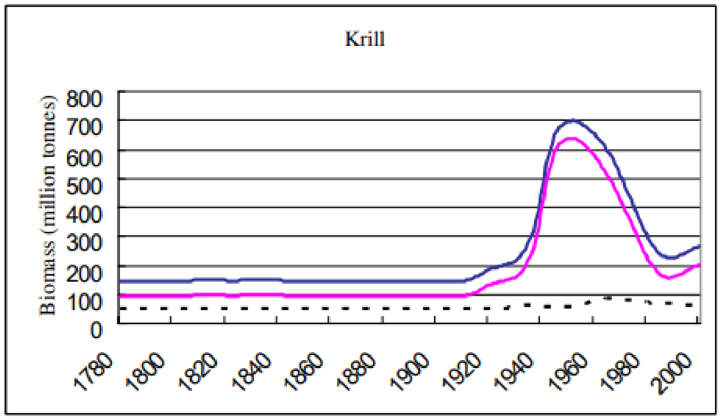

Figure 10. *Historical development of the krill stock. (Mori et al, 2006, pp. 264).*
Note: the dotted line represents stock size in area P, the pink line in area A and the blue line is the sum of both regions.

In the article they use the model, with the addition of catch data for the predators to estimate historical biomass and future development. Their 2000 estimate places the biomass at around 280 million tonnes, of which about 200 million inhabit area A, but that the stock would converge to an equilibrium of about a 150 million tonnes in the next century or two, 100 million in area A (Mori et al, 2006, pp. 264).

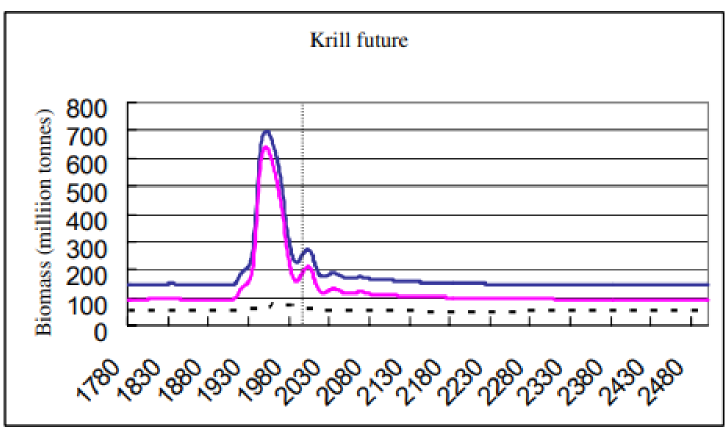

Figure 11. *Historical development and future projections of the krill stock. (Mori et al, 2006, pp. 264).*
Note: the dotted line represents stock size in area P, the pink line in area A and the blue line Is the sum of both regions.

Mori and Butterworths model also predicts the stock sizes for the predator species. In 2000 it places the stock of blue whales at around 2 000, minke whales at around 620 000, humpback whales at around 17 000, fin whales at around 40 000, fur seals at around 3 million and crabeater seals at around 15 million. For further comparison to the krill biomass, the numbers inhabiting area A are estimated to be 1 100 blue whales, 280 000 minke whales, 6 000 humpbacks, 10 000 fin whales, 3 million fur seals and 11 million crabeater seals. (Mori et al, 2006, pp. 263).

Since the numbers of individuals of these predator species as well as the biomass of krill as estimated by the model correspond relatively well to the estimates provided by observation, they make a good baseline for model analysis. Many of the differences between estimates can be explained by the fact that they cover different areas or areas of different sizes. For the sake of consistency, the model estimates for area A are the most convenient as abundance estimates from all species are derived on the same basis and cover the same area. The stock estimates used as baseline data for the year 2000 are summarized (Table 2).

Table 2. *Stock estimates used as the basis of modelling*

Species	Stock (tonnes)
Krill	200,000,000
Blue Whales	1,100
Minke Whales	280,000
Humpback Whales	6,000
Fin Whales	10,000
Fur Seals	3,000,000
Crabeater seals	11,000,000

5.6. Expected model limitations

This model and any results of analyzing it have some limitations. Although the model is quite complex and manages to simulate stock dynamics quite well to fit historical data, it does make simplifying assumptions about a very complex system and therefore may not be able to accurately predict every intricacy. For instance, the model does not simulate the mortality rate of predators to be dependent on the krill stock, only their reproduction. One would imagine that once all the food is gone from their habitat that they would either die or migrate, but the model simulates them living out their lifespan in the habitat without reproducing. The model does not simulate the effects of climate or other environmental conditions and the model does not account for spatial distribution of krill and predators and how their interactions are affected by geography. It is therefore important to keep in mind that precise figures may have a significant margin of error.

5.7. Reliance Weighted Index

The six predator species modelled in this paper, are directly reliant on the krill population as prey for survival as highlighted previously. To further evaluate the effect of the proposed krill management scenarios, it will be helpful to compare the effects of the scenarios on the predator stock levels with a simplistic figure. Therefore, a weighted index will be developed to simply illustrate the effect on the six predator stock levels in each scenario examined using scenario one as a base value in the index. The following equations are utilised:

$$NW_s = \frac{\sum_{i=1}^{n}(w_i \times \bar{N}^{j,a})}{\sum_{i=1}^{n} w_i} \tag{4}$$

$$I_s = \frac{NW_0}{NW_s} \times 100 \tag{5}$$

where,

NW_s is the weighted average of all six predator species a designated scenario, s.

$\bar{N}^{j,a}$ is the number of predators of species j from year 3500 to 4000

w_i is the weight of each species as defined by their reliance on krill as primary prey

I_s is the value of the overall index for each species

NW_0 is the base value for the index, which is the weighted average for scenario one

An average stock level will be calculated for blue whales, minke whales, humpback whales, fin whales, crabeater seals and fur seals in the expected equilibrium time frame of year 3500 to 4000 in each scenario. A weighted average will then be calculated utilizing the food web reliance percentages as described by Quentin & Ross, 1991 (4). The whale species included in the model and the crabeater seal are all classified as more than 90% reliant on krill as primary prey. Only, the fur seal has a reliance on krill as primary prey between 33% and 90% (Quetin & Ross, 1991). We will utilize 33% as a conservative estimate. The weighted average is then divided by the base value, which is scenario one's weighted average and multiplied by the chosen index value of 100 (5). Values greater than zero demonstrate the percentage difference between the compared values. Indices are computed for individual species as well as on a whole scenario level.

6. Analysis and results

The goal of the thesis is to analyze how the krill stock and the predators that depend on it react to different catch regulations. Two methods are considered: fixed catch limit and stock-based catch limit. For each scenario, multiple values for the catch limit are simulated as well as environmental differences in order to see what level of catches are sustainable, how high catches would have to be to impact the ecosystem and whether the two catch limit systems differ in their ability to accommodate change. When considered separately, the krill stock should be able to tolerate a very high level of catches. However, in line with the ecosystem-based management system employed by CCAMLR it is important to also consider the effect fishing has on other species krill interact with. The dynamics between prey and predator complicate the relationship between equilibrium catches and stock size and careless regulation could lead to unforeseen long-term consequences.

6.1. Scenario 1 – Fishing never exceeds the trigger level

For comparison, a reference scenario where catches never reach the trigger level is examined in this scenario. Area A encompasses most of statistical areas 48 and 58 (Figure 1). The trigger level for area 48 is 620 000, for 58.4.2 it is 352 000 tonnes and for 58.4.1 it is 440 000 tonnes. The combined total trigger level for area A is therefore 1 412 000 tonnes. Since most catches happen in concentrated areas in area 48, this reference case is not able to simulate the intricacies of spatial management and how concentrated fishing might affect local predator populations. This is an abstraction that assumes that the fishing effort is spread out over the entire area. To compensate for that, the total amount of annual fishing modelled will be 600 000 tonnes, significantly lower than the combined trigger level, but slightly higher than current catches.

To run the analysis, the model was applied to a time series of 2000 years, from the year 2000 to the year 4000. Historical catch data was applied to the years 2000 to 2020, after which yearly catches were 600 000 tonnes. At first glance, it is evident that the system is currently far from equilibrium (Table 3). The stock of krill does not reach its equilibrium state until around the year 2500, at about 92 million tonnes (Figure 12). Most predator species take some centuries longer, the fin whale stock is still adjusting in the year 3000 (Table 3; Figure 13).

Table 3. *Stock sizes with a low level of catches, 600 000 tonnes.*

Year	2000	2100	2500	3000	3500	4000
Krill	200.000.000	109.569.394	92.209.350	91.788.525	91.798.026	91.799.280
Blue whales	1.100	7.910	124.759	151.495	152.941	153.047
Minke whales	280.000	115.700	60.347	57.385	57.414	57.419
Humpback whales	6.000	74.309	72.055	71.974	71.976	71.976
Fin whales	10.000	70.476	151.814	112.325	108.956	108.638
Fur seals	3.000.000	8.978.588	3.189.486	2.667.731	2.665.591	2.666.335
Crabeater seals	11.000.000	4.158.767	1.253.633	959.107	951.152	951.272

In the first years, the krill stock lowers drastically before fluctuating until it starts a steady decline into equilibrium (Figure 12; Table 3). After a century of extensive whale exploitation, the stock of krill grew rapidly and is still adjusting. Minke whales and crabeater seals seem to have benefitted greatly from the lack of competition and their stocks are much greater than equilibrium will allow (Figure 13). The rest of the predators however have a much smaller stock. The blue whale stock grows at a rather even rate (Figure 13). It takes a few decades for the growth rate to pick up but between about 2200 and 2500, the stock recovers quickly until it nears its equilibrium in the year 3000. Minke whales and crabeater seals will decline steadily for the next 500 years (Figure 13). Humpbacks will recover rapidly over the next 100 years before slightly overshooting their equilibrium and declining into it by 2500 (Figure 13). Fin whales and fur seals will overshoot their equilibrium by quite a large margin and then steadily decrease in numbers until the year 3000 (Figure 13).

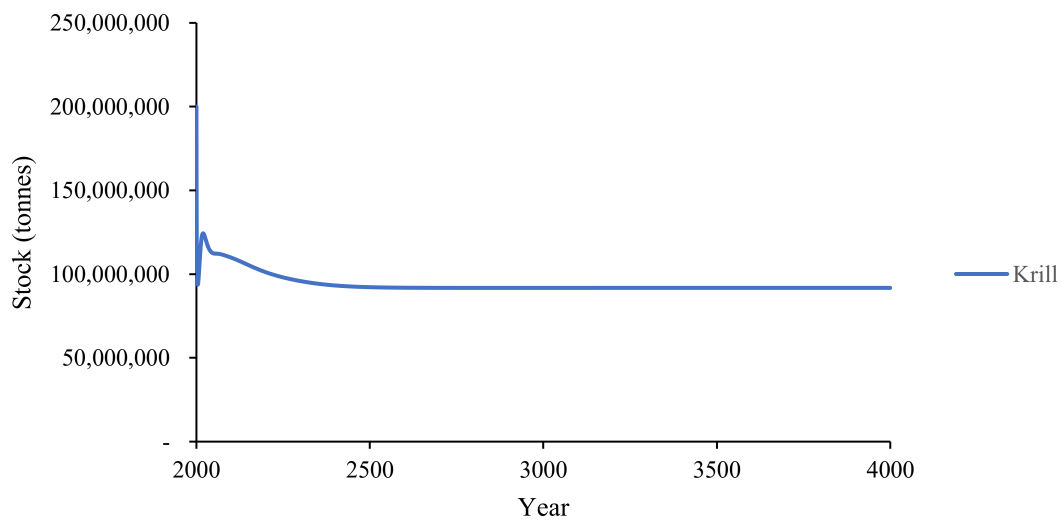

Figure 12. *The development of the krill stock with a low level of catches (600,000 tonnes).*

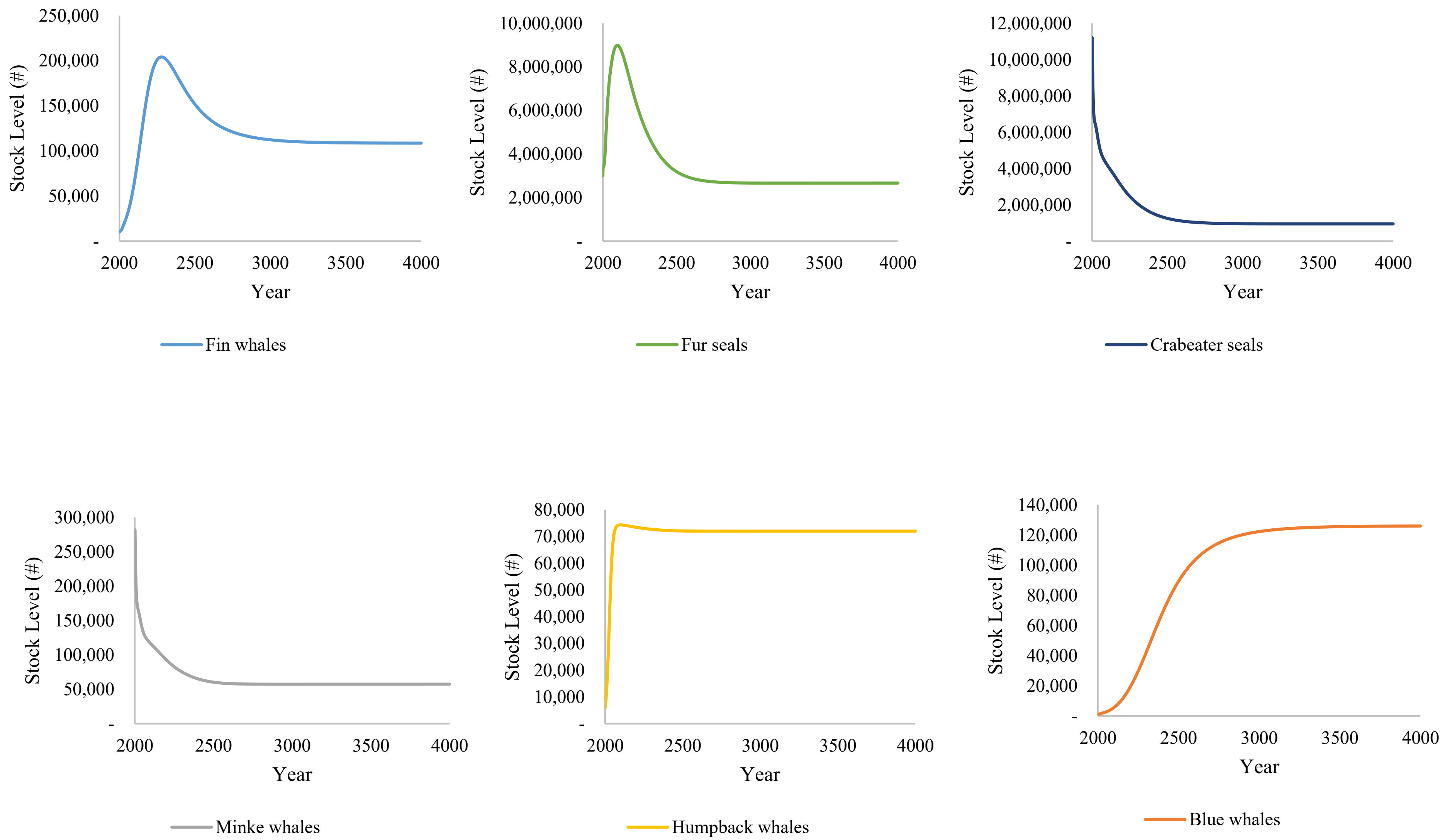

Figure 13. *The development of predator stocks with a low level of catches (600,000 tonnes).*

Note. All future figures describing predator stock development in a scenario will be listed in the Appendix A.

This apparent lack of equilibrium makes it very difficult to accurately set regulations that would influence the stock of krill to maximise profits. It also makes it very difficult to estimate the amount of krill that is ecologically feasible to extract. For instance, this makes it impossible to estimate a sustainable yield function as described earlier, and even if it were possible would such a function not be relevant until after a thousand years.

6.2. Scenario 2 – Fishing massively exceeds current trigger levels

In this scenario we will assume that a sufficient way to subdivide the catch limit into smaller management areas has been implemented and that the trigger level is no longer in effect. Then the catch limit stipulated by the conservation measures in areas 48, 58.4.1 and 58.4.2 adds up to 8,385 million tonnes, 5,3 from area 48, 2,645 million tonnes from area 58.4.2 and 440 000 tonnes from area 58.4.1. Assuming that the catch limit is binding after the year 2020, and fishing is evenly spread across the entire area, the model estimates that the stock of krill never reaches a stable equilibrium and will be extinct before the year 2800 (Table 4; Figure 14).

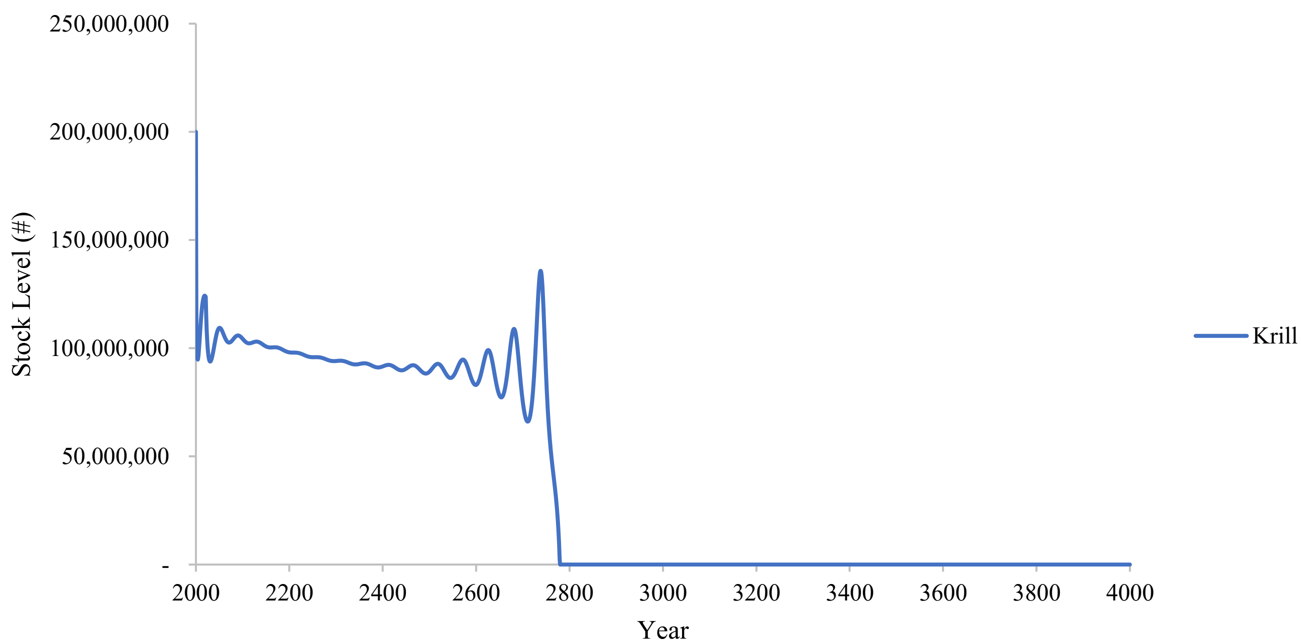

Figure 14. *The development of the krill stock with a high level of catches (8,385,000 tonnes).*

Table 4. Stock *sizes and krill catches with excessive level of catches (8, 385,000 tonnes).*

Year	2000	2100	2500	3000	3500	4000
Krill	200,000,000	103,407,937	89,123,013	-	-	-
Blue whales	1,100	5,089	72,392	72	0	0
Minke whales	280,000	98,638	54,354	2	0	0
Humpback whales	6,000	73,707	71,497	0	0	0
Fin whales	10,000	43,148	112,424	0	0	0
Fur seals	3,000,000	6,699,644	2,595,234	0	0	0
Crabeater seals	11,000,000	3,276,293	1,002,684	0	0	0

At around the year 2500, the stock starts to fluctuate wildly and increasingly until the down swing is big enough to wipe out the stock. The predator species all start to fluctuate at the same time as the krill stock (Table 4; Figure A1). It seems that the interaction between predators and krill leads into a spiral where a lower level of krill reduces the number of predators in the following year, which increases the growth of krill, leading to a higher number of predators and so on (Table 4; Figure A1). The system turns into a feedback loop that ends with extinction. If the catches are higher, the spiral happens earlier and vice versa.

Table 5. Stock *sizes and krill catches with catches under 7,200,000 tonnes.*

Year	2000	2100	2500	3000	3500	4000
Krill	200,000,000	104,601,120	90,544,101	89,647,193	89,670,778	89,683,447
Blue whales	1,100	5,551	82,468	116,448	120,212	120,762
Minke whales	280,000	101,578	56,075	51,023	51,096	51,126
Humpback whales	6,000	73,789	71,784	71,608	71,614	71,615
Fin whales	10,000	47,704	121,536	76,478	69,011	67,517
Fur seals	3,000,000	7,111,938	2,742,615	1,933,441	1,911,534	1,915,344
Crabeater seals	11,000,000	3,432,174	1,062,089	640,943	607,927	606,328

If the yearly catches are lower than 7.2 million tonnes a year, the system does not turn into such a spiral, at least not until after the end of the time modelled, in the year 4000 (Table 5; Figure A2). Of course, one must acknowledge that designing current regulations to prevent theoretical disasters that will happen after a thousand years may be unnecessary. However, this result would suggest that it is unwise to allow yearly catches to exceed 7 million tonnes with a fixed catch quota system. This leads to the conclusion that a fixed catch quota system seems to exaggerate natural fluctuations in the system and if the quota exceeds a certain level, the exaggeration leads to a spiral towards extinction.

6.3. Scenario 3 – Fishing exceeds current trigger level, but the catch limit is variable

To prevent the catch limit from exaggerating fluctuations, one could design a variable catch limit that would counteract, rather than reinforce them. If one could know the exact stock level each year, one could designate the catch limit as a percentage of the total stock size. Then fishing would be lower when the stock level fluctuates downward and higher when the stock level fluctuates upward. There is, however, a problem with information in this case. It is likely not possible for CCAMLR to know what the stock size is before the fishing season. It would most likely take quite some time and effort to estimate the stock size and to do so requires data gathered from fishing. If we assume data is gathered over the fishing season and that it takes less than one year to estimate the stock size using that data, one could set the catch limit as a percentage of the stock size as it was two fishing seasons earlier. In that case it is possible that instead of the catch limit counteracting the fluctuations that it will resonate with them and exaggerate them. It is conceivable that CCAMLR could use some modelling and calculations to estimate the two-year development of the stock and therefore be able to set the catch limit as a percentage of the current stock with some degree of accuracy. For these reasons, both scenarios will be modelled and analyzed; one where the catch limit is a percentage of the current stock, and one where the catch limit is a percentage of the stock as it was two years before.

6.3.1. Scenario 3.1 – Percentage of current stock

First, the case where CCAMLR can accurately estimate the current stock size and set a catch limit as a percentage of that will be analyzed. After 2020 a percentage catch limit is set and is immediately binding. For comparison with the fixed catch limit case, a percentage that broadly corresponds to about 8,4 million tonnes a year is set. This occurs with a catch limit of about 9,5% of the stock. This would lead to much higher catches to begin with, but the stock reaches equilibrium with about 8,5 million tonnes caught per year. Interestingly, this does not lead to stock collapse (Table 6; Figure 15).

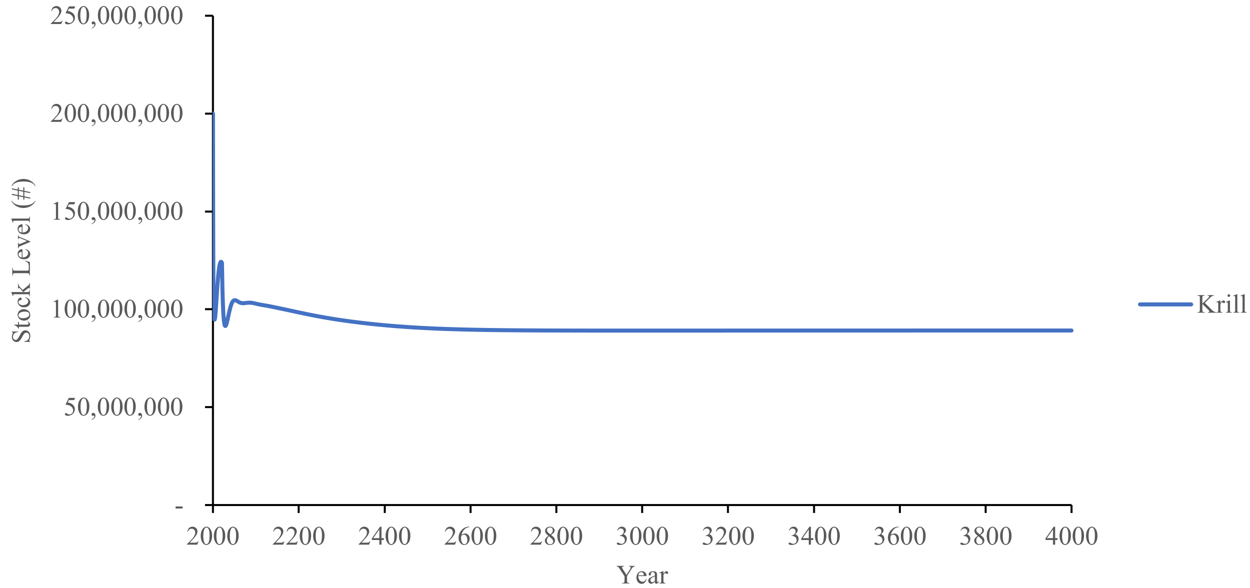

Figure 15. *Development of the krill stock with 9.5% catch limit.*

The krill stock reaches an equilibrium of about 89 million tonnes around the year 2500 and all the predators are perfectly capable of surviving under these circumstances (Table 7; Figure 15).

Table 6. Stock *sizes and krill catches with 9.5% catch limit.*

Year	2100	2500	3000	3500	4000
Krill	102.693.485,92	90.357.371,96	89.123.244,11	89.156.885,29	89.171.453,98
Blue whales	4.607,84	69.974,42	107.307,17	112.116,13	112.941,47
Minke whales	94.327,63	55.767,59	49.499,12	49.553,68	49.605,38
Humpback whales	73.514,24	71.754,90	71.515,67	71.521,60	71.524,28
Fin whales	38.468,01	113.930,78	68.958,03	59.951,26	57.839,95
Fur seals	6.157.114,43	2.712.212,60	1.769.152,01	1.728.441,92	1.733.527,63
Crabeater seals	3.061.497,88	1.048.378,71	574.671,92	527.023,81	523.097,10
Catch	9.755.881,16	8.583.950,34	8.466.708,19	8.469.904,10	8.471.288,13

In fact, all stocks would be able to sustain themselves under a much higher yearly catch (Table 6; Figure A6). It is not until the percentage catch limit nears 20% that some of the predator stock start declining (Table 7; Figure A5). At 19%, all the stocks do reach a sustainable equilibrium, with the exception of fin whales who are still converging toward some equilibrium by the year 4000. But the equilibrium stock sizes are all significantly lower than in the baseline scenario (Table 6).

Table 7. *Stock sizes and krill catches with 19% catch limit.*

Year	2100	2500	3000	3500	4000
Krill	91.230.599,00	89.012.427,99	86.183.116,39	85.997.332,90	86.048.362,68
Blue whales	2.169,82	20.030,28	49.985,49	60.385,92	64.021,02
Minke whales	65.000,21	51.456,79	41.250,34	40.151,08	40.270,44
Humpback whales	71.964,99	71.519,46	70.967,16	70.927,13	70.937,08
Fin whales	14.880,43	46.014,01	29.405,81	16.961,02	11.500,29
Fur seals	2.731.781,55	2.168.502,61	991.965,95	705.902,34	644.325,21
Crabeater seals	1.639.132,89	796.961,85	282.258,12	144.431,30	97.602,74
Catch	17.333.813,81	16.912.361,32	16.374.792,11	16.339.493,25	16.349.188,91

At a catch limit of 25% to 27%, fin whales are almost extinct, and all other stocks seem to oscillate significantly while seeming to remain close to some equilibrium (Figure 16; Figure A4). It seems a percentage catch limit of 25% to 27% resonates with the natural fluctuations instead of counteracting them (Figure 16; Figure A4). If the catch limit is 28% or higher, all predator stocks become extinct except humpbacks and the oscillation stop. A catch limit of 42% depletes the krill stock.

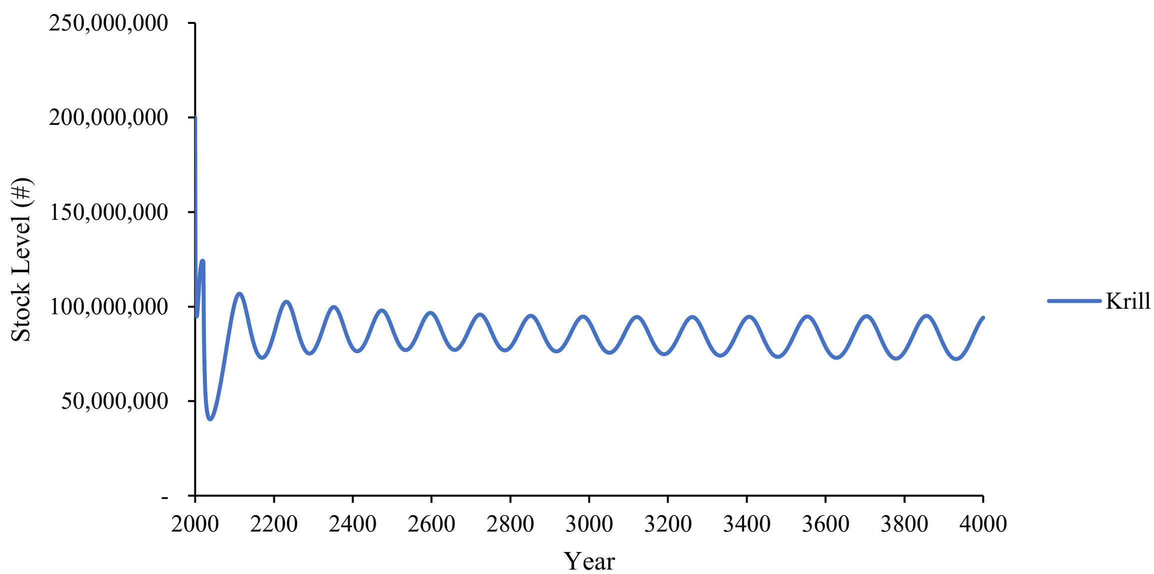

Figure 16. *Development of the krill stock with 26% catch limit.*

A catch limit of about 10% to 15% seems to be perfectly sustainable for all stocks and provide the fishery with a yearly catch of about 9 to 13 million tonnes (Figure A6).

6.3.2. Scenario 3.2 – Percentage of last known stock

Assuming that it takes a year from data collection to estimate stock size, CCAMLR could set the catch limit as a percentage of the last known stock size, which would have been two fishing seasons earlier. Starting in 2021, this catch limit becomes binding. This results in a very similar situation to scenario 3.1. The stock handles fishing quite well with a catch limit of 15%. No obvious resonance issues can be seen until the catch limit exceeds 20% of the stock, which does not begin to suffer serious declines until 23% (Figure A7).

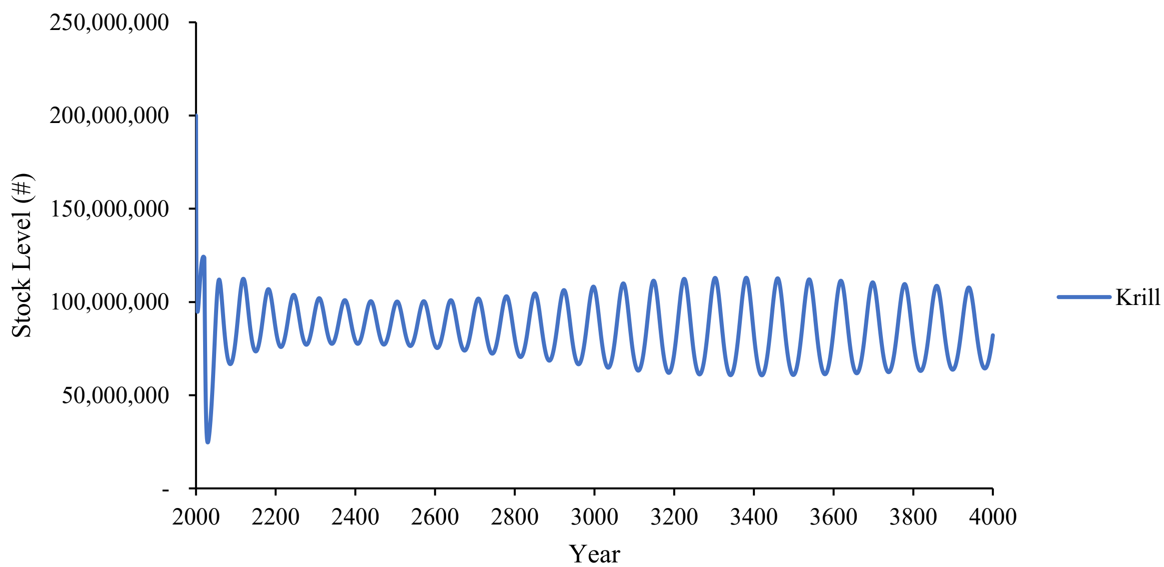

Figure 17. *The development of the krill stock with a 23% catch limit.*

However, unlike the fixed catch limit scenario, this system seems to be in equilibrium. The stock level oscillates around an equilibrium level, but the oscillations are not large enough to risk collapse (Figure 17). The predator stocks oscillate around equilibrium as well but the fin whales, fur seals and crabeater seals do not seem to tolerate this regime and approach extinction by the year 4000 (Figure A7; Table 8)

Table 8. *Stock sizes and krill catches with a 23% catch limit.*

Year	2100	2500	3000	3500	4000
Krill	88.880.477,25	98.800.579,23	107.555.871,07	60.882.932,11	82.131.845,08
Blue whales	1.203,08	7.343,17	24.801,10	33.464,07	31.289,57
Minke whales	38.242,54	45.108,12	41.083,48	32.471,46	26.398,94
Humpback whales	68.234,77	71.563,13	72.725,13	65.923,01	67.338,95
Fin whales	6.339,23	13.476,39	10.858,79	3.631,07	973,31
Fur seals	988.923,98	1.404.845,61	795.380,07	306.023,30	117.127,58
Crabeater seals	693.114,61	478.772,23	193.286,19	42.414,18	7.764,24
Catch	19.445.159,36	22.413.827,59	24.884.488,89	14.012.821,06	18.170.601,00

If the catch limit is raised any further, the oscillations get greater and by 27% all stocks become extinct almost immediately.

With a limit below 15%, the percentage catch limit is much safer than the fixed catch limit and it does not seem to be necessary to use stock data from the current fishing season (Figure A8). It is worth noting that constantly updating research on stock sizes and adjusting catch limits accordingly is a much more expensive way to regulate than a fixed catch limit. It is however much safer and better suited to deal with changes in the circumstances of the krill stock and predator populations.

6.4. The effect of sea ice reducing krill recruitment

Since krill recruitment is highly dependent on sea ice, climate change can potentially have severe effects on the Antarctic ecosystem and therefore on the viability of the fishery. Without precise estimates on how much sea ice is expected to decrease and how much that will affect recruitment, it is not possible to accurately estimate how much of a threat climate change is to the fishery. It is, however, possible to demonstrate what kind of effects such a development might have. In this analysis we explore a case where sea ice recession reduces the krill recruitment factor, r, by 20%, from 0,4 to 0,32. There is little literature available that describes the possible effects of climate change on future sea ice development or how much this would affect recruitment. In this analysis, the assumption is made that the recruitment would be reduced by 20% to have an estimate of what the resulting effects could be.

With a fixed catch limit, as described in scenarios 1 and 2, the fluctuations that lead to extinction start to appear at a catch limit of 4,7 million tonnes. The extinction does not happen before the year 4000 however and it is not until the catch limit reaches 5 million tonnes that it happens. There is a risk that extinction will eventually happen due to the fluctuations with a lower catch limit, but no indication of that appears before the year 4000. In comparison to scenario 2, the same result happened with a catch limit of 7,3 million tonnes. Climate change could therefore reduce the maximum sustainable harvest by about 2,6 million tonnes, or about 36%, if it reduces the recruitment factor by 20%.

With a percentage catch limit based on current stock sizes, as in scenario 3.1, the stock sizes start to oscillate with a catch limit of 15% to 16% and fin whales and crabeater seals are endangered. With a catch limit of 20%, all species except humpback whales face extinction by the year 2500. With a catch limit of 32%, humpbacks face extinction as well and the krill stock will deplete with a catch limit of 33%. With a recruitment rate of 0,4, this development with a catch limit of 25% to 43%. The catch limit that leads to oscillations lowered by 10 percentage points, and so did the catch limit that leads to extinction of the krill stock. The catch limit that leads to predator extinction, except for humpbacks, lowered by 8 percentage points.

With a percentage catch limit based on the stock size as of two years earlier, as in scenario 3.2, the stock sizes start to oscillate at a catch limit of about 15%, much like in scenario 3.1. Fin whales and crabeater seals face extinction with a catch limit of 20% and fur seals and blue whales follow along with a catch limit of 21%. All species face extinction when the catch limit reaches 25%. In scenario 3.2, the same development happened between a catch limit of 20% and 27%. The catch limit that leads to extinction only lowered by about 2 percentage points, but the catch limit that leads to significant oscillations lowered by 5% percentage points. If scenario 3.2 is considered with a catch limit of 10%, the equilibrium stock size is slightly lower when the recruitment factor is lower, by about 4 million tonnes. This leads to a yearly yield that is about 300 000 tonnes lower. It is noteworthy that scenario 3.2 showed better performance, in terms of predator conservation, than 3.1 when recruitment is lower, while 3.1 showed better performance before.

6.5. Reliance weighted index

To simply contrast the effects of krill stock variability in scenarios 1 to 3, an index is used to illustrate each scenario's performance in terms of predator stock levels relative to the status quo scenario 1. The application of a 9.5% catch limit with variable catches scored the highest in the index, 63 points, for predator stock levels compared to the status quo scenario where catches remain at 600,000 tonnes annually throughout the equilibrium period, year 3500 to 4000 (Table A4; Figure 18). It was followed by the second variation of scenario 3.1 where the catch limit is 19% with variable catches and resulted in 24 points (Table A5; Figure 18). Scenario 3.2, where catch limit is set at 23% ranks at 11 (Table A7; Figure 18). The third variation of scenario 3.1, 25% variable catch limit ranked with 8 (Table A6; Figure 18). Scenario 2 yields extinction of all predator species illustrating the importance of ensuring the krill stock is not fished in excess of 7,200,000 tonnes (Table A3; Figure 18).

This index illustrates that predator stocks benefit most in the long term through management based on percentage-based catch limits, due to the success of predator stocks when percentages are at 9.5% or 19%. This suggests an optimal percentage catch limit range may be between 9.5% and 19%. Management regimes such as scenario 2, where the catches do not exceed 4.7 million tonnes are also successful in achieving a stable equilibrium for the krill and predator species involved by year 4000. In the aforementioned successful scenarios, predator populations are also able to reach equilibrium when tested in the sea ice scenario.

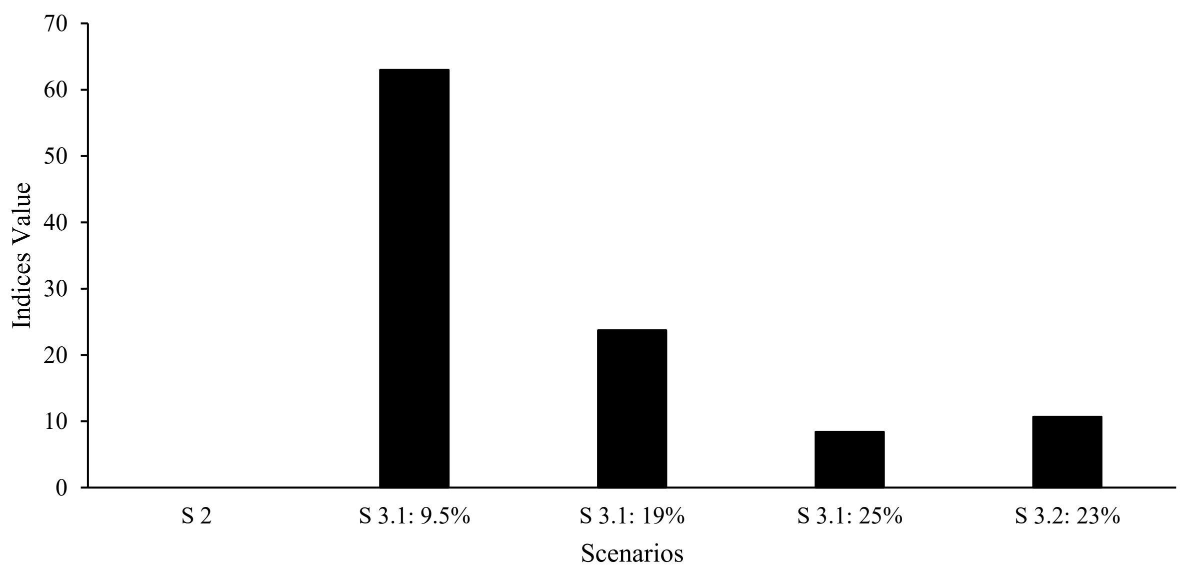

Figure 18. *Reliance indices for six predator species in each krill management scenario.*

Note. S = scenario.

There are several expected limitations with the reliance weighted index. Strictly considering abundance calculated through weighted average is a simplification that allows for simple comparison of predator stock levels. Increased inter-species competition between the predator species may have additional affects not considered on krill dynamics and inter-predator species. The weighted average is not the most precise measurement of the abundance changes over 500 years, where food web reliance weights also carry a degree of uncertainty. This may alter the timeline to establish a stable equilibrium. It is also not known how predator species habitat, physiology, breeding and lifecycles will react to increasing water temperatures and receding sea ice. This index assumes all species are able to survive and breed successfully in future conditions which may or may not occur.

7. Discussion and conclusions

7.1. Summary of results

The results of the analysis are summarized in Table 9. For each of the scenarios, a few different values for the catch limitations are considered in order to gain insight into how different levels of catches affect the dynamics of the system. Each scenario and each catch limit within are given values for how they hold up to different criteria. These criteria are:

Annual catch. This factor gives some idea of the economic benefit of this configuration.

Oscillation. In the table this is given a yes (Y) or no (N) value. A negative value in considered preferable because even though oscillation may not be bad in and of itself it leads to more uncertainty and risk and in some cases causes unsustainability.

Sustainability. If the krill stock can sustain itself under the relevant configuration, this factor is given a Y, and an N otherwise.

Sea ice test. If the krill stock can sustain itself in this configuration even if sea ice recession decreases recruitment by 20%, this factor is given a Y, and an N otherwise.

Predator index factors. The remaining factors are an index for how well the different predators thrive in these configurations compared with the baseline scenario 1. The final factor is a weighted average for all predators. Any value over 50 is considered acceptable, values between 30 and 50 are considered low but not dangerously so, and values under 30 are unacceptable.

Table 9. *Summary of results*

	Catch limit	Annual catch ('000 tonnes)	Oscillation	Sustainable	Sea ice test	Blue whale	Minke whale	Humpback whale	Fin whale	Fur seal	Crabeater seal	Total
Scenario 1	< 600 000t	600	N	Y	Y	100	100	100	100	100	100	100
Scenario 2	8,385mt	8,385	Y	N	N	0	0	0	0	0	0	0
Scenario 2	7mt	7,000	N	Y	N	79	89	99	63	72	64	78
Scenario 2	< 4,7mt	4,700	N	Y	Y	87	93	100	76	82	77	86
Scenario 3.1	42%	0	Y	N	N	0	0	0	0	0	0	0
Scenario 3.1	26%	20,000	Y	Y	N	7	52	96	0	2	0	29
Scenario 3.1	19%	17,000	N	Y	N	37	68	98	10	21	10	43
Scenario 3.1	9.5%	8,900	N	Y	Y	72	86	99	51	63	53	72
Scenario 3.2	27%	0	N	N	N	0	0	0	0	0	0	0
Scenario 3.2	23%	18,000	Y	Y	N	23	59	96	2	9	2	35
Scenario 3.2	9.5%	8,900	N	Y	Y	72	86	99	51	63	53	72

Note. Preferable or acceptable values are colored green, non-dangerous low values are colored yellow, and non-preferable or unacceptable values are colored orange.

7.2. Discussion

The most interesting and significant results are that the prey-predator dynamics create a rhythmic natural fluctuation in the system that fishing can inadvertently exaggerate. With a fixed catch limit, the system can easily spiral out of control, ending in extinction of all species. This is what would happen if the current catch limit of 8,3 million tonnes, not the precautionary trigger level of 1,4 million tonnes, would be binding. Note that this is the combined catch limit for statistical areas 48 and 58. The same can happen with a variable catch limit based on a percentage of the entire stock, but that counteracts some of the fluctuations and allows for much more fishing than would otherwise be possible. Even if the regulatory regime can not estimate current stock size completely accurately and must use two-year-old data, this still allows for much more fishing than a fixed catch limit. In each of the scenarios considered, there is a level of catches that is completely sustainable, a catch limit below 4,7 million tonnes for a fixed catch limit and a catch limit between 10 and 15% for a percentage catch limit. The fixed catch limit provides lower catches, but a higher equilibrium stock for the predator species. The variable catch limit provides a much higher yield from the fishery, but this leads to a lower equilibrium stock size for predators. The predator stocks are still quite large and sustainable, but if one were to prioritise an even higher stock level for them, one could lower the percentage catch limit quite significantly, while still providing more yield than the fixed catch limit can.

The variable catch limit is also more equipped to deal with the effects of sea ice recession. If recession were to lower recruitment and leave a smaller equilibrium stock, the catch limit would automatically become lower as stock estimates are updated. If this were to happen with a fixed catch limit, the regulations would have to be specifically updated in response.

A variable catch limit based on a percentage of stock size does require a lot more work to implement than a fixed catch limit. This would require CCAMLR and SCAR to continually work on updating stock estimates, requiring several people on duty every year. The compliance and surveillance scheme CCAMLR already operates should provide a steady stream of data for use in this regard.

Although not explicitly modelled in this analysis, if the catch limitations imposed by CCAMLR should ever become binding and demand for krill should exceed the limits currently in place, it would be recommended to implement an individual catch quota system. This system allows for a much more flexible and economically efficient fishery and prevents any sort of race between fishermen to reach the catch limit. It would be easily implemented with a fixed or variable catch limit system and could integrate spatial management as well.

7.3. Further research

Much research is needed to make analysis such as this one more accurate. Very little information can be found about krill recruitment and natural mortality due to the difficulties surrounding monitoring and understand a wild species in its natural habitat. The parameter estimates from the model seem to fit well with stock development, but it would be prudent to have further research into the matter to be able to confirm or update the model. The model does make simplifications that ease calculations and work could be done on discovering the stock dynamics and interactions of each species, and including more species. A more precise model would make the results closer to reality and therefore a very useful tool for resource regulation in Antarctica.

CCAMLR has for decades been waiting for a scientific assessment of predator-pray interaction in the krill fishery, specifically in regard to spatial management. How the distribution of krill and its predators and how migration patterns between areas affect the results of this analysis in unknown.

The model demonstrates that climate change causing sea ice recession in Antarctica can be serious threat to the ecosystem and the viability of the fishery. Assessments that could predict the extent to which climate change could cause a reduction in krill recruitment under different climate scenarios could be used to further establish the cost of climate change to the krill fishery.

It is interesting to note that, according to the model prediction, the biomass of krill was exceptionally large between 1940 and 1990, reaching a peak of about 700 million tonnes in 1960 from about 170 million in 1900 and 230 million in 1995 (Mori et al, 2006, pp. 263) (Figure 10). This would correlate very well with the historical catch trends observed in the krill fishery. Interest in it started in the 1960s and slowly increased until about 1990 when catches decreased significantly (Figure 10). After 2010, when the stock level had risen to about 270 million tonnes, interest seems to be rising again (Figure 11). One could speculate that while the stock level was very high in 1960s through the 1970s, the cost of harvesting was quite low, but after 1990 they were high enough to dissuade further harvests (Figure 11)). Then in the present, a higher stock size coupled with possible technological improvements make the fishery more profitable than before . Quantifying this relationship and confirming whether it is significant would be an interesting avenue for further study.

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9. Appendix A

Table A1. *Estimated values for parameters in krill Dynamics & Predator Dynamics (Morri & Butterworth, 2006)*

Region	A	P	N/A
r(a)	0,40	0,58	
K(a)	822.000.000,00	125.000.000,00	
B(1780,a)	92.600.000,00	52.100.000,00	
N(1780,b,a)	163.332,00	26.861,00	
N(1780,m,a)	47.155,00	271.720,00	
N(1780,h,a)	71.589,00	47.095,00	
N(1780,f,a)	151.505,00	87.187,00	
N(1780,s,a)	2.898.590,00	-	
N(1780,c,a)	241.045,00	733.511,00	
N(2000,b,a)	758,00	1.109,00	
N(1985,m,a)	325.963,00	420.598,00	
N(1997,h,a)	5.046,00	4.859,00	
N(1997,f,a)	10.649,00	27.361,00	
N(1930,s,a)	175,00	-	
N(1976,s,a)	262.422,00	-	
N(1991,s,a)	1.234.240,00	-	
N(2000,c,a)	11.794.500,00	3.753.920,00	
B(b,a)	170.000.000,00	70.000.000,00	
B(m,a)	145.000.000,00	52.900.000,00	
B(h,a)	22.300.000,00	23.100.000,00	
B(f,a)	128.000.000,00	71.900.000,00	
B(s,a)	146.000.000,00	-	
B(c,a)	134.000.000,00	73.400.000,00	
η(b,a)	0,000000040	0,000001000	
η(m,a)	0,000000300	0,000000200	
η(h,a)	0,000001250	0,000001500	
η(f,a)	0,000000040	0,000000070	
η(s,a)	0,000000004	-	
η(c,a)	0,000000007	0,000000006	
λ(b)			450,62
λ(m)			32,13
λ(h)			108,00
λ(f)			110,40
λ(s)			2,71
λ(c)			5,51
μ(b)			0,16
μ(m)			0,20
μ(h)			0,18
μ(f)			0,16
μ(s)			0,28
μ(c)			0,24
M(b)			0,03
M(m)			0,04
M(h)			0,08
M(f)			0,05
M(s)			0,07
M(c)			0,07

Table A2. Scenario 1 - Status Quo – Catches remain at 600,000 catch limits

Species	*Avg. equilibrium stock level from year 3500-4000*	*Species Index*	*Weight*	*Weighted average*	*Overall Index*
Blue whales	153,014	Base value	90%	432,282	Base value
Minke whales	57,418		90%		
Humpback whales	71,976		90%		
Fin whales	108,740		90%		
Fur seals	2,666,078		33%		
Crabeater seals	951,201		90%		
Sum	***4,008,427***				

Table A3. Scenario 2: Catches greatly exceed trigger levels at 8 000 000 tonnes

Species	*Avg. equilibrium stock level from year 3500-4000*	*Species Index*	*Weight*	*Weighted average*	*Index*
Blue whales	0.02	0.00	90%	0	0
Minke whales	0.00	0.00	90%		
Humpback whales	0.00	0.00	90%		
Fin whales	0.00	0.00	90%		
Fur seals	0.00	0.00	33%		
Crabeater seals	0.00	0.00	90%		

Table A4. Scenario 3.1. Variable catches are based on 9.5% catch limits

Species	*Avg. equilibrium stock level from year 3500-4000*	*Species Index*	*Weight*	*Weighted average*	*Index*
Blue whales	112,636	74	90%	270,427	63
Minke whales	49,585	86	90%		
Humpback whales	71,523	99	90%		
Fin whales	58,662	54	90%		
Fur seals	1,731,056	65	33%		
Crabeater seals	524,164	55	90%		
Sum	***2,547,625***				

Table A5. Scenario 3.1. Variable catches are based on 19% limit

Species	*Avg. equilibrium stock level from year 3500-4000*	*Species Index*	*Weight*	*Weighted average*	*Index*
Blue whales	62,473	41	90%	102,424	24
Minke whales	40,196	70	90%		
Humpback whales	70,932	99	90%		
Fin whales	13,904	13	90%		
Fur seals	666,995	25	33%		
Crabeater seals	117,603	12	90%		
Sum	***972,104***				

Table A6. Scenario 3.1. Variable catches are based on a 25% catch limit

Species	*Avg. equilibrium stock level from year 3500-4000*	*Species Index*	*Weight*	*Weighted average*	*Index*
Blue whales	18,096	0.12	90%	36,267	8
Minke whales	31,736	0.55	90%		
Humpback whales	70,108	0.97	90%		
Fin whales	829	0.01	90%		
Fur seals	159,914	0.06	33%		
Crabeater seals	15,228	0.02	90%		
Sum	***295,911***				

Table A7. Scenario 3.2. Percentage of last known stock at 23% (worst case scenario)

Species	*Avg. equilibrium stock level from year 3500-4000*	*Species Index*	*Weight*	*Weighted average*	*Index*
Blue whales	35,641	0.23	90%	46,220	11
Minke whales	33,840	0.59	90%		
Humpback whales	69,391	0.96	90%		
Fin whales	2,201	0.02	90%		
Fur seals	228,816	0.09	33%		
Crabeater seals	23,074	0.02	90%		
Sum	***392,963***				

Figure A1. *The development of predator stocks with scenario 2 (8.385mt).*

Note. All figures x-axis display year and y-axis display stock level (#).

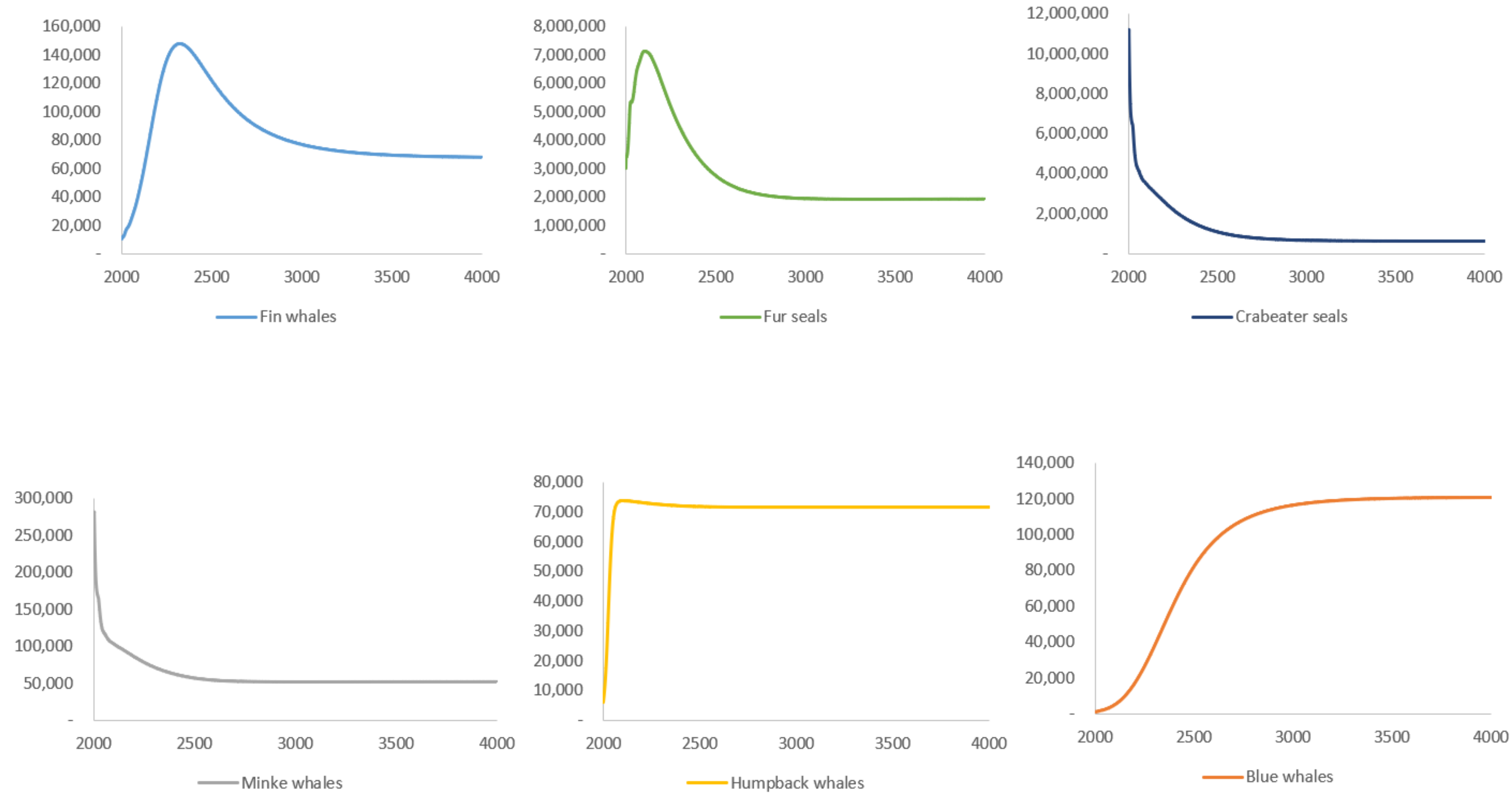

Figure A2. *The development of predator stocks in scenario 2 (<7.2mt).*

Note. All figures x-axis display year and y-axis display stock level (#).

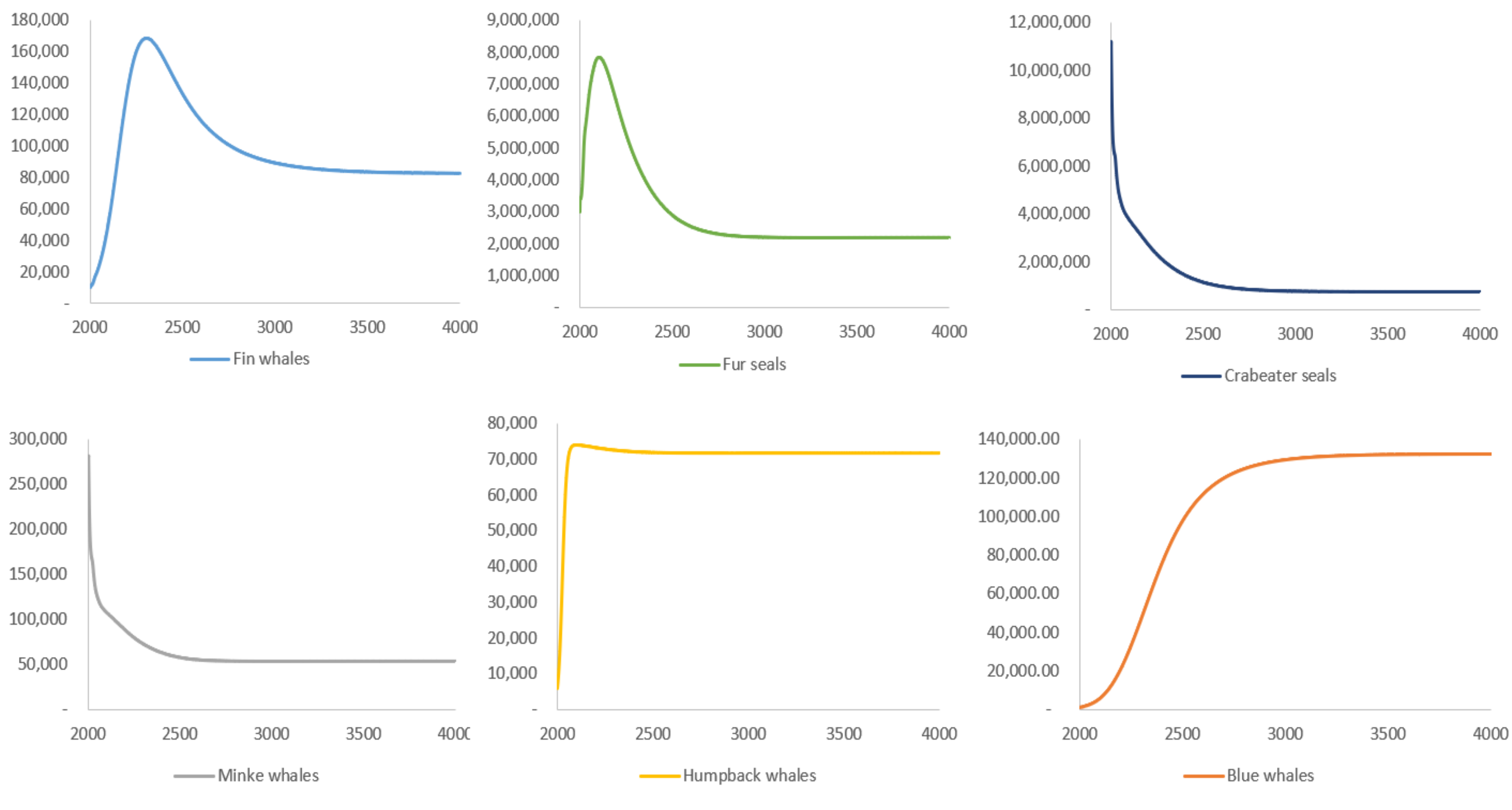

Figure A3. *The development of predator stocks in scenario 2 (<4.7mt).*

Note. All figures x-axis display year and y-axis display stock level (#).

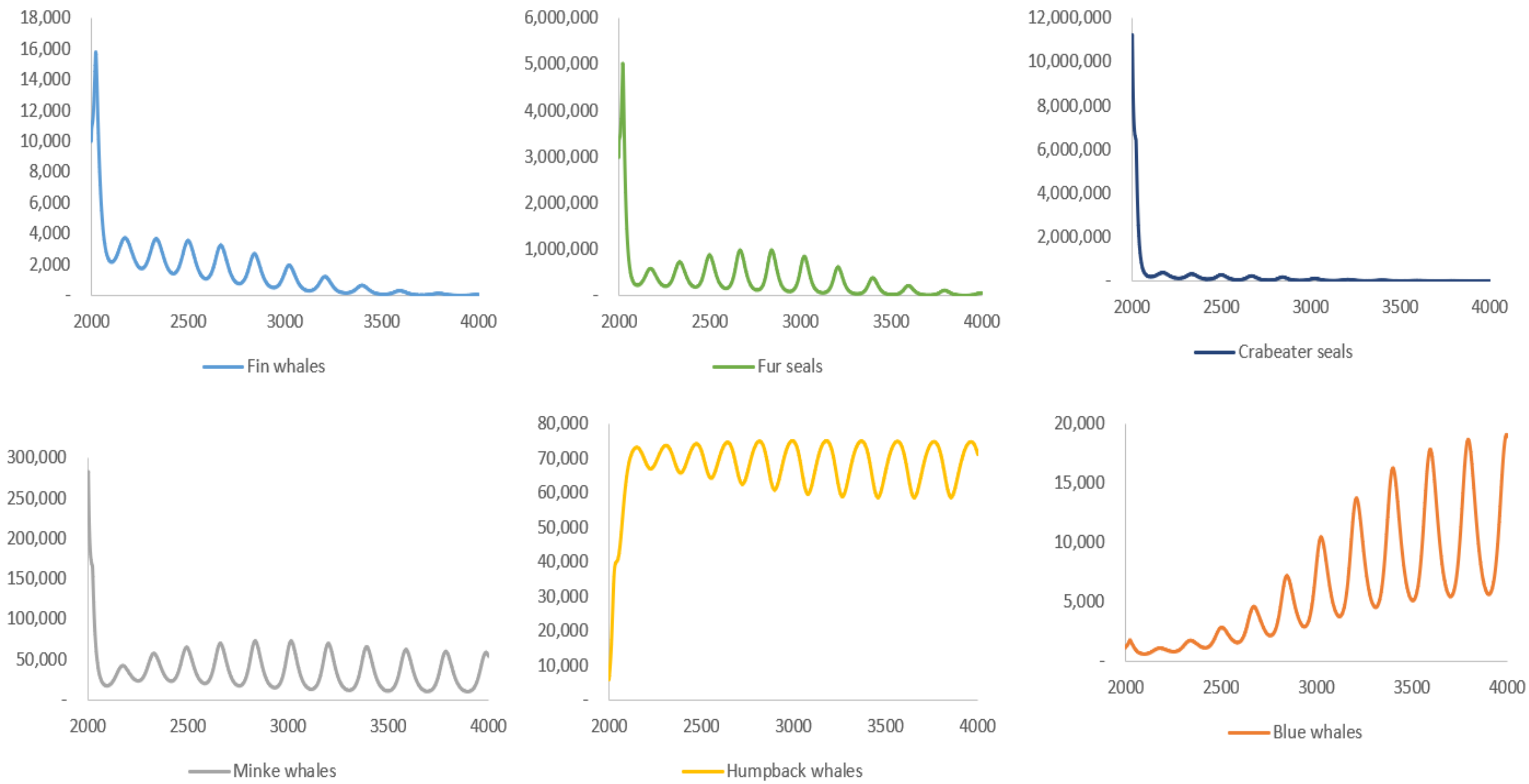

Figure A4. *The development of predator stocks in scenario 3.1 (26%).*

Note. All figures x-axis display year and y-axis display stock level (#).

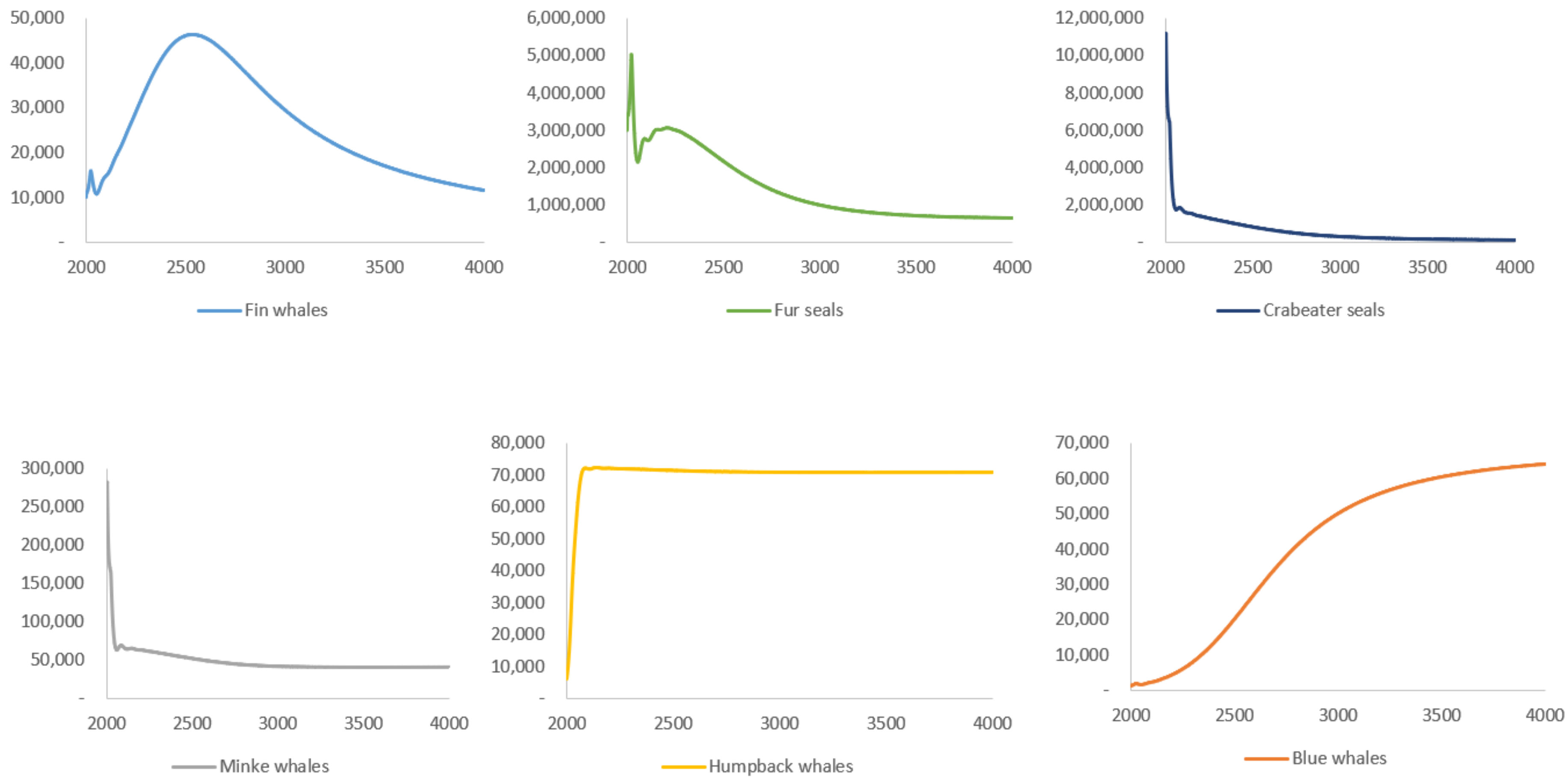

Figure A5. *The development of predator stocks in scenario 3.1 (19%).*

Note. All figures x-axis display year and y-axis display stock level (#).

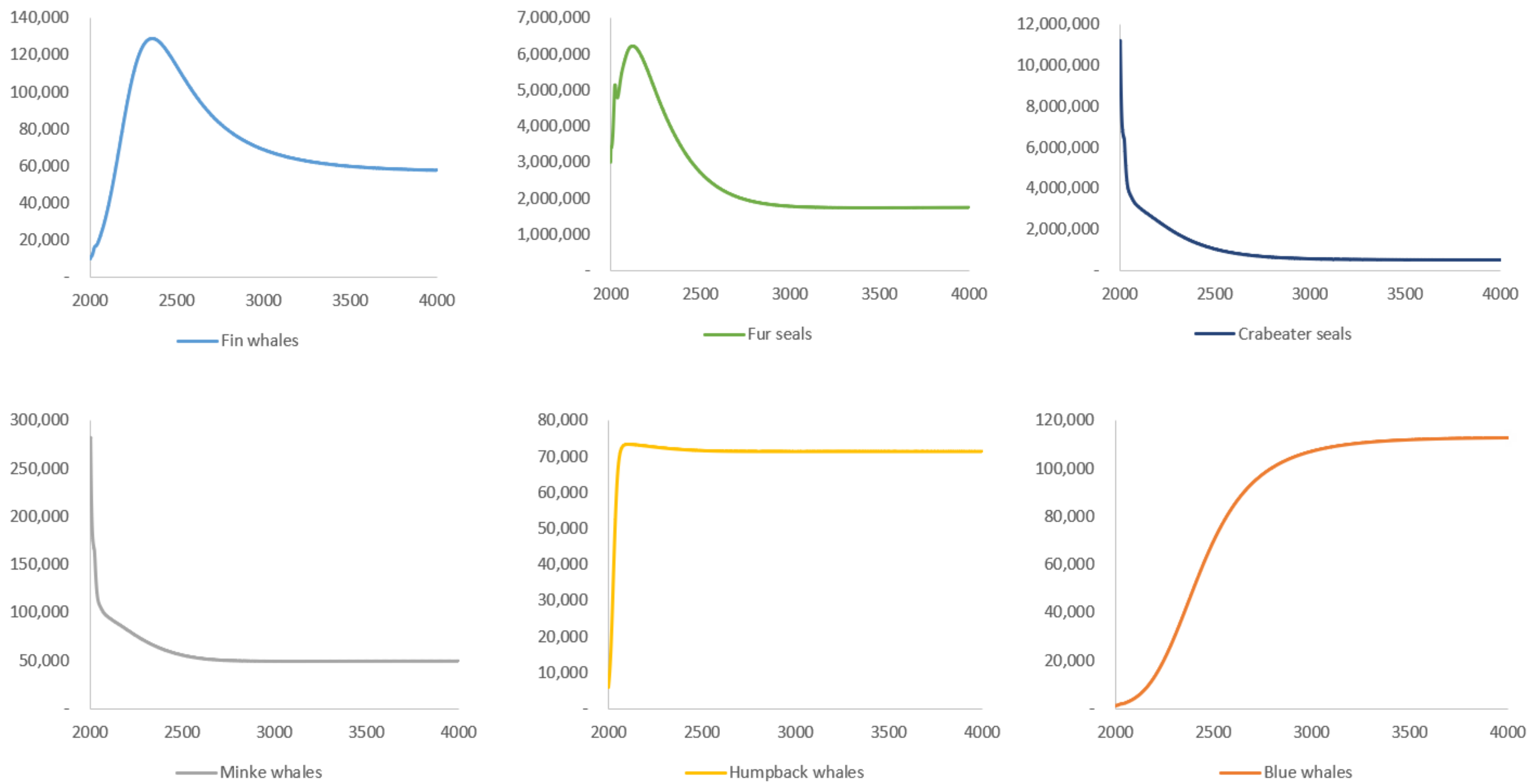

Figure A6. *The development of predator stocks in scenario 3.1 (9.5%).*

Note. All figures x-axis display year and y-axis display stock level (#).

Figure A7. *The development of predator stocks in scenario 3.2 (23%).*

Note. All figures x-axis display year and y-axis display stock level (#).

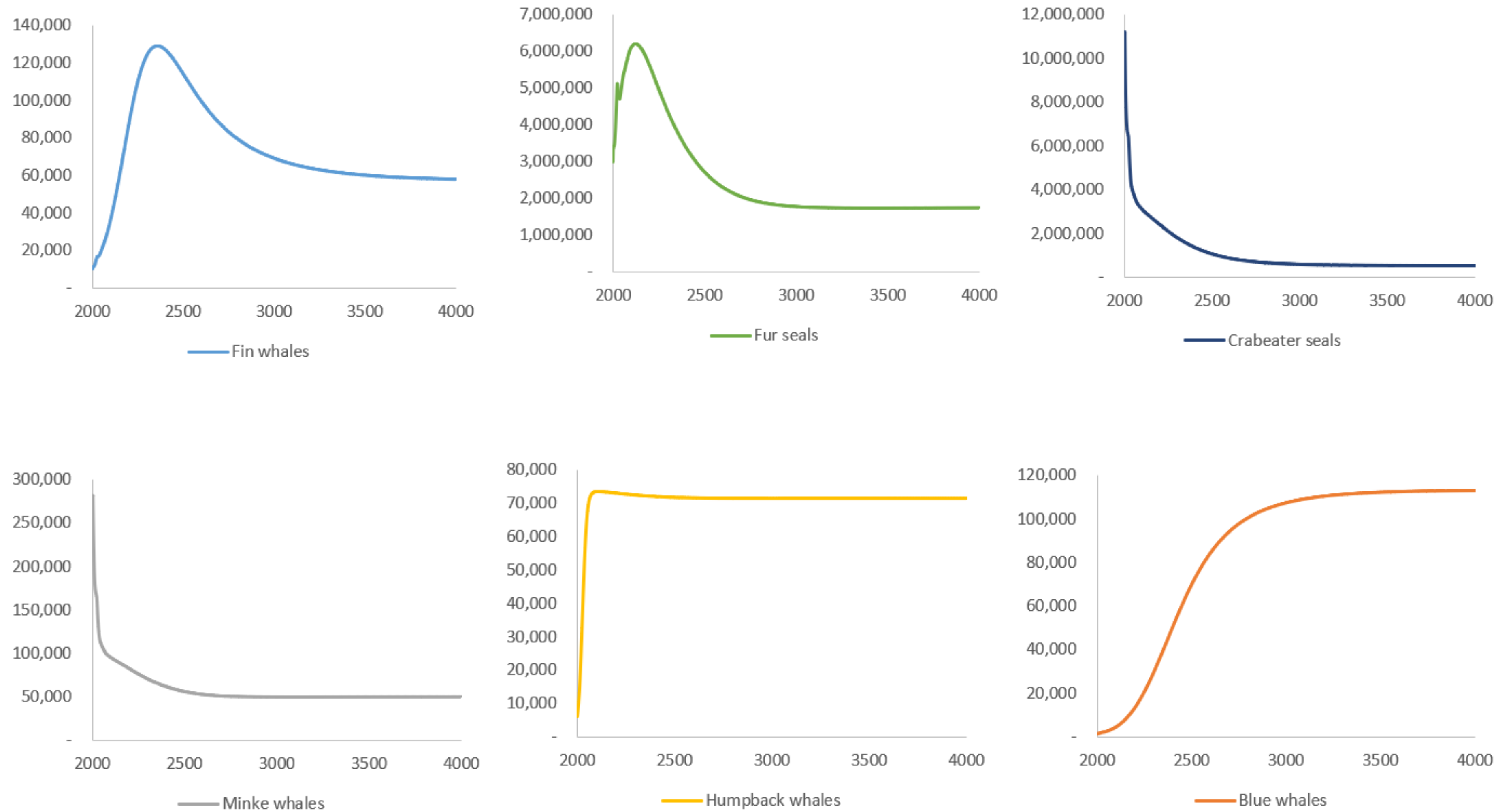

Figure A8. *The development of predator stocks in scenario 3.2 (9.5%).*

Note. All figures x-axis display year and y-axis display stock level (#).