The Effects of Human Activities on The Ecosystem of Kelp Forests in Norway

A System Dynamics Modelling Approach

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Master of Philosophy in System Dynamics

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Abstract

This thesis aims to contribute to existing knowledge about the ecosystem of kelp forests in Norway. The thesis revolves around the creation of a model that is a simplified conceptual representation of the ecosystem, which I augmented with empirical data and estimates, to make it more realistic and relevant for the Norwegian context. The model values are based on an ecosystem under ideal environmental conditions (from mid-Norway). The model successfully recreates historical trends of the real system, while still maintaining its simplicity. I then identify the main mechanisms that contributes to driving a shift in state from kelp forest to urchin barren. The main mechanism starts with the reliance of gadid fish population on the L.Hyperborea kelp forest to uphold numbers that can counteract an independent population growth of the green sea urchin (S.Droebachiensis). This is because urchins can graze down entire kelp forests within a few years if they are not controlled by predators. This mechanism constitutes a strong reinforcing feedback loop which shifts dominance at thresholds decided by different levels of urchins in the respective states. In Norway, the two leverage points humans have on the ecosystem is kelp trawling and fish harvest, which both can tip the system to change from a kelp forest to an urchin barren. Fish harvest of the coastal gadid fish was found to be the more impactful leverage point of the two. The more pressure humans put on the kelp forest, the more fragile it becomes, proposing that environmental fluctuations that the system otherwise can handle might now push the system beyond its tipping point. I find that with trawl landings of 60% of a local kelp forest, the common 5-year trawling interval could drive the system to a barren state after three trawling periods. With a one-year extension of the interval, to 6 years, the collapse of the kelp forest was avoided. With a predicted increase in kelp trawling, and current trawling landings of up to 75% of local forests, the length of fallow period between each trawling might decide if the forest will collapse or not. The systems knowledge revealed by this thesis and its findings could be used for policy design and to inform decision-making in managing kelp ecosystems.

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Glossary

Alginate	A biomaterial that can be manipulated to have many properties and uses. See further explanation: (Lee & Mooney, 2012).
Biomass	The total weight within a selection of biological matter.
Benthic	relating to the ocean floor
Canopy	The upper layer of the kelp forest which is formed by the tallest kelp individuals and their leaves.
Epiphytes	On growths on the kelp which consists of other seaweeds like red algae, small kelp etc. housing small animals.
Hapteron/Holdfast	Visually the root of the kelp, which function is to lock the kelp to the rocky substrate on which it grows, not a nutrition absorbent like in terrestrial trees.
Invertebrates	Small animals without a spine.
Kelp	An umbrella term for brown macro algae. But refers to Laminaria Hyperborea in this paper.
Lamina	The leaf or blade which grows on the top of the kelp.
Laminaria Hyperborea	A forest forming species of brown macro algae, also called kelp, found in the northeast Atlantic from Portugal to Svalbard.
Trawling	A technique to harvest kelp, dragging a 3-4-meter-wide fork like sledge along the ocean floor that rips up the canopy forming kelp individuals leaving small kelp individuals.
Stipe	The stem of the kelp.
Sea Urchin	A ball shaped animal covered with spikes that lives on the seafloor praying on both small animals and organisms, and biomaterial.

1 Introduction

Management of kelp - A resource of the commons

Kelp is an umbrella-term for brown macro algae that grows along the world's coasts. It is a common marine resource used worldwide for a range of purposes. Kelp is most commonly used as human food and manure, but in Norway it is largely used for extracting alginate (a manipulable biomaterial), which use stretches from cosmetics to medicine (Lee & Mooney, 2012). Harvesting of kelp, called kelp trawling, is normally managed to maximize net harvest, with few norms that considers the effects of trawling on the ecosystem (Lorentsen et al., 2010, p. 2054). Along the Norwegian coast it is the kelp species Laminaria Hyperborea that dominates (Gundersen et al., 2021, p. 2), and which will be the species I refer to when writing "kelp" further in this paper. Approximately 150,000 tonnes of kelp is harvested in Norway annually, which yields 5500 tonnes of alginate (Lorentsen et al., 2010, p. 2054). Though the amount of kelp harvested the last 50 years has been fairly stable, both the scientist and the industry says that harvesting of wild kelp in Norway will increase forward (Bekkby et al., 2010, p. 397; Hegnar, 19.11.2021; Mac Monagail et al., 2017, p. 372; Kjell Magnus Norderhaug et al., 2020, p. 6; Norderhaug, 2020, p. 13).

The management of common resources has for long been problematic. As human population and consumption increases, there is need for more resources to sustain the growth, and the pressure on "the commons" increases (Hardin, 1968). Its exploitation often leads to depletion, and consequently economic and ecological disaster, because it is hard to understand complex dynamic systems (Davis et al., 2020, p. 191). This phenomenon is most famously formulated by Garret Hardin in the paper *Tragedy of the Commons*, 1968 (Berkes, 1985). In coping with the increasing demand for resources, marine resources are expected to become more important (Bekkby et al., 2010, p. 397). The kelp trawling industry in Norway is in the beginning of an expansion, as more actors are starting to establish a presence, thus consequently we can expect a rising pressure on the kelp resources (Mac Monagail et al., 2017, p. 372; Norderhaug, 2020, p. 13).

The kelp forest is a part of a complex ecological system, which is more difficult to study and monitor than environments on land due to factors such as wind, waves, depth, and underwater movement (Bekkby et al., 2010, p. 396). The kelp forest constitutes

«…three-dimensional habitats that provide shelter, food or growth substrate for a multitude of other organisms. The most visible of these include many species of seaweeds, invertebrates, fish, seabirds, and mammals. The rich assemblages of associated life make kelp forests biodiversity hotspots»

(Bengtsson, 2011, p. 21)

The Norwegian kelp forests are even compared with tropical rainforests because of their great biodiversity of life, as one individual kelp (on average 1 meter tall) can house up to 100.000 individuals of invertebrates and other small animals (Lorentsen et al., 2010, p. 2054; Norderhaug, 2021, p. 5).

Pic.1 - A trawled corridor in a kelp forest of the coast of Haugalandet, south Norway. Photo: Alginor (Hegnar, 19.11.2021).

So, harvesting of kelp, or kelp trawling, has bigger consequences than normally perceived. Moreover, the wide variety of life that depends on the kelp forest is also crucial to the health of the kelp itself. The loss of biomass of dependent life within the ecological system can eventually feedback to affect the kelp biomass negatively. The most known factors for this interconnectedness within the food web are mammal's and fish's predation on different sea urchins, as urchins are the only animal that noticeably grazes on kelp. Furthermore, humans, mammals and seabirds also "predate" on fish, adding to the complexity of the systems behaviour. That means, that changes in the population of these predators can indirectly affect the population of the kelp. For example, sea otters are known to eat a lot of sea urchins. So, when a sea otter population was hunted to near extinction in the 1800s, it led to an increase in urchins that in turn led to a depletion of the local kelp forests (Lorentsen et al., 2010, p. 2054). Sea urchins are known for large-scale kelp deforestation in many areas, where the urchin's bloom is connected with human fishing (Bengtsson, 2011, p. 22; Norderhaug & Christie, 2009). Following a modernization of the fishing fleet in Norway in the 1970s, the population of coastal fish decreased and there was a massive increase of the destructive green sea urchin Strongylocentrotus droebachiensis, stretching from mid Norway all the way to the Russian border, laying the long and otherwise kelp rich coast almost completely barren (Norderhaug, 2021, p. 6; Norderhaug & Christie, 2009, p. 515).

The decrease of kelp forests gravely affects the coastal production and diversity. The forest is an important habitat and nursery area for coastal fishes such as the Atlantic wolfish, haddock, coastal cod. Their population size have remained at low levels in the down-grazed areas which is expected to impact seabirds and marine mammals (Norderhaug et al., 2020, p. 166). The loss of kelp production will also affect food chains in the adjacent coastal ecosystems, because kelp forests are export systems that provide primary and secondary production for ecosystems on deep and shallow waters (Norderhaug & Christie, 2009, p. 523).

Harvesting of kelp, called kelp trawling, is done by a Norwegian invented method of dragging a 3- to 4-meter-wide fork-like dredge on the ocean floor through kelp forests that grows on hard ocean substrate between 2 to 30 meters deep. The tallest canopy forming kelps is detached from the hard substrate, leaving from nothing to only small juvenile kelp left in its path (Norderhaug, 2021, p. 9). This technique creates random strips of naked corridors in patches of the kelp forests as there is no present method that ensures a more systematic way of harvesting. The corridors experience a profound decrease in biodiversity which decreases further with the more trawling corridors in close proximity. The kelp itself grows back in these patches to its former height, in denser numbers, after 3-4 years under ideal conditions, whilst the weight is often thought to be back after 5 years, but less research is done on the on-growths of epiphytes and the associated fauna though studies has shown that the epiphyte community had only grown back to 1/3 of its pre-harvesting biomass after a 4 year fallow period (Rinde, 2007, p. 8; Steen, 2005, p. 54; Steen et al., 2016, p. 2715). The epiphytes are the main habitat for the thousands of small animals that lives in the forests, and these important on-growths, and the full weight of each plant is thought to need at least 8 years to fully return (Greenhill et al., 2021, p. 2; Steen et al., 2011, p. 18). The re-growth time of kelp, epiphytes and the connected fauna change with latitude and other indices of growth, like depth and wave exposure (Norderhaug, 2021, p. 44). The Norwegian coast from latitude 58 to 64 is divided into ca 2 km long areas that stretches from the coastline to several km into the ocean (Rinde et al., 2006, p. 9). The long coastline above 64 degrees north is closed for kelp trawling due to the overgrazing from the green sea urchins (S. droebachiensis), which is the species in Norway that I will refer to as "sea urchin" or "urchin" further in this paper. The normal policy for trawling in Norway allows trawling in one area every five year. An exception is four years in Rogaland (south Norway) due to higher growth rates. At lat. 63-64, in Sør-Trøndelag, there will be a 6-year frequency policy due to environmental precaution as the kelp forest is still re-growing (Greenhill et al., 2021, p. 7). The regrowth of areas from 64 degrees north and above comes after the catastrophic sea urchin grazing that happened 50 years ago, which is a long time ago comparing to a human lifetime and gives an idea of how stable these barren states of the ecosystem might be (Norderhaug et al., 2020, p. 168). The time for the ecosystem to fully re-establish after trawling is longer than the present frequency of outtake from one area. Even though today's trawling practise in Norway is regarded sustainable because a lot of forest are untouched after trawled, but even so, the ecological function of the forest is crippled for several years, dependent on the landings and the forests ability to regenerate (Norderhaug, 2021, p. 7).

There is the predicted increase in pressure on the kelp resource that makes the current practice alarming. Because from the devastating down grazing in the north there is measured drastic decline in fish (also because of overfishing), seabirds, and sea mammals that used the kelp as habitat and nourishing grounds. There is not much empirical research done as to why the massive down grazing happened, but there are strong theories. And, when the sea urchin has taken over, there is no well-known way to reverse it (Norderhaug et al., 2020, p. 168). The reason as to why kelp is finally returning in northern parts of Trøndelag and southern parts of Nordland is thought to be due to rising sea temperatures which the reproduction of sea urchins is sensitive to (Christie et al., 2019, p. 2848; Fagerli et al., 2013, p. 1), and infection of deadly parasites that can decimate entire sea urchin populations quickly (Scheibling & Anthony, 2001, p. 139). Thus, a further increase of temperature along the northern coast is assumed to help kelp regrow if we can manage it well. But kelp is also sensitive to rising sea temperatures and the growth of kelp in the most southern parts of Norway can be expected to slowly decline as a result (Gundersen et al., 2021, p. 14; Vea & Ask, 2010, p. 492; Voerman et al., 2013, p. 125).

The importance of the ecosystem of these underwater forests has been long known, as Darwin himself addressed it:

> *'I can only compare these great aquatic forests . . . with the terrestrial ones in the intertropical regions. Yet if in any country a forest was destroyed, I do not believe nearly so many species of animals would perish as would here, from the destruction of the kelp. Amidst the leaves of this plant numerous species of fish live, which nowhere else could find food or shelter; with their destruction the many cormorants and other fishing birds, the otters, seals, and porpoise, would soon perish also; and lastly, the Fuegian[s] . . . would . . . decrease in numbers and perhaps cease to exist.'*
>
> *Charles Darwin, 1 June 1834, Tierra del Fuego, Chile (Darwin 1909, pp. 256–257).*

Problem behaviour

The problematic behaviour of the system in focus is the change of state from a rich kelp forest to urchin barrens. We know that high fishing pressure can be a cause of these shifts because it reduces the predators of the sea urchins. Decrease of kelp forest through kelp trawling also reduces the predatory fish because these fish are reliant on the small animals that live on the kelp that disappears in trawled areas (K. M. Norderhaug et al., 2020, pp. 164, 166). Coastal gadid fish is fish in the cod family and are the most abundant fish species along the Norwegian coast. The kelp forests are important habitat for gadid fish and those fishes are the most important controller of the sea urchins in Norway (Enoksen & Reiss, 2018; Lorentsen et al., 2010, p. 2055; Norderhaug et al., 2020; Teagle et al., 2017, p. 93). So, the predicted increase in kelp trawling might be an issue for the ecosystem.

These shifts of state are observed all over the world. And one state can be dominant for hundreds or even thousands of years while a shift of state can be completed only within one year (Filbee-Dexter & Scheibling, 2014, p. 14; Hagen, 1983, p. 178). In Fig.1.1.1, the problematic shift in state is illustrated. The difference in the graphs is to illustrate that globally there are different thresholds for amount of urchin that a kelp forest can contain before a shift of state occurs. The grey line in graph "A" indicates that the system may be in an unstable state for a time period were relatively small changes to local variables may start a shift. Understanding the factors that contribute to the change of state is crucial for further management of the kelp ecosystem (Filbee-Dexter & Scheibling, 2014, p. 2).
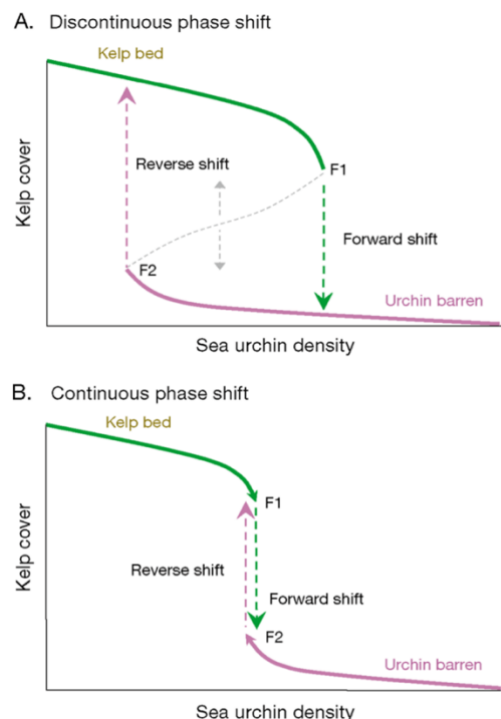
Fig.1.1.1 – Phase shift from kelp forest to barren ground (Filbee-Dexter & Scheibling, 2014, p. 3)

Given the above broad context of kelp ecosystem, we now consider the historical and predicted behaviour of some key performance indicators (KPI's) to help us narrow the focus of the problem under study. The biomass of the kelp forest, coastal gadid fish, and sea urchins are the main KPI's. Seals and Sea Birds are secondary KPI's. Together these five stocks are the KPI's I will use to monitor the state of the system.

I hypothesise that the ecosystem will be more likely to collapse in locations where fishing and trawling increases. In Fig.1.1.2, the A scenario is an illustration of how an increase in fishing and trawling can make urchins increase above the threshold which the kelp forest can hold, which makes the kelp forest collapse. Whilst B illustrates how a decrease in fishing and trawling will keep the kelp forest stable.
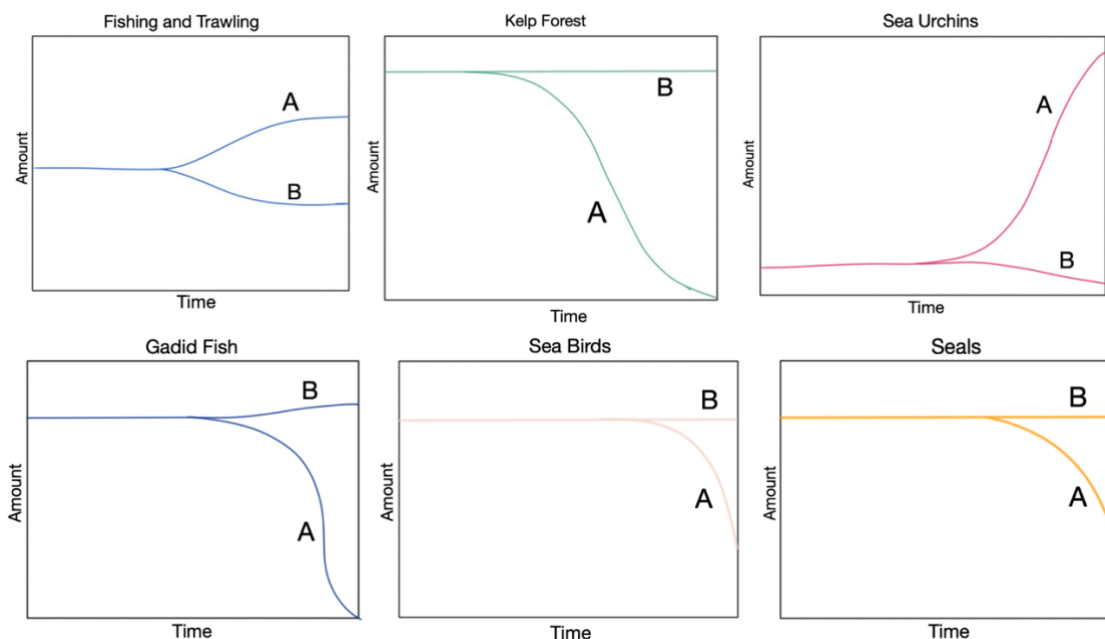

Fig.1.1.2 – Qualitative Hypothesised Behaviour of System

We see that when the green line, representing kelp, vanishes, so does the rest of the system, except the sea urchin, creating what is called an urchin barren ground.

Understanding, managing and restoring the kelp forest is important because it is a source of food, manure, a possible biofuel, source for alginate, and an entity for carbon storage (Hynes et al., 2021, p. 2; Norderhaug, 2020, p. 7). It's also home for important commercial fish species which can disappear if the sea urchins create barrens that can persist over a long time (Filbee-Dexter & Scheibling, 2014, p. 2). This calls for building understanding of the complex ecological system of the kelp forest before scaling up the exploitation of this common resource, to potentially mitigate some of the adverse consequences from human exploitation that has followed previous decision-making.

Decision-making in resource management is theorized to be governed by short sighted, selfish desires to increase one's own gain, causing the "tragedy of the commons" (Hardin, 1968). It is not only selfishness or short-sightedness that drive decisions, but also misconceptions of the feedback loops in the system. System understanding can contribute to a more long-term view of the system and reveal the long-term consequence of current actions which may alter one's short-term decisions to avoid such consequences (Moxnes, 2000, pp. 326-327).

As mentioned, these kelp forests are home to several different animals and smaller organisms, thus trawling and harvesting has the potential to decrease biodiversity and affect the feeding ground for fish and other animals. Thus, this thesis responds to the call for building systems knowledge about the ecosystem of kelp and the potential consequences of kelp trawling on the ecosystem as we know that complex systems are hard to predict and understand, there is a need to increase knowledge on the matter. This is particularly important due to an expected increase in harvesting of the forest forming kelp.

Research Purpose

Research Objectives

My research purpose is to build a semi-conceptual dynamic simulation model that captures the main driving loops of the ecosystem, which determines the tipping point between a kelp forest state and a sea urchin barren state. I will analyse the model to gain a systems understanding on how human activity might impact the ecosystem. By semi-conceptual, I mean that the model is firstly a simplified conceptual representation of the ecosystem, which is then augmented with empirical data and estimates, where available, to make it more realistic and relevant for the Norwegian context. This thesis, thus, hopes to contribute to existing knowledge about the stability of the ecosystem of the kelp forests in Norway.

Research Questions

The research questions I investigate in this paper are:

1. Can a simple model be derived from existing literature about the kelp ecosystem in Norway that captures the main dynamics of the shifting stable state behaviour from kelp forest to sea urchin barren ground?

2. What are the key feedback mechanisms that are active in driving the system to a shift in state?

3. What are the leverage points in the system that have the potential to affect the state shift of the system?

4. Can the insights gained from a simplified ecosystem model be useful for policy design?

2 Literature review

This is an *integrative literature review* in the sense that I will critically synthesize secondary data (peer-reviewed research papers) about the research topic which I use to formulate a simulation model following the System Dynamics method (explained under Methodology) by creating partly new structure formulations on former built ecosystem models based on literature on the ecosystem of kelp. And I summarize the body of literature on ecosystems of kelp to identify data gaps and conclusions I must draw as an effect (Dudovskiy, 2022).

The devastating effects of sea urchin blooms on kelp forests are well documented all over the world (Fagerli et al., 2015, p. 1215). And since the kelp forest is an important primary producer in the coastal ecosystems their demise can have cascading local effects on all trophic levels and even on distant ecology (Norderhaug & Christie, 2009, p. 521; K. M. Norderhaug et al., 2020, p. 164).

A pristine kelp forest is seen as a stable system state as they have persisted several thousand years along the worlds coasts, but at several occasions collapsed to barren areas (Filbee-Dexter & Scheibling, 2014, p. 10). In the paper just referenced, Filbee-Dexter & Scheibling discusses and summarizes the changes from kelp forest to barrens with literature from all over the world. They write that the dynamics of the shifting state of the system are not well enough understood, that there are thresholds to be found that can help us understand the dynamics to further reverse or even avoid losing the important coastal kelp forests. The paper I am writing can be seen as a local and slightly more specific dive into the problem that Filbee-Dexter and Scheibling addresses.

Overfishing of predators (coastal cod in Norway) on the urchins are the most common explanation for the shift from kelp forest to urchin barrens (Enoksen & Reiss, 2018; Lorentsen et al., 2010, p. 2055; Norderhaug et al., 2020; Norderhaug & Christie, 2009, pp. 516, 523; Teagle et al., 2017, p. 93), but kelp trawling could also be thought to contribute to such a shift as it can have great effect on the kelp forest biomass and composition (Christie et al., 1998, p. 50). Even though kelp trawling is a long tradition in Norway, research on the effect of trawling and general research on the kelp and its role in marine ecosystems has been rather scarce compared to the research from the coasts of America and more temperate areas (Norderhaug & Christie, 2009). Combining research from both the north-west and north-east Atlantic gives a bigger volume of research, but as kelp and coastal ecosystems is found to grow very differently in different places, even significant different only within the Norwegian coast, we cannot generalize this body of literature to accurate represent its growth and role in the ecosystem to one specific area (Norderhaug et al., 2020, p. 163). To fully address the relationships of this system in Norway my information-gathering is thus mainly from mid-Norway, and then supplemented with other research from the North Atlantic, and even some support for theories that can be broadly generalized from other oceans. I have chosen mid-Norway as the main area because it is one of the areas which there has been produced more reports and peer-reviewed literature about the kelp ecosystem than other places along the Norwegian coast. The model structure is made from existing ecosystem models from the discipline of System Dynamics. The model parameters and data are mostly derived from a review of literature from mid-Norway.

The kelp ecosystem is commonly divided into kelp, invertebrates, sea urchins, and fish (Norderhaug & Christie, 2009, p. 521), but also commonly include sea mammals and birds (Bengtsson, 2011, p. 21; Norderhaug, 2021, p. 5). I have modelled one stock for each of the

mentioned except for invertebrates as their function in this conceptual model can be directly represented by the kelp forest, which decision is further explained under the chapter "Limitations and Improvements".

Though I have found approximations of the system I am modelling in fields and methodology, to my knowledge, there is no known System Dynamics model of the kelp ecosystem. However, there are System Dynamics models of growth with other species, and interactions between two species or more using the generic predator-prey equations e.g., (Dudley, 2008), and many more is available in the Wiley Online Library within the System Dynamics Review journal.

The predator-prey equations, or model, are the dominant theory in modelling population dynamics within ecology. It explains how a specific population intrinsically increases as a fraction of its own population size, and how the size of the population in a specific area will reach a physical maximum due to environmental restrictions. Within an environment there are many indices that can affect the growth of a population. For instance, food availability. If a predator species is reliant on a prey species that declines, the amount of available food per predator will decrease and the predator population will decrease as an effect as there are too little food to uphold growth. It that sense, the predator population causes the decline of the prey population as a result of high rates of predation, which feeds back to reduce its own population over the longer term as they erode the population they rely on for growth (Wangersky, 1978). And as the equations can easily be applied to grazer-grazed dynamics (Noy-Meir, 1975, p. 459), I use the principles of the Lotka-Volterra predator-prey model as the basis of my conceptual model of shifts in balance between kelp forest and barren states, showing how changes in this primary producer of the ecosystem, the kelp forest (which state is assumed to dictate the carrying capacity of coastal cod (Vondolia et al., 2019, p. 32)) can cascade through the trophic levels through sea urchins and fish, up to seals and sea birds.

To make an conceptual model of these shifts in stable states is important because using accurate mechanistic models to explain it are beyond our reach because of the complexity of the system which, when regarding the kelp ecosystem, lacks research, and determining the resilience of these critical transitions of complex systems is one of the biggest challenges in environmental science (Hirota et al., 2011, p. 235). And in this case it is explaining the collapse and re-growth of the ecosystem of kelp that is calling for further understanding, especially in regard of how humans can affect the systems (Filbee-Dexter & Scheibling, 2014; Norderhaug et al., 2020, pp. 168-170).

3 Methodology

Research Method

I will use the System Dynamics (SD) method which is a field of study, or a discipline, based on Systems Thinking and has become a profession with its out spur from the University of MIT (Massachusetts Institute of Technology), USA, with the prominent professor, J. Forrester (Ford & Ford, 1999, p. 5). It is a method to improve understanding of complex systems, to understand the source of policy resistance, and to design more effective policies (J. D. Sterman, 2000). The method fundamentally entails an interdisciplinary approach making mathematical simulation-models of parts of real systems, be that social, biological, economic systems etc., to identify structures of loops and feedback mechanisms that drive the various systems behaviour (Sterman, 2002). Further, the new understanding of the system is then used to design and test policies to affect the system in a desired manner (Taylor et al., 2010).

The SD approach entails creating a model in the form of a Stock and Flow Diagram (SFD), (which I do so, using the modelling software Stella Architect). The model strives to represent system components we focus on by using mathematical equations to establish the cause-and-effect relationships between different components, which often tends to be nonlinear and circular (feedback loops). Operationalizing the model with equations, gives us the possibility to simulate the behaviour of the system. Though, the model constitutes only a hypothesis of how the system in focus works, as a tool we can use to create and test hypothesised behaviour that the model simulation produces (Ford & Ford, 1999, pp. 172-173).

We can all imagine how a specific system works to some degree or have a specific understanding of the system in focus. This is called a mental model; how we perceive the system and is something we use constantly to understand the world around us. If a mental model is lacking or faulty, the decisions made to affect that system in reality might produce unexpected consequences. To test and learn how to affect a system in a desired way can often be time consuming and too costly. Especially, when it comes to big complex systems as we can find in the environment, like ecosystems. That is why creating simulation models on the computer is such a good tool to be able to test the systems behaviour and reaction before we affect it in reality (Ford & Ford, 1999, pp. 3-5).

> *«The salmon model is a system dynamics version of the type of modeling commonly performed by population biologists. System dynamics adds clarity and ease of experimentation compared to these models.»*
>
> *(Ford, 2020, p. 383)*

> *"...the ability to simulate the information feedback in the system is a truly unique feature of the system dynamics approach."*
>
> *(Ford, 1997, p. 77)*

Research Approach

I have formulated a simulation model of the ecological system that the Laminaria Hyperborea kelp forest supports and are connected with by collecting quantitative data on the ecosystem of kelp forests through peer-reviewed research papers and governmental rapports (secondary

data), to identify themes and patterns to create a conceptual framework of the system. I look to understand behaviour and to capture the driving forces of a phenomenon, the state shift. Then, making the model nature more empirical by empirical parameterization, though there are still assumptions. Further, I investigate the problem that human activity can impose on the behaviour of the system, to then address solutions.

The model structure is ensured to be a valid structure through following the guidelines laid down by Forrester and Senge on how to justify a model structure (Forrester & Senge, 1979).

Research Ethics

My only source of information is through secondary data, which consists of research papers and news articles that are found available online which I properly cite by using the newest citation format (APA 7th) through the reference program EndNote 20, which method avoids any ethical quarrels.

Dynamic Hypothesis

A dynamic hypothesis is the hypothesised cause- and effect relationships of a certain system that is thought to create the behaviour that is problematized. The model (SFD) constitutes a detailed dynamic hypothesis which can be visually aggregated to get an overview of the driving feedback loops of the systems behaviour. Such a visual aggregation is called a Casual Loop Diagram (CLD). It consists of names of system parts with positive or negative arrows between them, representing the effect one part has on the other. A positive arrow from A to B says that when A increases so will B. A negative arrow from A to B says that when A increases B will decrease as an effect. What we look for in a CLD is the closed loops of the system, called feedback loops. A reinforcing feedback loop will constantly try to amplify the values in the loop, or behaviour of the loop, whereas a balancing feedback loop will try to minimize or stabilize the behaviour (Ford & Ford, 1999, p. 69), which process is found under the chapter "Model Structure Validation".

Feedback Story

Below, I will first show you a picture of the detailed dynamic hypothesis, the model (SFD), then I will show the CLD of that model to help me explain the major feedback loops of the hypothesised system.
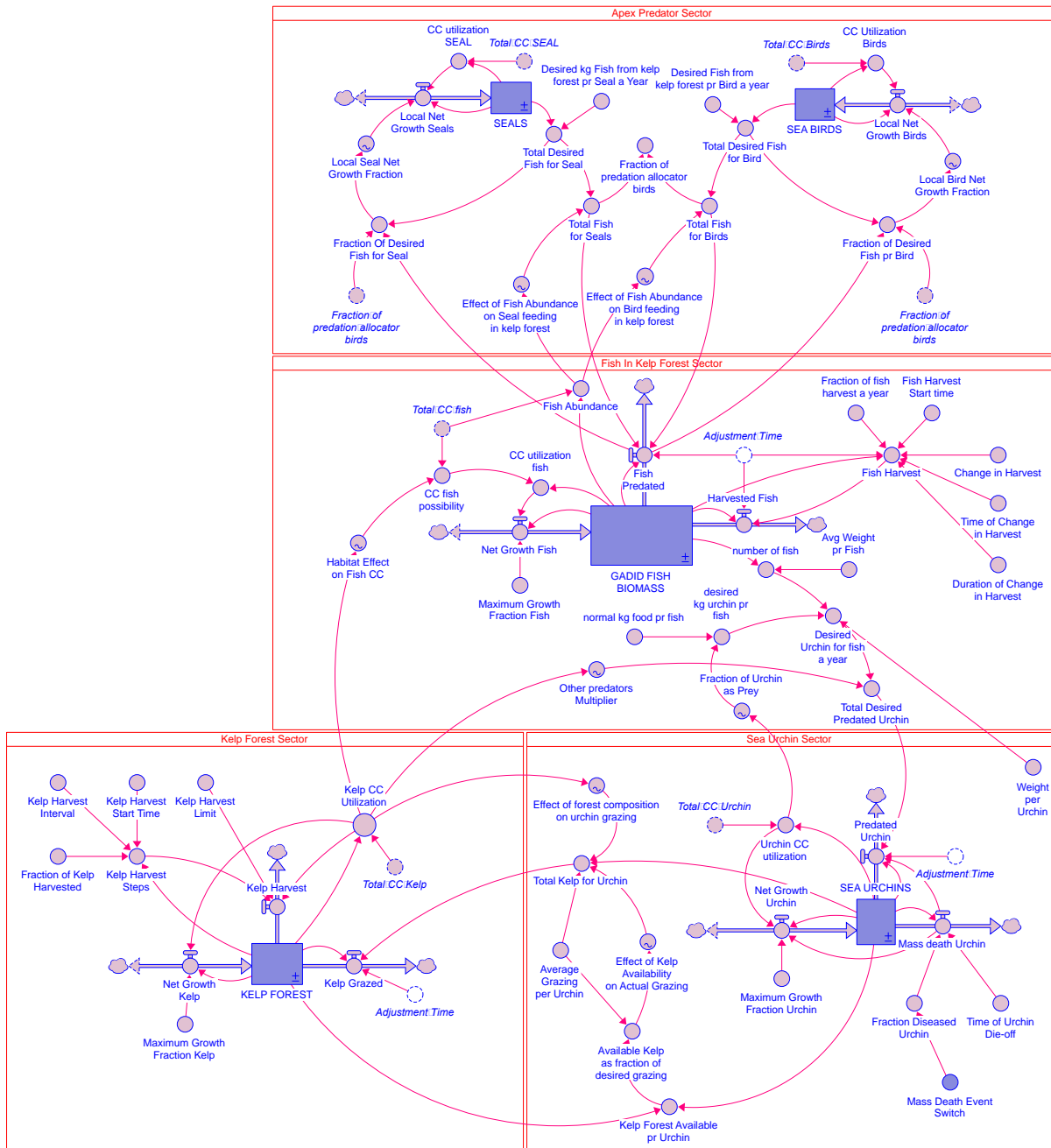
Fig.1.1.3 – Stock and Flow Diagram (SFD) of the Kelp-Urchin Ecosystem

In the model, shown in Fig.1.1.3 above, the main sectors are Kelp Forest Sector, Sea Urchin Sector and Fish in Kelp Forest Sector. The Apex Predator Sector containing seals and sea birds has minor infliction on the model behaviour and is thus mainly included to see how a decline in kelp forest ultimately will affect the upper food chains.
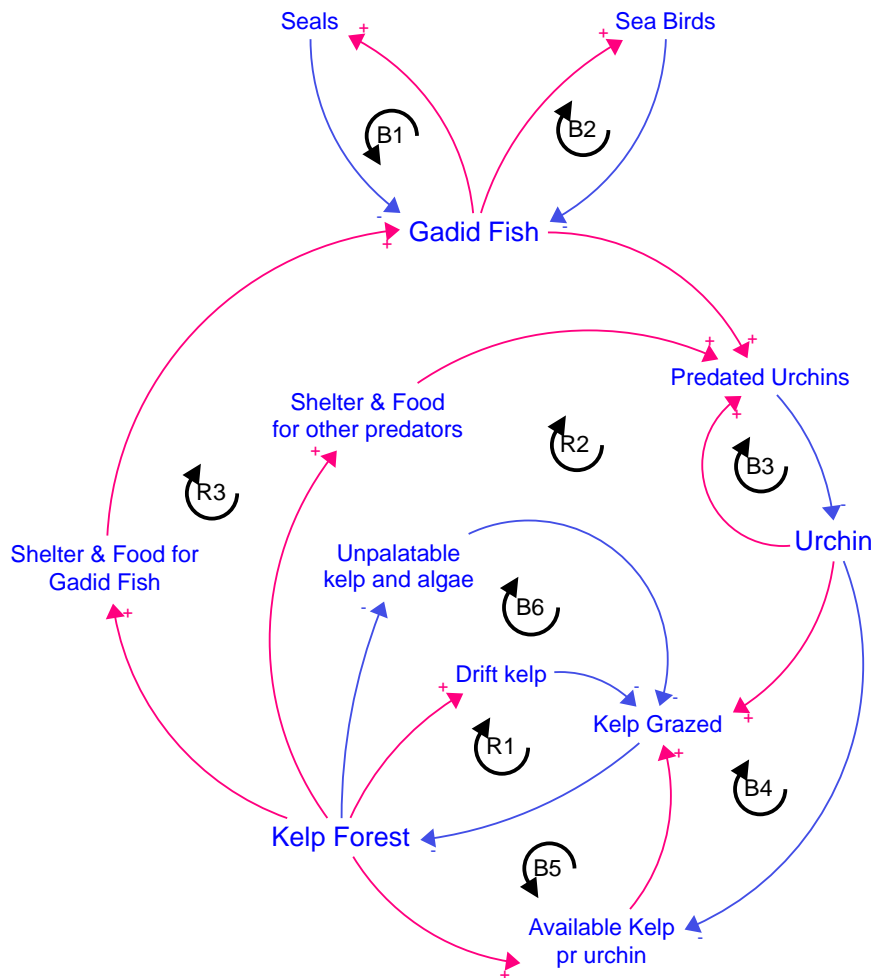
15

Fig.1.1.4 – Casual Loop Diagram (CLD) of the Kelp-Urchin Ecosystem.

Here, I will describe the feedback loops through the CLD above, where the letter B is short for "balancing feedback loop" and the letter R is short for "reinforcing feedback loop". There are two stable equilibriums in the system, one at the CC of kelp forest and one at the CC of sea urchins. The effect of each stock's CC on the respective stock is a balancing loop, which disables the stock from growing indefinitely and making it decreasingly increase towards an equilibrium. These loops are an integrated part of the growth functions of the stocks, which function is explained in the "Model Structure Validation" chapter, thus not visualized in the CLD.

B1 – Seal'n'Fish
This balancing feedback loop represent the predation pressure seals have on the gadid fish population. Gadid fish is found to dominate the diet of seals (Bjørge et al., 2002, p. 29; Nilssen et al., 2019, p. 144). It is balancing because if fish increase, so does seals, and when seals increase then fish will decrease, which again will make seals decrease. Such a relationship will go towards a stable state, or a balance between the increase and decrease of the model parts.

B2 – Bird'n'Fish

This balancing feedback loop represent the predation pressure sea birds have on the gadid fish population, as sea birds eat gadid fish (Bustnes et al., 1997, p. 19; Lorentsen et al., 2004, p. 166). It is balancing because if fish increase, so does birds, and when birds increase then fish will decrease, which again will make birds decrease. Such a relationship will go towards a stable state, or a balance between the increase and decrease of the model parts.

B3 – Density Effect of Urchin Population

This balancing feedback loop shows how a decreasing urchin population will result in less predated urchin and vice versa. It is determined by a density effect based on that the diet of gadid fish will consist of more urchins when urchins get more abundant (Hagen, 1983, p. 186).

B4 – Urchin restricted grazing

Urchins graze extensively on kelp (Norderhaug & Christie, 2009; Scheibling & Anthony, 2001). This is a balancing feedback loop because an increase in Urchins results in less Available Kelp pr Urchin, which decreases the total Kelp Grazed, which will have a positive effect on the Kelp Forest, which then increase predators, thus Predated Urchins, ending up with a negative effect on itself, Urchin. So, if we start with an increase of urchin, it will end with a decrease of urchin, and vice versa, in this loop isolated.

B5 – Kelp restricted Grazing

This is a balancing feedback loop as less Kelp Forest will result in less Available Kelp pr Urchin, decreasing the amount of Kelp Grazed, which again enables more growth of the Kelp Forest.

B6 – Unpalatable Kelp & Algae

When the kelp forest is in its early development stages, faster growing organisms like L.Saccharia comes to dominate the ocean floor. This smaller kelp species is much less palatable for urchins which decreases their grazing pressure on the forest in the early stages. Sporelings of L.Hyperborea finds shelter within the L.Saccharia stands for their early growth phase until their stipe growth maximises after 1-2 years shooting towards the surface which increases their light conditions, shading for the others, and outcompetes the smaller kelps and algae (Leinaas & Christie, 1996; Scheibling & Anthony, 2001, p. 143). So, its balancing because when the kelp forest decreases there will be more unpalatable organisms, which decreases the grazing pressure and enabling kelp to increase.

R1 – Drift Kelp

When the kelp forest is well grown it is the Laminaria Hyperborea kelp (the preferred food of urchins) that is dominant. And with more kelp there will be more drifting pieces of kelp, especially from the gradual shedding of laminas (leaves) (Harrold & Reed, 1985, p. 1165), which the urchins are found to utilize as they can decrease their movement (energy output), by grazing less directly on growing kelp (Filbee-Dexter & Scheibling, 2014, pp. 10, 16; Scheibling & Hamm, 1991, p. 114). So, more kelp decreases grazing, enabling kelp growth, making it a reinforcing loop.

R2 – Kelp Forest enables Other Predation

This is a reinforcing feedback loop because when the Kelp Forest increases, so does the many predators that resides or rely on the kelp forest, directly or indirectly, which is found to predate on urchins (Bustnes et al., 1997, p. 16; Hagen, 1983, p. 186; Lorentsen et al., 2022, p. 307). Then urchins decrease, creating a lower grazing pressure on the Kelp Forest, which will reinforce the growth of the forest.

R3 – Kelp Forest enables Gadid Fish

This is a reinforcing feedback loop because the Kelp Forest is the home of gadid fish, making the possible amount of fish increase if the forest increases (Bjerknes et al., 2006, p. 6; Vondolia et al., 2019, p. 32). With more of the urchin predator, gadid fish, the more Predated Urchins there will be, resulting in less Urchins, then less Kelp Grazed, which again enables more Kelp Forest.

4 Model Structure Validation

In this chapter I will explain and verify the model, its relationships, variables, and values, and show the tests done to assess the sensitivity of the model and its parts.

Structure & Parameter Verification

This chapter contains a detailed description of the model, with explanations of the relationship and values as found in the literature. When verifying the model structure one must compare the structure of the model with what is known of the real life system and see to that there are no contradictions (Forrester & Senge, 1979, p. 9). Here, I will first lay out the literature used to verify the overall structure which this limited system is based on. I will then go further into detailed structure- and parameter verification of the most important parts of the system and those variables that contains assumptions and/or need further explanation, based on the relevant literature of the coastal ecosystem. The rest of the model are found with explanations and references to the literature under "Appendix B: Model Documentation".

Several structural components of this model are grounded in the logistic function of Malthus which aims to explain single species population growth. This function is further elaborated by Lotka and Volterra to explain behaviour of the interactions of two species where one preys upon the other, called the Lotka-Volterra predator-prey model. This is widely used as the base for further elaborations of the dynamics in an ecosystem with several species that interacts (Berryman, 1992; Wangersky, 1978). The logistic growth equation is what I base the inflow (net growth rate) to all the population stocks in my model on. The equation is:

Inflow = Maximum Growth Rate*Population (1- Population/Carrying Capacity)

In my model, the inflows are termed Net Growth because it is conceptualized as the average natural change in the population stock, as the sum of natural births and deaths over a long enough time interval. The value of Maximum Growth Rates (a fractional rate of increase in the population) is based on literature (where data from Norway is prioritized) of the specific population, also called the biotic potential (Wangersky, 1978). In the Apex Predator Sector, the growth rates are determined by the predation success on their prey (fish), only reaching maximum at a certain level of consumption, which should only be done if the level of prey over time is found to correlate sufficiently with the population of the predator. In the sectors, Kelp Forest, Sea Urchin and Fish in Kelp Forest, the Maximum Growth Rates are constant exogenous variables, because they are not dependent on the feeding success on the other. To further explain their relationship, the kelp forest is a primary producer, not reliant on predation but environmental factors to grow, working as a prey for urchins. I do not include environmental factors that are known to affect the kelp forest and associated fauna, such as temperature, wave exposure, depth, light, and properties of the water in this model, but assume a constant favourable environment (Sivertsen, 1997, p. 2878). The similarities of such "grazer-grazed" relationship is similar enough to make use of the "predator-prey" formulations to explain it (Noy-Meir, 1975, p. 459). With Sea Urchins it is found that although their increase is very much affected by the availability of kelp, their decrease is not (Leinaas & Christie, 1996, p. 533). And even though the amount of gadid fish strongly affects the deaths of sea urchins, sea urchins are not their main source of food (Enoksen & Reiss, 2018, p. 251; Norderhaug et al., 2020, p. 166). The growth rate is either way constantly under regulation by the carrying capacity (CC). The stock at any time is divided on the CC, giving us a fractional representation of the stock in relation to the CC. When we subtract that fraction from 1, we get

the fraction left of the stock to reach the CC. This value is multiplied with the growth fraction, limiting the growth as the stock closes in to the carrying capacity.

There is a weakness of the logistic function. If the stock is initialized in its CC, the CC Utilization (Population/Carrying Capacity) will be in absolute zero nullifying any multiplying effect from the growth rate. This formulation is used by many because it's a good way to explain population behaviour e.g.; (Morecroft, 2015, p. 13), so it's just a thing to be aware of when using this formulation in a model.

Modelling of similar ecosystems is often done with lower time units than years. With a lower time unit, it is common to split species into age groups or mature and juveniles as it will help explain behaviour over short time intervals and thus the numerical specifics are more important for the purpose of their model results. For that kind of modelling there can also be need to include specifics of deaths and births instead of a net growth that combines them (Bekkby, 2009; Johnson et al., 2013; Weller et al., 2016).

That's an overall explanation of the structure. I will from here go into detailed explanation of the model's structural relationships and parameter values with the supporting literature, and at times assumptions based on reason. The complete list of parts in the model and explanation is found in the appendix, under Model Documentation.

Kelp Forest Sector

Kelp Forest
This stock represents the full forest with kelp plants, epiphytes (on-growths) and the associated fauna.

The S-shaped increase of the forest is a result of the predator-prey equation in Net Growth, and it fits with the real systems behaviour. Because, it is found that 4 years after a drastic reduction of sea urchins juvenile kelp were found on 40% of the ocean floor of the former barren area, while most of the growth happened in the last year, indicating a slow but increasing growth in the early stages of the forest (Leinaas & Christie, 1996, p. 531). And, as kelp quickly reaches their maximum hight or canopy layer, the holdfast, stipe, and associated fauna might seems recovered but will still need several years to reach its full size and potential, so it's a decreasing increase in the late stages (Christie et al., 1998, p. 56).

Initial KELP spm (Controls Stock Sector)
The starting value for each of the stocks in the model are determined by an exogenous variable that can be found in the model sector called "Controls Stock Sector". The variables are termed the "initial" value, which value is per square meter (sqm=m^2). The initial value of kg kelp per m^2 is set to 27 kg pr m^2 as a kelp forest biomass is known to be close to its carrying capacity under good conditions (Rinde, 2007, p. 69). Rinde's time units is months, thus including more detailed behaviour of the system and fluctuations around the equilibrium. My model is much simpler, having only urchins that can keep the forest below CC. And since the urchins in my model can get close to zero, the equilibrium of the kelp forest happens virtually at CC.

Maximum Growth Fraction Kelp

The growth rate of the kelp forest after harvest is calibrated through the logistic equation to a value that fits the historical findings saying that a kelp forest's full re-establishment and recolonisation takes a minimum of eight years (Greenhill et al., 2021, p. 2). With a fractional growth rate of 0.8 and a carrying capacity (CC) at 30 kg kelp, the forest reaches 95% of its CC after 8 years, when initializing the kelp stock with 1 kg kelp pr m^2. The calibration is done in isolation from the rest of the model, meaning it is the behaviour we could expect from a regrowing kelp forest in ideal conditions. I initialized the stock with 1 kg kelp in the calibration because there are normally spores or juvenile kelp left after a spot is harvested (Greenhill et al., 2021; Sivertsen, 1991, p. 7).

Kelp CC pr sqm (Controls CC Sector)

The carrying capacity (CC) of the kelp forest is found in the Controls CC Sector in the model. The CC is set to 30 kg pr m^2, which assumes good environmental conditions, based on the findings of Rinde and Steen (Rinde, 2007, p. 77; Steen, 2005, p. 1).

The relationship between the stock (kelp, epiphytes and fauna) and the CC is a simplification since the carrying capacity of the kelp (Kelp CC) is a measure of maximum weight of kelp in an area, not regarding on-growth and associated fauna. I defend the simplification by that the kelp is set to grow in speed with the full restoration of the area (not just the kelp biomass), and that sea urchins eats down the kelp entirely and cannot leave only epiphytes. Also, the fish is reliant on full restoration and not just kelp biomass.

Net Growth kelp

The inflow to the Kelp Forest Stock, the growth rate, is assumed to rely on the kelp forests carrying capacity with the equation from Lotka-Volterra, as explained initially in this chapter. This equation decreases the growth rate when the kelp forest (stock) goes towards the CC or zero. The maximum growth rate will thus be found when the kelp forest is halfway to its CC, creating a turned U-shape behaviour in the net growth flow (Noy-Meir, 1975, p. 461).

Kelp Trawling

Kelp Trawling is one of the two outflows of the kelp forest, because L. Hyperborea accounts for about 90 % of the national (kelp) harvest (Rebours et al., 2014, p. 1946). And it is harvested approximately 150,000 tonnes of L. Hyperborea annually in Norway (Lorentsen et al., 2010, p. 2054).

Kelp Grazed

One of two outflows from Kelp Forest is the grazing from Sea urchins. The sea urchins, S. droebachiensis, is the main herbivore in Norwegian kelp forests, which graze extensively on L.Hyperborea kelp and can graze down entire forests (Norderhaug & Christie, 2009; Scheibling & Anthony, 2001).

Sea Urchin Sector

Sea Urchin

The stock that represent the number of urchins, based on an average weight per urchins of 0.02kg (Michelsen et al., 2022, p. 12). The reasoning for use of average weight is found under *Maximum Growth Fraction Urchin*.

Effect of Kelp Availability on Actual Grazing

The effect of kelp availability on urchin actual grazing is a graphical function. When the amount of kelp available per urchin is below the found average grazing, the average grazing will decrease. There is no well documented effect of kelp availability on grazing behaviour, but I can use the mentioned findings by Scheibling and Anthony's laboratory experiments (under *Average Grazing per Urchin*) with generic behaviour used in the Lotka-Volterra model.

The lower grazing rate of kelp was based on season and not kelp availability, as well as the upper grazing rate. That tells us that the lower rate can get lower if there is too little kelp to sustain it, but the upper limit will not increase with more kelp. The maximum grazing, they found to be 2.5 g a day = 0.91 kilo a year, the lower was 1 g a day, and the average was found to be 1.7 g a day (Scheibling & Anthony, 2001, p. 144). For this to be in an effect graph (a multiplier) I need to find what 1.7 (the average) is multiplied with to get the maximum, 2.5/1.7 = 1.47. The number that will multiply the average grazing pressure per urchin to get the maximum pressure is thus 1.47. I've set a linear relationship from the max grazing rate to 0 based on possible versions of this relationship derived from predator-prey models by Swart and by Noy-Meir (Swart, 1990, p. 95) & (Noy-Meir, 1975, p. 461). As seen in these articles, several developments of the effect-lines can occur. Since there are little documentation of the exact line in the system in focus, a straight line from 0 to maximum grazing was chosen as it fit better with historical behaviour.
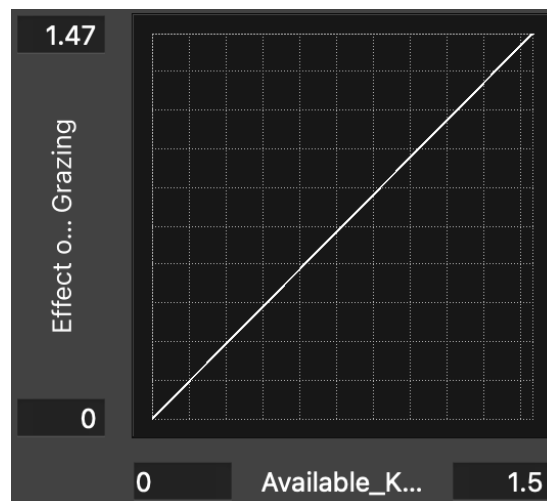

Fig.1.1.5 – Graphical Function: Effect of Kelp Availability on Actual Grazing

As to what level of available kelp per urchin the maximum grazing will occur is hard to say. As seen, in Fig.1.1.5, I have set it to occur approximately when the amount of kelp available per urchin reaches the maximum each urchin can prey, which is 1.5 times average grazing. There are several articles that shows a similar graph but uses actual amounts and not a fraction. But, with some calculation, the values from the paper about prey availability by Lampropus shows us one example of how maximum feeding happens when food (or prey) availability is approximately 1.5 times the normal feeding. At page 610, Fig.1, we see that maximum consumption is 70 prey individuals. We then must assume that the normal or average prey density is half of its maximum, 45 (90/2=45). If we then divide the maximum consumption on the average density we get, 70/45= 1.55 (Lampropoulos et al., 2013). Meaning that the maximum food intake will be when the available food is approximately 1.5 times higher than the average food intake.

This graphical effect on grazing alone do not create behaviour that fit with historical behaviour of the system. That is because the grazing pressure is also affected by the composition of the forest, and not just the amount available. The forest composition will be an additional structure variable that is not found in classic Lotka-Volterra model.

Effect of forest composition on urchin grazing
To fully explain the relationship of grazing pressure of urchin on the kelp forest we need to take the forest composition into consideration.

Grazing activity is in part a function of available drift kelp and algae (Filbee-Dexter & Scheibling, 2014, p. 15; Harrold & Reed, 1985, p. 1165). When the kelp forest is low, there will be few growing kelp (L.Hyperborea), which is the preferred food of the green sea urchin (S. droebachiensis). Their grazing rate is lower on other food sources like algae and the smaller kelp, Laminaria Saccharina, which are thought to initiate the regrowth of a kelp forest after an urchin die-off (Leinaas & Christie, 1996; Scheibling & Anthony, 2001, p. 143). In the open coast experiment of Leinaas & Christie, when algae, and the faster growing L.Saccharina, started a re-vegetation of a barren ground, kelp was found in 10% of the area after 3 years and in 40% of the area after 4 years, where other algae and L.Saccharina was dominant (covering 70-100% of the ocean floor) within a year after an urchin die-off/removal) (Leinaas & Christie, 1996, p. 531). This gives an indication to that at the very low stages of the forest the urchin grazing will be very low but increase quickly as kelp will outcompete the smaller vegetation fast.

Further, Scheibling and Hamm found that there are enough drifting algae for urchins in pristine kelp beds for urchins to avoid exposing themselves to predators, which they do when grazing directly on the kelp. Thus, grazing on kelp is thought to decrease when kelp is abundant (Christie et al., 2019, p. 15; Filbee-Dexter & Scheibling, 2014, pp. 10, 16; Scheibling & Hamm, 1991, p. 114). Combining that with the findings of Lorentsen, saying that fish in the kelp forests seems abundant when kelp cover was more than 50%, indicating enough prey for fish, which again is a result of a rich flora, which lastly gives a high level of drifting kelp particles (Lorentsen et al., 2010, p. 2058).
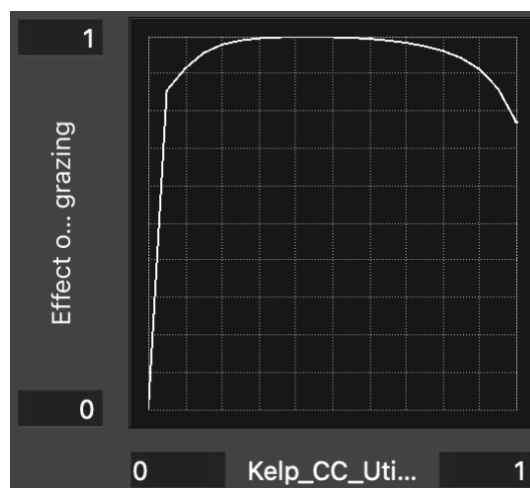

Fig.1.1.6 - Graphical Function: Effect of Forest Composition on Urchin Grazing

The exact values are guesstimates as the relationship is only documented qualitatively but are also calibrated so the behaviour fits historical data. As seen in the picture of the graphical function in Fig.1.1.6, the calibrations favour a sharp decrease of fractional grazing rate from

one towards zero when the total kelp forest is very low, as kelp (L.Hyperborea) itself will be very scarce, if any there at all. At 60% of maximum CC there will be an increasingly decreasing grazing pressure, of a lesser magnitude, to a minimum of 77% of the current grazing pressure. In between these two points the forest composition effect on grazing will be 1 (no effect).

Total Kelp for Urchin
The total amount of kelp that urchins will try to eat per year consists of the *Average Grazing per Urchin* (0.02 kg urchin) multiplied with the number of urchins in the Sea Urchin stock, and further multiplied with how the availability of kelp and the forest composition affects their ability to consume kelp. The equation looks like this:

SEA_URCHINS*Average_Grazing_per_Urchin*Effect_of_Kelp_Availability_on_Actual_Grazing*Effect_of_forest_composition_on_urchin_grazing

This structure is based on extensions of the Lotka-Volterra model (Noy-Meir, 1975, p. 461).

Initial Urchin sqm (Controls Stock Sector)
In pristine kelp forests there are found very few to no urchins. Sivertsen found a mean value of 2 urchin individuals pr m^2 in kelp beds (Sivertsen, 1997, p. 2876), thus the initial value of sea urchins in the sea urchin stock is set to be 2 urchins per square meter (sqm), via this exogenous variable (Initial Urchin sqm).

Urchin CC pr sqm (Controls CC Sector)
The carrying capacity of urchins is the maximum number of adult urchins (20 g each) that a barren ground can sustain per square meter. In Norway it is found numbers of 50-60 adult sea urchins per square meter in barren as the upper averages of one area (Fagerli et al., 2013, pp. 120, 125; Leinaas & Christie, 1996, p. 525). So, I have set the CC to 60 adult sea urchins pr m^2.

Maximum Growth Fraction Urchin
The growth rate of urchins is known to change a lot, and to be affected by their consumption, so the model could benefit from making the rate endogenous. But the research on population growth of urchins is very much lacking, where the only found research done is on individual growth and biological processes of single urchins. Thompson found that size and health of eggs and gonad size increase with more kelp in diet. He also found that individual growth stops with low food rations but that they re-allocate resources to reproduction effort, counteracting the increased mortality with low kelp consumption (Thompson, 1982, p. 51). Which means bigger and fewer spawn while on a kelp diet, and smaller but more eggs while not. Skadsheim's Fig.4, illustrates this dynamic effect on the population, seeing that when urchin is fewer, they are bigger and when they are more, they are smaller (Skadsheim, 1995, p. 203). That is an indicator to that when the urchin population closes in on its CC, and kelp gets scarce, the total biomass will be fairly stable as the composition of the population changes from big to smaller sized urchins.

To include the dynamics explained above into the model, an average size of urchin comes in handy as a simple way to reflect the grazing pressure. Based on the above I argue that the growth rate of urchin population can be set to a constant as a function of the population size for this model's purpose.

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Then the growth constant is calibrated to be approximately 0.7, with the mentioned CC. It is based on historical data saying it can take 1 to 6 years for urchins to complete down grazing of a kelp bed to barren ground (Hagen, 1983, p. 185; Sivertsen, 1997, p. 2880).

Adding a classical grazer-grazed (predator-prey) connection here would not fit as the ability of sea urchin populations to persist on barren grounds is due to great phenotypic plasticity in response to low food availability, with other words, a decrease in kelp availability does not result in decreasing population (Norderhaug & Christie, 2009, p. 515).

Net Growth Urchin

As in kelp, the equation is derived from the described Predator-Prey model, but with an additional feature:

$$\text{IF Mass\_death\_Urchin>0 THEN 0 ELSE}$$
$$(\text{SEA\_URCHINS*Maximum\_Growth\_Fraction\_Urchin})*(1-\text{Urchin\_CC\_utilization})$$

The IF THEN ELSE function tells the model to stop growth when a massive urchin die-off happens. That is because the inflow (Net Growth Urchins) adds to the stock of urchins based on the previous year in the same DT as the mass death subtracts from the stock. That results in a smaller decrease than the die-off suggests because there will also be added urchins at the same time interval. This function stops any inflow during the DT a die-off happens, fulfilling the functional effect of the die-off, which is removing the set percentage of the urchin population at a DT, including those born the same time.

Mass Death Urchin

Urchin populations is periodically eradicated by disease, which gives the kelp bed a chance to re-establish (Scheibling & Anthony, 2001, p. 139). This is thus one of two outflows of the urchin stock. It is only active when or if the urchin population is affected by a mass mortality event such as a parasite infection or a drastic increase in sea temperature (Fagerli et al., 2013, p. 120; Norderhaug & Christie, 2009, pp. 521-522).

The event is enacted by a PULSE function which pushes a value that otherwise would happen over a whole year in only one DT (1/500 year). This makes the program (Stella Architect) visualize the outflow to be four times higher than it should. To avoid too detailed maths, if we divide the visualized outflow with the DT (500) we find the actual amount that is subtracted from the stock, which also fits with the set value in *Fraction Diseased Urchin* timed with the current stock.

Predated Urchin

One of two outflows from the urchin stock. Urchin is predated by a number of different predators, like all life stages of gadid fish, crabs, seals, otters, birds and smaller invertebrate predators etc., (Fagerli et al., 2014, p. 208; Norderhaug et al., 2020, p. 164; Scheibling & Hamm, 1991, p. 106). As in *Net Growth Urchin*, the flow is restricted by Mass death Urchin to be zero if an urchin die-off event occurs to prevent the stock going to minus.

It is also restrained by a MIN function to prevent the Predated Urchin outflow from exceeding the amount that is in the stock at any time. It will rather extract whatever is in the stock over a 1-year interval. In addition, the outflow also has an If Then Else-function that stops the outflow when there is a Mass Death Urchin event so the two outflows avoiding adding up to an amount that would send the stock to a negative value.

Fish in Kelp Forest Sector

Gadid Fish Biomass

The stock in the fish sector represents the total biomass of gadid fish that at any time resides within kelp forest we model. Gadid fish along the Norwegian coast consists mostly of Cod and Saithe. Kelp forests are important habitat for the costal species of this fish family (Lorentsen et al., 2010, p. 2055). The family of gadid fish is the most important controller of urchin populations in Norway, as well as being a commercially important family of fish (Enoksen & Reiss, 2018; Norderhaug et al., 2020; Teagle et al., 2017, p. 93). Most of the values and rates of feeding and growth is based on coastal cod, also done by Salvanes, using the measure of cod to represent other fish that competes with cod (Salvanes, 1992, p. 11).

Initial Fish sqm (Controls Stock Sector)

Bodkin found there to be 0.112 kg fish pr m^2 in a kelp forest in California (Bodkin, 1988, p. 233). In Norway the number is found to be similar. Lorentsen found there to be 25 fish pr 15x5 meter in a kelp forest (Lorentsen et al., 2010, p. 2058). Mounting up to a 0.3333 fish pr m^2, if I assume the same average weight on fish it mounts up to 0.116 kg fish pr m^2.

I chose to round the number up to 0.12 kg fish pr m^2, because counting fish physically is found to scare them away (Norderhaug et al., 2005, p. 1284).

Fish CC pr sqm (Controls CC Sector)

To find the carrying capacity of gadid fish in kelp forest I took the amount of fish found by Lorentsen (in *Initial Fish sqm*), 0.116 kg fish pr m^2. Then, since the coastal cod population has decreased drastically the last years, from 350 thousand tonnes to 200 since 1984 (Vondolia et al., 2019, p. 30), and the annual harvest of coastal cod is 20% of the fish stock, I can assume a higher CC. Based on the above I do a calculative estimation of the CC. First I multiply the recent found amount of fish with the fractional difference between the number of coastal fish now and that of 1984 (350/200=1.75), which gives us 0.116 x 1.75 = 0.203. Lastly, I add the 20% annually harvested fish, 0.203x1.2 (20%), giving the number 0.2436 fish per m^2, which I round to 0.24 kg fish pr m^2 as my approximation of carrying capacity for gadid fish in the kelp forest.

It is worth mentioning that Vondolia's measures for CC of coastal cod (0.35 kg fish pr m^2) is way higher than mine because they assume that coastal cod and artic cod has the same carrying capacity (Vondolia et al., 2019, p. 39), even though it is know that the carrying capacity of cod can vary greatly already in different areas and sub-populations in mid Norway. Further, 75% of all coastal cod is found above 67 degrees north, indicating a much higher CC north than in the south, as well as other indices like maturity time, area use, and growth rates (Bjerknes et al., 2006, pp. 11-12; Salvanes et al., 1995, p. 24; Salvanes et al., 2004, pp. 242, 243, 247).

CC Fish Possibility

This represents the CC of fish after the habitat effect. Lorentsen found a 90% decrease in small gadid fish in trawled areas. And since current trawling practise leaves large parts of the forest intact around the trawled areas we can assume that the remaining 10% is due to the surrounding kelp forest and that a complete removal of the forest would make the decrease in fish close to 100% (Lorentsen et al., 2010, p. 2054; Vondolia et al., 2019, p. 32).

Habitat Effect on Fish

The level of kelp forest affects the CC of fish. In Norwegian coast there are large areas covered in kelp forests that are important habitat for coastal cod (Bjerknes et al., 2006, p. 6). The amount or level of a kelp forest is known to affect the possible amount of fish in the same forest, and Vondolia assume that carrying capacity of coastal cod depends on kelp forest (Vondolia et al., 2019, p. 32). In kelp areas that were newly harvested the number of small (<15 cm) gadid fish was 92% lower than in un-harvested areas (Lorentsen et al., 2010, p. 2054). Secondary production (small game and invertebrates), which is the nourishment of young cod, decreased with 70 to 98% after trawling. Reestablishment of flora and fauna follows the regrowth of the kelp (Rinde et al., 2006, pp. 7, 9). Gadid fish decreased by 75% from areas with more than 50% kelp coverage to areas with less than 25% kelp coverage. When kelp cover was less than 25% there were very few fish. When more than 50% there was abundant with fish in the kelp forest, indicating an S-shaped behaviour, thus the graph in Fig.1.1.7 (Lorentsen et al., 2010, p. 2058).
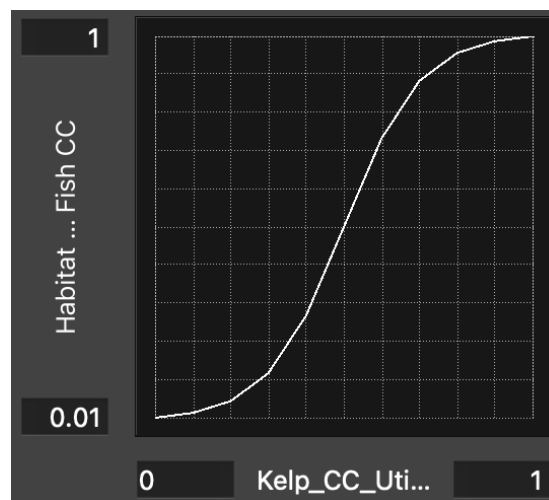
Fig.1.1.7 - Graphical Function: Habitat Effect on Fish

Maximum Growth Fraction Fish

Vondolia guessed the constant growth rate of costal cod to be 0.5. Based on an upper and lower limit of found growth rate in Artic Cod (0.6 and 0.33, respectively) (Vondolia et al., 2019, p. 39). But Bjerknes states that costal cod has a higher growth rate than artic cod. In addition, Bjerknes says that costal cod reproduction rate increases further south (Bjerknes et al., 2006, p. 11). So, I will use the highest normal growth rate found in artic cod, 0.6, and guess a 0.2 increase = 0.8 to be the maximum growth rate of costal cod.

Net Growth Fish

The growth rate of the of the fish stock. Governed, as the other growth flows in this model, with the Lotka-Voltera equation, where closing of the stock towards zero or the CC will decrease the growth rate in an up-down U-shaped behaviour, creating an S-shaped behaviour of the fish population.

Desired Urchin for Fish a Year

It is well documented that gadid fish, like cod, eats sea urchins and contribute to controlling the urchin density (Norderhaug et al., 2020, p. 166).

The number of urchins that one average fish would eat a year is found by multiplying the *desired kg urchin pr fish* with the total *number of fish* and then dividing that on the *weight per urchin*. The equation below shows a double dividing sign (//) which enables a function in the

modelling program that prevents the equation to divide by zero, which else would result in an error.

((desired_kg_urchin_pr_fish*number_of_fish)//Weight_per_Urchin)

Fraction of urchin as Prey
Sea Urchin is up to 20% of cods prey (Enoksen & Reiss, 2018, p. 251). It is thought that the fraction of urchin in diet will increase when they are abundant (Hagen, 1983, p. 186). And in Salvenes, Table 3, they show cod at different ages to feed 5500 mg pr m2 on benthic animals a day, which is about 20-70% of the diet of the age-classes that moves out of the fjords to the kelp forests (Salvanes, 1992, pp. 13, 18). Predators on benthic game is opportunistic and will prey on what is available (Norderhaug et al., 2020, p. 166). So, if the benthic community will be overtaken by urchins, we can assume a higher fraction of the benthic diet to consist of urchins. To not make an overestimation, I set the upper value of urchin in diet of fish to be 45%.
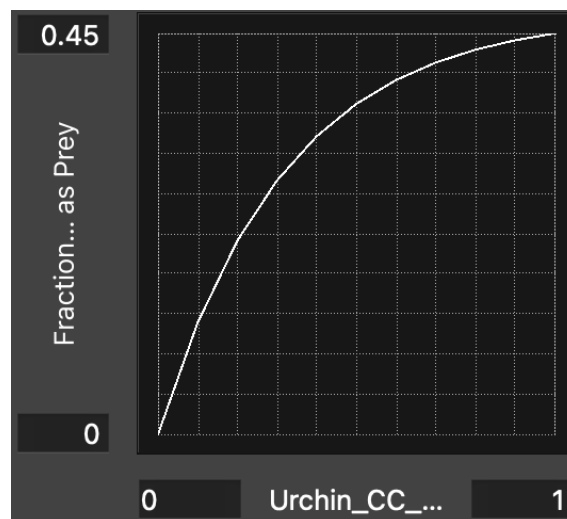
Fig.1.1.8 - Graphical Function: Fraction of Urchin as Prey

I use a concave curve as the effect of density or abundance (from 0 to 1) on predation pressure as it is a common way to explain predation pressure (Morecroft, 2015, p. 22; Swart, 1990, p. 95).

Other Predators Multiplier
The representation of predation pressure from other predators of the sea urchin. There are several other predators than cod of sea urchins, like sea birds, wolffish, flounders, halibut, otters, crab, lobster and bunch of smaller invertebrate predators (Bustnes et al., 1997, p. 16; Hagen, 1983, p. 186; Lorentsen et al., 2022, p. 307). I will assume the same reliance by other predators on kelp forest as that of cod. Thus, an S-Shaped effect of kelp forest on other predators.
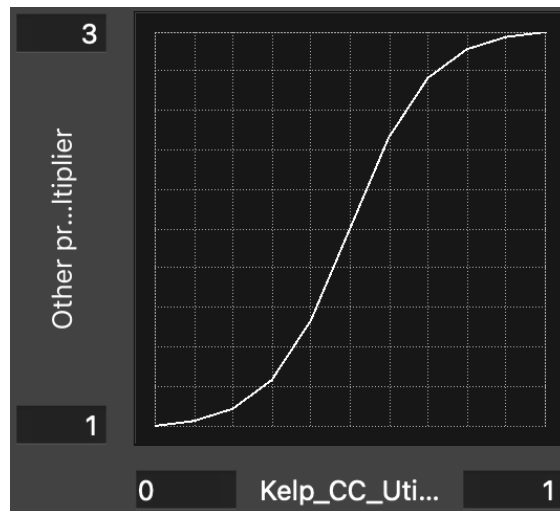
Fig.1.1.8 - Graphical Function: Other Predators Multiplier

The upper value of which the predation pressure from gadid fish is multiplied with a guesstimate (x 3), calibrated in the model to fit historical data, and is only based on that there are many other predatory species that prey on urchin and that some of them can feed extensively on urchins, e.g. sea birds (Bustnes et al., 1997, p. 16).

Harvested Fish
One of two outflows from the fish stock (Gadid Fish Biomass) that represents the human fishing pressure on costal cod. If the desired harvesting is larger than what is in the fish stock the flow is limited by a MIN-function that subtracts no more than what is in the stock over one time unit (year).

Fish Predated
One of two outflow from the fish stock (Gadid Fish Biomass) that represents the predation pressure from sea birds and seals. If the desired predation from them combined are larger than what is in the fish stock the flow is limited by a MIN-function that subtracts no more than what is in the stock over one time unit (year).

Apex Predator Sector

Modelling the local growth of sea bird and seal appearance in kelp forest is probably not well reflected by a population growth model. The model produced behaviour of their return to forage in the kelp forest might be way to slow as the fish abundance is high long before both seals and birds are shown to appear in the kelp forest again (shown in the result chapter). Especially for birds, as they are more reliant on kelp forests for foraging and are known to be well interlinked with availability of gadid fish availability (Bustnes et al., 2013). This could also be the case the other way, when kelp forests decrease, they might easily move to richer areas. I have tried to compensate for this effect, though it is highly speculative.

Seal

Seals
The stock that represents the number of seals in the area modelled kelp forest at any time.

Local Net Growth Seals
The local growth rate of the of the seal stock is a bi-flow (in- and outflow). It is local because I only measure the average number of seals that is found to forage in the kelp. With other words, what normally would be deaths in a population equation is here labelled as migration. The inflow is governed with the generic population function as the other populations in this model.

Local Seal Net Growth Fraction
The fraction predated fish of the desired amount is put into a table function which shows the effect of their total foraging success on the net growth of the seal population. If they get less than they desired the growth rate will decrease from its maximum growth rate. If food is scarce the growth rate will go to minus, decreasing the total population. I use a concave slope based on Weisse, to determine the growth rate based on food levels (Weisse et al., 2002, pp. 1448-1449).

Fig.1.2.1 - Graphical Function: Local Seal Net Growth Fraction

The maximum growth fraction is based on found growth rates of fur seals (not in Norway), which is around 9-17 % increase in population a year (Wickens & York, 1997, p. 245). I did not find direct numbers from Norway, but trying to calculate such a number from Bjørge's paper ((Seals in one big haul-out site is 40) x (Pups 150/Seal population 750) – Seal in haul-out site 40/max age 30 = 8 - 1.333333 = 6.66667/Seals in haul-out site 40 = 0.1666675) which resulted in a similar value, 16.7% (Bjørge et al., 2002). Thus, a maximum growth rate of 0.17 (17%) seems fitting. But since seals forage much less in kelp forests than deep basins (8 kg vs 66 kg a year). I must assume that seals will quickly change foraging ground as kelp forests is depleting, thus I need to make a guesstimate of change in local growth. Since they get almost 8 times of their food from outside a kelp forest, I will multiply their local growth rate by 8. 0.17x8=1.36. Maximum population disappearance of seals from kelp forest is set to 10% and is also multiplied with 8, equalling 80%.

I use a concave curve in the effect graph merely because that seals are an apex predator as sea birds, feeding on the same prey, thus one could expect a similar resilience to short food supply.

Fraction of Predation Allocator Birds
The weight of fish predated by birds and seals are divided to get the fraction of their respective predation pressure which is combined in the predation outflow of the fish stock, so I can use

the value of the outflow from predation on fish to affect the growth rate of each predator by separating the combined rate through this fraction.

Effect of Fish Abundance on Seal Feeding in Kelp Forest

Knowing that fish predate on urchin, there will probably be some fish swimming in the barren areas if there is some kelp forest in proximity. Thus, I assume that foraging by seals in areas with low fish abundance will be at least a bit more than zero. I set it to the same as for birds as that is the only number I got on such a relationship. 0.05.
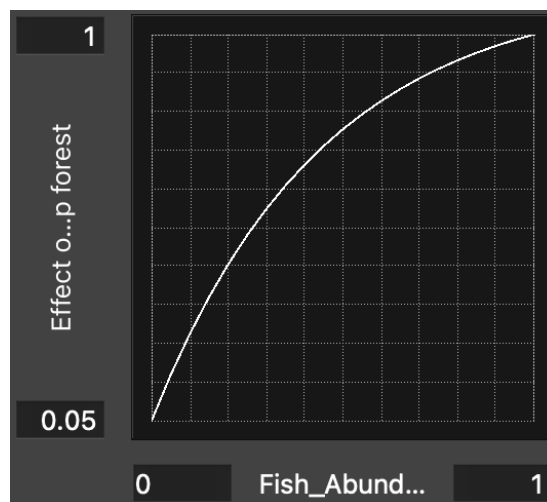
Fig.1.1.9 - Graphical Function: Effect of Fish Abundance on Seal Feeding Kelp Forest

I use a concave curve as the effect of density or abundance (from 0 to 1) on predation pressure as it is a common way to explain the predation pressure on fish population based on attributes of fish behaviour and composition (Morecroft, 2015, p. 22; Swart, 1990, p. 95).

Sea Bird

Sea Birds
The stock that represents the number of sea birds in the area modelled at any time.

Initial Birds sqm (Controls Stock Sector)
I found no relevant data on sea bird pr square meter or any other metric, nor the frequency of birds in kelp forest. All we know is that sea birds forage mainly in and around kelp forests (Dalsgaard et al., 2020). I made very approximate estimates of bird pr kelp square meter based on a map in Dalsgaards paper on sea birds and kelp forest. I read the map in Fig.1 on page 136, to find the area covered in kelp and divided that approximate area size on the total number of birds in the present colony. My estimations went: Knowing that one harvest section is 1852 m from north to south (Lorentsen et al., 2010, p. 2055). And the map is approximately 35x50 km = 1750 km. The grids on the map is harvesting sections, and the squares seems to be (1852x(1852/2)), so two grids would be 1852x1852 = 3429904 m^2, making it 3.43 km^2. Of the 1750 km the map covers, and about 225 km is covered by kelp. Then I will guess that 60% of that is pristine kelp forest. 225x0.6= 135 km^2 of pristine kelp forest. 135 divided with number of birds, 2050 = 15.2 birds per km^2. That's 0.000015 per m^2.

Local Net Growth Birds
The in- and outflow of the bird stock. The net growth of birds is the sum of increase and decrease rate in birds per area of kelp. The flow is governed by a normal population dynamics

formulation, as used in all growth flows in this model, where growth decreases towards the CC or zero. As for seal, I use a concave slope, based on Weisse, to determine the growth rate based on food levels (Weisse et al., 2002, pp. 1448-1449).

Local Bird Net Growth Fraction

The fraction predated fish of the desired amount is put into a table function which shows the effect of their total foraging success on the net growth of the bird population. If they get less fish than they desire the growth rate will decrease from its maximum growth rate. If food is scarce the growth rate will go to minus, decreasing the total population.

Maximal growth rate is derived from Norway (Bustnes et al., 2013). In Fig.3 at page 238, in Bustnes' paper, the highest growth rate was about 1.2 and the lowest -1. And, at page 242, they state that food availability explains up to 40% of the variation in population. Since I am not modelling other factors, the growth rates will be from 1.2x0.4 = 0.48 to -1x0.4 = -0.4.
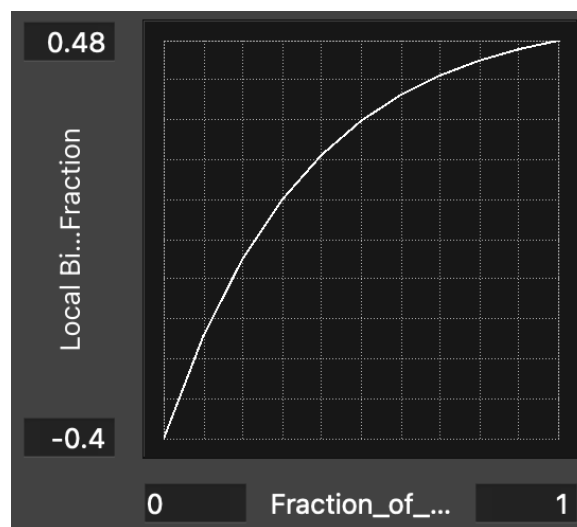
Fig.1.2.3 - Graphical Function: Local Bird Net Growth Fraction

The choice of graphical shape seen in Fig.1.2.3, a curved line being steep towards zero, is based on that seabird mortality does not increase much before the food resources are scarce (Cairns, 1988, pp. 262-263).

Desired Fish from kelp forest pr Bird a year

Votier found that seabirds consume 15-20% of their bodyweight (Votier & Sherley, 2017), but Saraux found that seabirds needs to consume 30-80% of their mass daily. With the wide range in consumption, the average intake is 35% of their weight a day. An average of seabird body mass from the Norwegian sea is 460 g (Saraux et al., 2020, p. 266). 460g = 0.46kg, which 35% of is 0.161 a day. In a year that is 58.7 kg.

Further, seabirds eat mostly young Gadid fish, making up approx. 60-90% of their diet (Bustnes et al., 1997, p. 19; Lorentsen et al., 2004, p. 166). That is an average of 75% of diet. 58.7 x 0.75 = 44 kg fish pr year.

Effect of Fish Abundance on Bird Feeding in Kelp Forest

It is found that sea birds favour kelp forest as habitat using up to a 100% of their foraging ground in kelp forests. But sea birds can also use up to 20%, more common 10%, of their

foraging area in barren grounds. I will thus assume that their foraging pressure only decreases to 5% when fish abundance is low (Bustnes et al., 1997, p. 17).
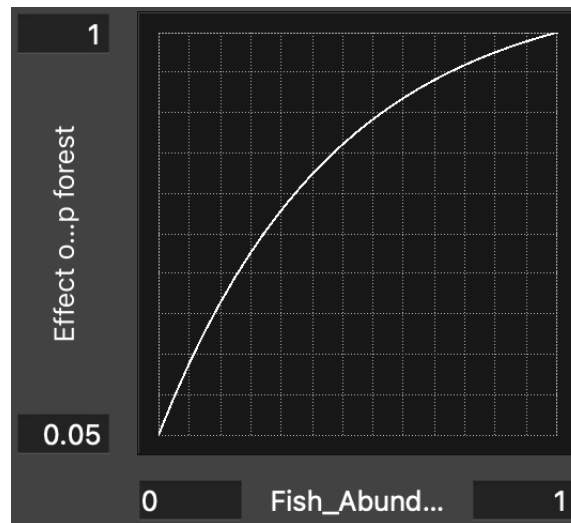

Fig.1.2.2 - Graphical Function: Effect of Fish Abundance on Bird Feeding in Kelp Forest

As seen in Fig.1.2.2, I use a concave curve as the effect of density or abundance (from 0 to 1) of fish on predation pressure as it is a common way to explain the predation pressure on fish population based on attributes of fish behaviour and composition (Morecroft, 2015, p. 22; Swart, 1990, p. 95).

Technical Model Specifics

The time span of the model simulation is set to 100 years because barrens are known to last for several decades and speculated to be a stable state of the system, meaning in theory it can last forever (Filbee-Dexter & Scheibling, 2014, p. 2). The time units are therefore "year". The program Stella Architect, which I used to model, is set to count the changes in values 500 times each time unit (a year), formally called delta-time or DT. This value was selected to avoid integration error, as evidenced by the lack of further noticeable changes to the model behaviour. The integration method is set to RK4 (Runga Kutta 4th edition), which is the best method to get right behaviour from equations like the "Pulse" function that I have used in the outflow "Mass Death Urchin" and the outflow "Harvest of Kelp".

The dimensional consistency of units and equations of the model values is ensured by integrated unit error warnings in the Stella Architect program, giving the modeller a chance to continually check the dimensional consistency of the model (Barlas, 1996, p. 191).

Boundary Adequacy

The model must be evaluated to see to that the level of aggregation and structure is relevant for its purpose in regard of its boundaries (Forrester & Senge, 1979). The model is meant to capture the dynamics of the state shift in the kelp forest and to find out what parameters we can address as leverage points to affect this state shift. This process is done through the literature review and structure verification chapters. As I find a plausible hypothesis to be that fishing pressure and/or harvesting of kelp are parameters that can and has been a part of the state shift of the ecosystem by indirectly affecting predation pressure on urchins or decreasing the forests to levels that gives urchins a higher grazing pressure than the re-growth of kelp. This makes the model pass the boundary adequacy test (Forrester & Senge, 1979, p. 15).

Sensitivity Analysis

During the sensitivity analysis, I went through all variables and tested them with a value-range that the parameter is likely to possess in reality. This will show us how sensitive the model is to changes in a particular parameter. The changes are observed in the KPI's, which tells us about the effects the changes have throughout the system. The KPI's I will focus on is firstly the stocks: Kelp Forest, Sea Urchins and Gadid Fish Biomass, secondary is Seals and Sea Birds. Since my model is of the conceptual sort, it is mostly the behavioural changes that interests us, meaning that I am looking for changes in the shapes of the curves on the graphs instead of specific numerical changes. But it is also important to find the tipping point of the model and find which parameters can contribute to the tipping. Since the system modelled is by nature a sturdy system, changes in most parameter values are expected to not be very sensitive when tested in the base run of a stable state pristine kelp forest. The sensitivity of the system is expected to be much higher when the system is close to a tipping point (a shift of dominance), which it in general will be when the number of sea urchins are close to what is found to be the maximum number of urchins a kelp forest can withstand (above 15 urchins pr m^2) before a shift of dominance to an urchin dominated barren occurs (Fagerli et al., 2015, p. 1220; Hagen, 1983, p. 180; Leinaas & Christie, 1996, p. 533; Skadsheim, 1995, p. 203).

A summary of the tests, the range tested, the base value of the parameters, if they are sensitive to change and how confident I am in the values, are listed in Table.1, below. The complete sensitivity analysis is found under Appendix A – Sensitivity Analysis.

Table.1 – Sensitivity Testing

Parameter	Base Value	Range	Sensitivity	Confidence
Kelp Forest				
Maximum Growth Fraction Kelp	0.85	0.425-1.225	Slightly	Confident
Fraction of Kelp Trawled	0	0-0.75	Very Sensitive	Confident
Initial KELP sqm	27	15-41	Not Sensitive	Confident
Kelp CC pr sqm	30	15-41	Not sensitive	Confident
Sea Urchins				
Maximum Growth Fraction Urchin	0.7	0.35-1.05	Sensitive	Confident
Average Grazing pr Urchin	0.56	0.365-0.912	Not Sensitive	Confident
Effect of Kelp Availability on Actual Grazing	Diagonal	Curved, Diagonal , S-Shape	Not Sensitive	Fairly Confident
Effect of Forest Composition on Urchin Grazing	Steep beginning, decline in end	Shapes	Not Sensitive	Fairly Confident
Average Weight pr Urchin	0.02	0.01-0.03	Not Sensitive	Confident

Initial Urchin sqm	2	0-20	Sensitive	Confident
Urchin CC pr sqm	60	20-60	Not Sensitive	Confident
Gadid Fish				
Maximum Growth Fraction Fish	0.8	0.4-0.9	Not Sensitive	Confident
Habitat Effect on Fish CC	S-Shaped	Shapes	Not Sensitive	Fairly Confident
Other Predators Multiplier	S-Shaped	Shapes	Not Sensitive	Fairly Confident
Fraction of Urchin as Prey	Upward curve	Shapes	Sensitive	Confident
Normal Kg Food pr Fish	0.85	0.3-0.9	Sensitive	Confident
Avg Weight pr Fish	0.35	0.2-0.6	Slightly Sensitive	Confident
Initial FISH sqm	0.12	0.1-0.35	Not sensitive	Fairly Confident
Fish CC pr sqm	0.24	0.2-0.35	Not sensitive	Fairly Confident
Fraction of Fish Harvested a Year	0.2	0.1-0.5	Not Sensitive	Confident
Seals				
Local Seal Net Growth Fraction	Upward curve	Shapes	Not sensitive	Little Confidence
Desired kg Fish from kelp forest pr Seal a Year	4	2 kg - 6 kg	Not sensitive	Confident
Effect of Fish Abundance on Seal feeding in kelp forest	Upward curve	Shapes	Not sensitive	Fairly Confident
Initial SEAL sqm	0.0000023	0.00000115-0.00000345	Not sensitive	Fairly Confident
Seal CC pr sqm	0.0000024	0.0000012-0.0000036	Not sensitive	Not Confident
Sea Birds				
Local Bird Net Growth Fraction	Upward curve	Shapes	Not sensitive	Fairly Confident
Desired Fish from kelp forest pr Bird a year	44	35-53 kg	Not sensitive	Confident
Effect of Fish Abundance on Bird feeding	Upward curve	Shapes	Not sensitive	Confident
Initial Birds sqm	0.000015	0.0000075-0.0000225	Not sensitive	Fairly Confident
Bird CC pr sqm	0.00002	0.00001-0.00003	Not sensitive	Not Confident

Kelp Forest Sector

The kelp forest stock is what tells us if the system is in a stable kelp forest state. The kelp forest sector is the most sensitive sector, which is expected as kelp affects the gadid fish sector and the sea urchin sector directly and invasively. That is because the level of kelp forest controls the CC of fish and the predation pressure on urchins. Further, the kelp stock level decides the

grazing pressure through three feedback loops (R1, B5 & B6, in the CLD under *Feedback Story*). The most sensitive parameter in this sector is *Fraction of Kelp Trawled* as it directly can decrease the kelp stock of up to 75% of its stock in a year. The values of the parameters in the kelp stock are also those with most documentation making me very confident on the behaviour effects from this system sector.

Sea Urchin Sector

The Sea Urchin stock is what tells us if the system is in a barren state. The sector is in general fairly sensitive from the base run (kelp dominance) but shows increasing sensitivity when the number of initial urchins is increased towards the threshold of 15 urchins. The number of initial urchins is thus the most sensitive parameter, followed by its maximum growth fraction and its CC. The values of the parameters in this stock are also well documented.

Gadid Fish in Kelp Forest Sector

The gadid fish sector is slightly less sensitive, where the highest sensitivity lies in the parameters that affects the predation of urchins (*Fraction of Urchins as Prey* and *Normal kg Food pr Fish*). The sector's sensitivity also increases when closer to a tipping point. The confidence in the parameters tested are also confident to be within real possibilities.

Apex Predator Sector

This sector with seals and sea birds are meant to be an indicator of how the systems behaviour will be observed in the higher trophic levels and are a small part of the forces that swings the system state to one or the other. The sector was thus expected to show the very low sensitivity found here. The confidence of the test values in this sector is also lower than the other sectors but will anyways have no significant effect on the system in the real scenarios.

Extreme Condition test

There are two extreme condition tests that need to be done. First I have checked each structural relationship by partial model testing to ensure that the model parts and relationships is robust under extreme conditions (Forrester & Senge, 1979, p. 12). One way the model structure is made robust is by using MIN functions in the flows of stocks to avoid the impossible outcome in this system of a stock going to minus. Second is observing the behaviour produced by the model by imposing extreme values on different parameters. The values tested can theoretically happen but are not likely to occur in real life, which enables us to see if the system reacts appropriately (Forrester & Senge, 1979, p. 27). I will further in this chapter show you two scenarios from the extreme condition testing.

To test if the system behaves as expected under extreme conditions, I start by setting the *Maximum Growth Fraction Kelp*, *-Fish*, and *-Urchin* to an extreme and unlikely value of 0, to see if the system responded appropriately, and not showing any mathematical errors.
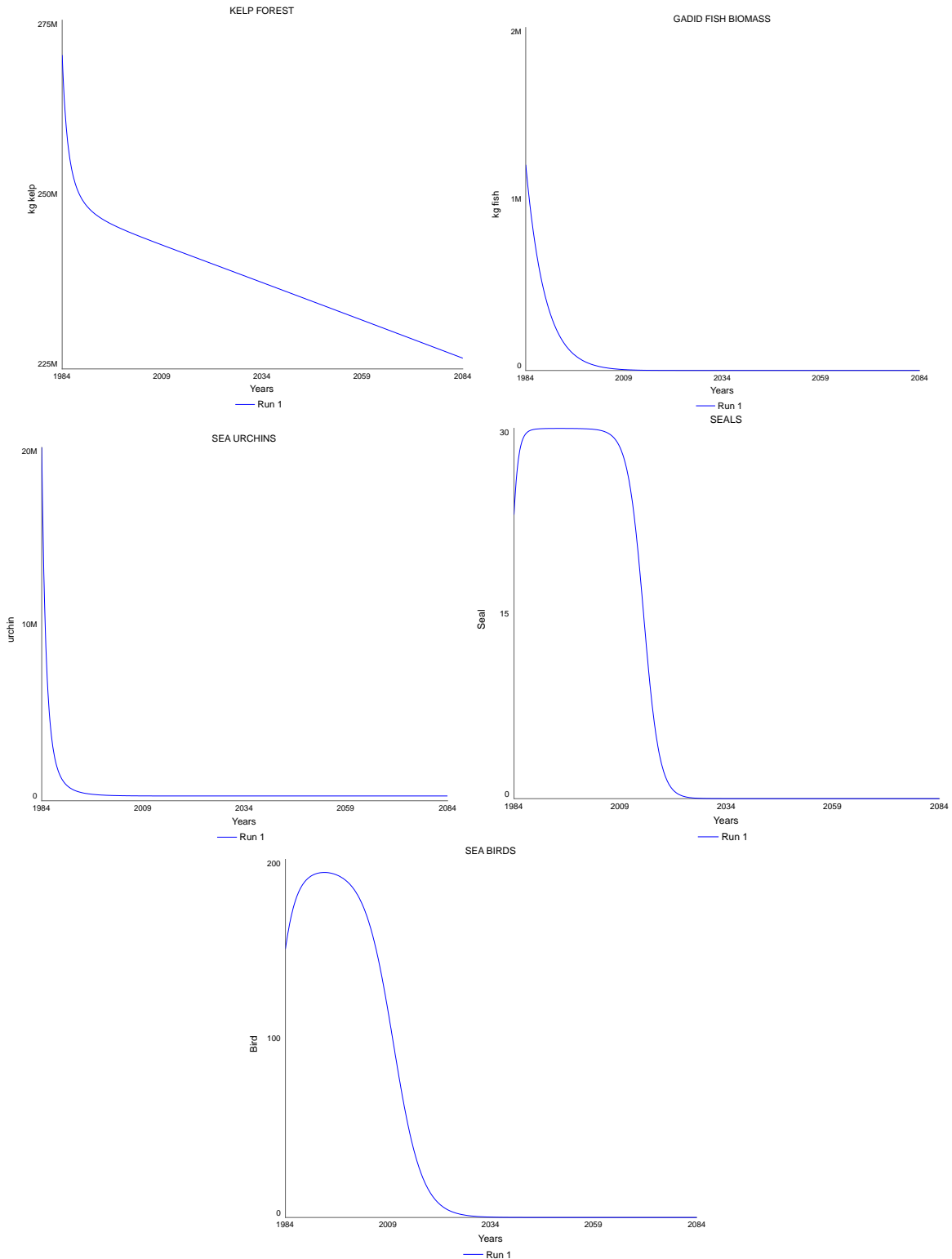
Fig.1.2.4 – Extreme Test: Maximum Growth Fractions = 0

In Fig.1.2.4 we see the expected behaviour of the system, without errors, where all stocks decline. When there is no growth rate, we expect the kelp forest to be grazed by urchins, the fish to decline as its CC (reliant on kelp forest) declines and predation from sea birds and seals. Sea birds and seals then die off as there are not enough fish to uphold their reproduction. The sea urchins can live to about a hundred years, so the model time range fits fairly with the behaviour of the sea urchin stock, but less with an extension of the simulation time period.

Also, we see that when there are a stable number of sea urchins the kelp forest declines linearly, indicating that if there were no sea urchins the kelp forest would persist at the level it was initiated in. This is counter intuitive when the growth rate is zero as they in real-life has a life span of 10-20 years, thus in real life we would expect a gradual decline. This is a weakness of this level of aggregation of the model and simplification of the ecosystem.

In the second test run I imposed an extreme change of the parameter *normal kg food for fish* to the unlikely value of 0. To get a wider understanding of its implication I also enable the mass death event by setting *Mass Death Event Switch* to 1. We would then expect predation on urchins to be zero, which in turn would enable urchins to grow to its CC making the rest of the system collapse.
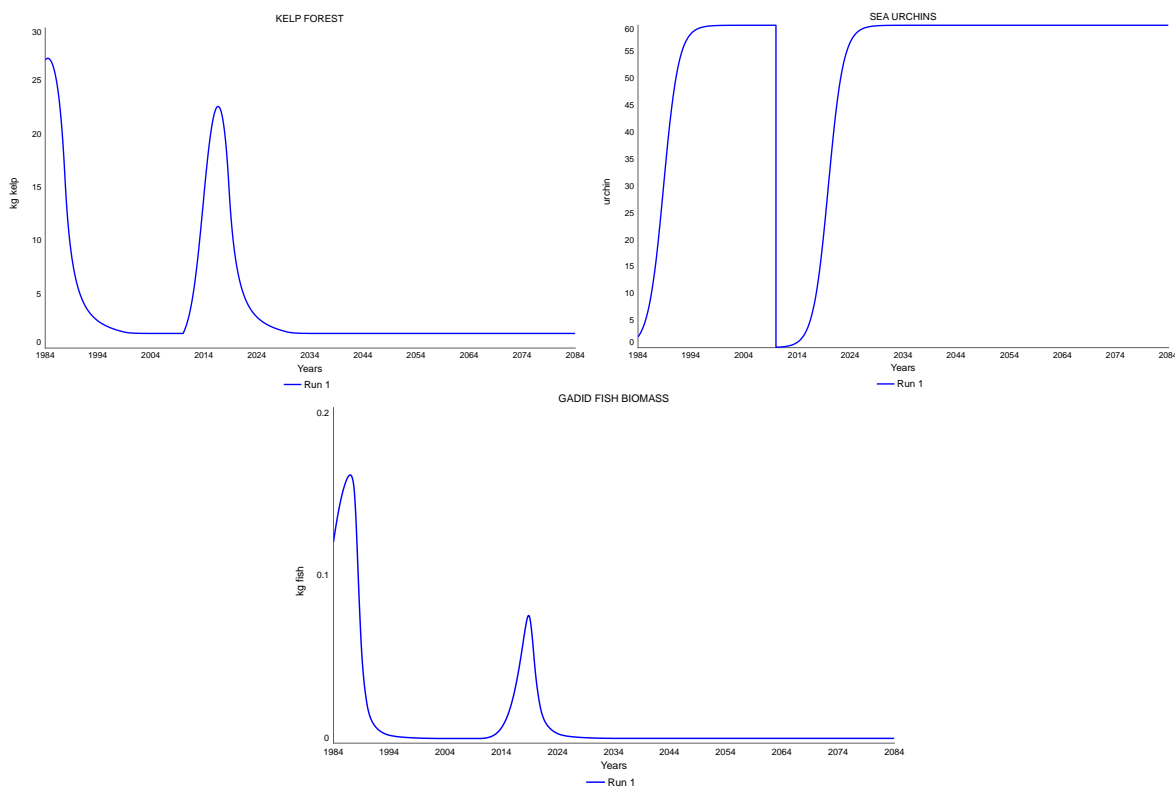
Fig.1.2.5 – Extreme test: No predation (Kelp Forest & Sea Urchins)

As we see in Fig.1.2.5, the system behaves as expected. When fish are set to normally eat no food, the equations that govern the predation by fish on urchins is all multiplied with zero, resulting in no predation. As predation is the only controller of urchin population (except the mass death event), the population is free to grow to its CC. When the number of urchins increase, the grazing pressure on kelp will then surpass kelp's ability to regrow, making the kelp forest collapse by decreasing to its minimum. When the mass death of urchin kicks, in at year 2010, the normal response would be that the increase in fish would create a predation pressure that would surpass the urchin's ability to regenerate. But as we see, urchins climb back on top, because of the lack of predation.

Behaviour Reproduction Test

The model behaviour must be seen in comparison with the behaviour of the real-life system to assess how well they match (Schwaninger & Groesser, 2018, p. 129). So, here I will compare real life observations with the behaviour of the three main KPI's (Kelp Forest, Sea Urchin, Gadid Fish Biomass) produced by the model. As there are few models made of the system I am here modelling and thus little to no detailed graphs of the behaviours, I will use qualitative historical data to determine the compatibility of the model's behaviour with observed values.

We start off by looking at the kelp forest's regeneration time. Kelp forests are found to need more than 8 years to fully grow back after trawling (Greenhill et al., 2021, p. 2; Steen et al., 2011, p. 18). To test if the model reproduced this behaviour, I initialised the kelp stock at 1 kg kelp pr m^2 with zero urchins. The produced behaviour of the model is shown in Fig. 1.2.6, below.
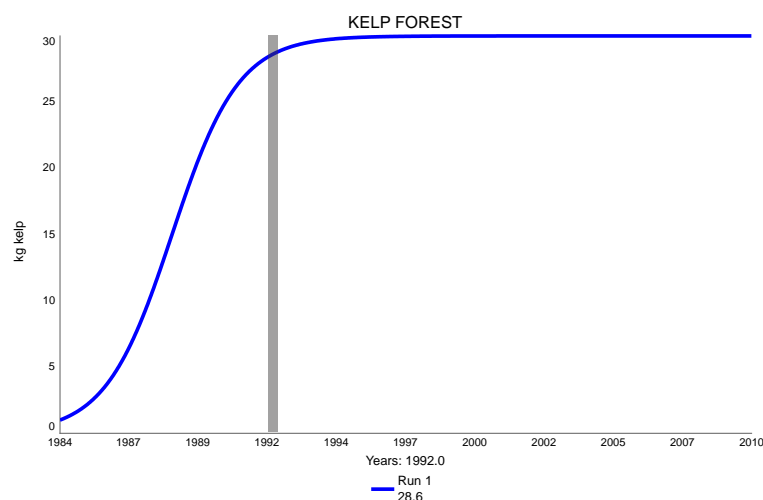
Fig. 1.2.6 – Behaviour reproduction: Kelp Forest Re-growth Time

The vertical grey line is drawn 8 years into the simulation. At this point the forest has not yet reached its peak, but very close, which aligns well with the historical observed data that a kelp forest needs more than 8 years to fully replenish after kelp trawling (a reduction of kelp forest without urchins).

Further, sea urchins can decimate a forest within 3-6 years (Hagen, 1983, p. 185; Sivertsen, 1997, p. 2880). Hagen believes that a down grazing in Norway started in 1974 and that the forest disappeared in 1978 or 1979. If we add an error margin on the start year of 1, the disappearance of the kelp forest took between 3 and 6 years. And Sivertsen found kelp beds could be grazed down within 6 years. However, they have no records of the amount of sea urchins in the areas they first observed and termed as kelp forests that later became barren. If there where urchins under the canopy in these areas, the understory plants (the juvenile kelp) might have already suffered losses. So, the time for the sea urchins to create a barren might be longer. A surer historical observation is that forests that inhabit more than about 15 urchins were in negative transition phases which always resulted in barrens (Fagerli et al., 2015, p. 1220; Hagen, 1983, p. 180; Leinaas & Christie, 1996, p. 533; Skadsheim, 1995, p. 203). I must expect that when sea urchins already have accumulated to densities of 15 urchins per square meter, the kelp forest will have suffered some loss. Thus, to test if the model reproduces historical behaviour when I set the initial urchins to the known transition level of 15 urchins pr

m^2, I set the initial kelp forest to 20 kg pr m^2. The behaviour of the model is shown in Fig.1.2.7, below.
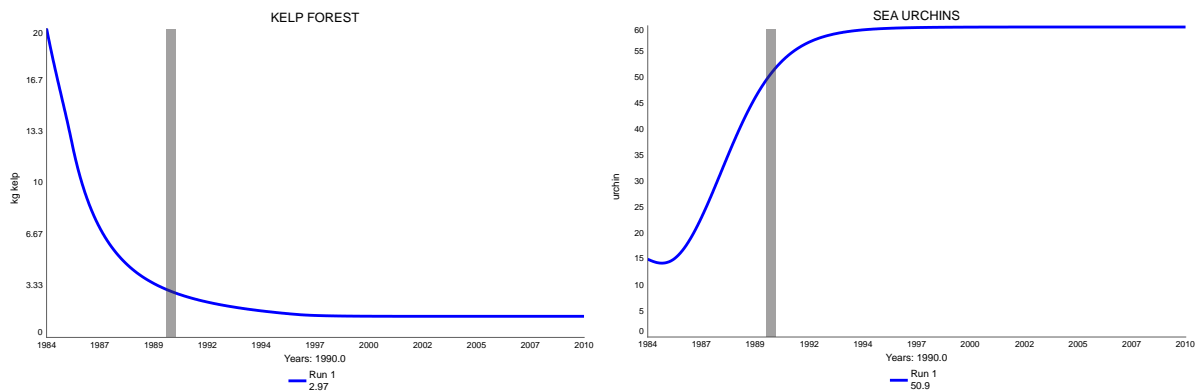

KELP FOREST

SEA URCHINS

Fig.1.2.7 – Behaviour Reproduction: Down Grazing Time

The vertical grey line is set 6 years into the simulation. At this point the kelp forest has been grazed down to 3 kg per m^2, which is 10% of the carrying capacity of 30 kg, at which point the urchins has reached 51 individuals per m^2. Since the model is an aggregation of a whole trawling section, meant to include the outer bands of which kelp forest often are untouched by urchins due to high wave exposure, the kelp forest stock never goes to zero. So, this behaviour aligns very much with historical data. Especially considering another observation of Sivertsen, that 7 out of 8 observed localities (which adds up to be ca. 90%) were barren after approximately 6 years (Sivertsen, 1997, p. 2880).

It takes 14 years for a forest to re-establish from a barren state. Leinaas & Christie finds L.Hyperborea to use more than 4 years to cover 40% of the ocean floor of a sea urchin barren after sea urchins has been removed/suffered a drastic reduction (Leinaas & Christie, 1996, p. 531). The 40% cover seemed to happen during the last year so I will assume a 90-100% coverage the year after (if there is little to no grazing pressure), then 9 years (more than 8 years, as we have established earlier) after that for the full ecosystem to recover. That's sums up to an estimated 14 years in total for a L.Hyperborea forest to fully recover from a urchin barren after a drastic reduction of sea urchins.

KELP FOREST
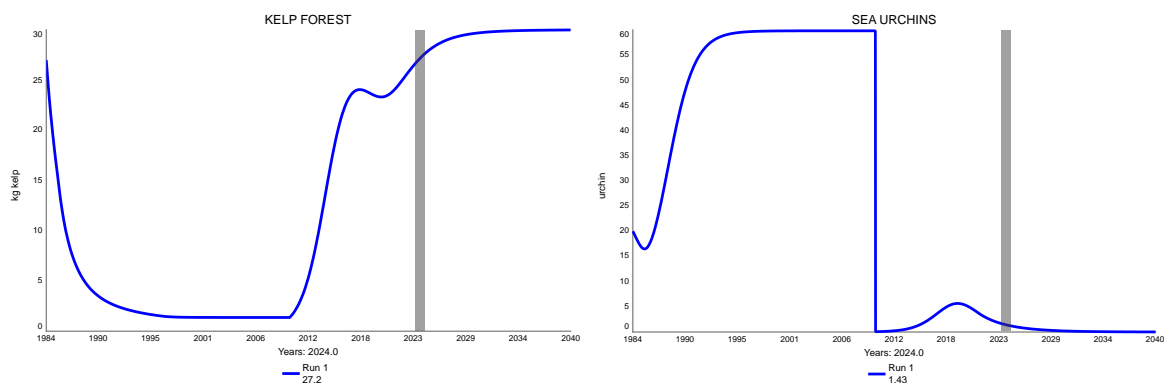
SEA URCHINS

Fig.1.2.8 – Behaviour Reproduction: Kelp Forest Re-growth from a Barren

As seen in Fig.1.2.8, I have set the model to reach a full barren state, then imposed an extensive sea urchin die-off at year 2010. 14 years after the sea urchin die-off (indicated by the grey line), the kelp forest has replenished beyond its initial value of 27 kg pr m^2, and sea urchins are below the number of which can be found in a pristine kelp forest (2 urchins pr m^2). The short

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dip in kelp forest around year 2018 is due to a slight increase of sea urchins at the same time. Urchins increase at this point because the predation pressure of the few fish that lurks in the area is lower than the urchin's growth rate. But because grazing from urchins is lower when the kelp forest is low, the kelp forest's growth rate is initially well above the grazing pressure, letting the forest reach high levels before the grazing pressure is being felt, at which point the forest has reached a level where enough predators will return to push the urchin's population down again. A similar dip in kelp forest and bump in sea urchin population is also observed in Vega, an island in the southern part of northern Norway, after an urchin die-off in a barren area that lead to a re-establishment of the local kelp forest (Leinaas & Christie, 1996, pp. 527, 530). The bump in sea urchins can be seen in fig.2 in the referred paper, and the dips in kelp forest can be seen if fig. 6 in the same paper. The dip Leinaas and Christie found though, happens only a year after the urchin die-off and is only prevalent for a year, whilst my model behaviour shows that the dip in kelp forest happens 7 years after the urchin die-off and lasts for approximately 3 years. I show this because it at least verifies the behaviour produced by the model. The difference in timing and duration is firstly because their observations is of a small area compared to what my model aggregates, and that they do not measure biomass of kelp but rather area covered. Also, because my model is made to represent a vast area the variation in urchin bumps in the different localities within will accumulate to happen over a longer period of time.

For the gadid fish's reaction to the kelp forest there is fewer detailed observations, but if we use the findings of Lorentsen saying that in newly trawled areas the number of small (<15 cm) gadid fish was 92% lower than in un-harvested areas (Lorentsen et al., 2010, p. 2054), we can use that to compare with the level of gadid fish that the model shows in a scenario where a part of the kelp forest has been reduced drastically by kelp trawling.
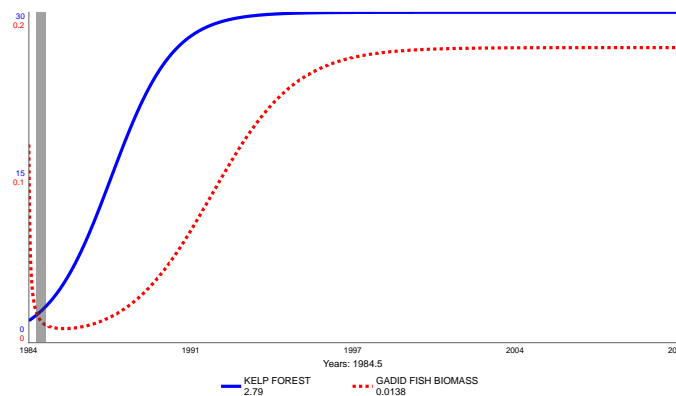

Fig.1.2.9 – Behaviour Reproduction: Gadid Fish Biomass level compared to Kelp Forest level

In Fig.1.2.9, we see can see the reduction in gadid fish shortly after a hypothetical trawl harvest, done by initializing kelp with 2 kg pr m^2. The grey lines show the reduction of fish after half a year after trawling. The value is 0.0138, which is 7.7% of (0.178) the value of fish when the kelp forest is on top. That is a 92.3% reduction of fish shortly after kelp trawling which fits well with the mentioned historical observations.

I have not found literature of the effect on sea birds and seals after their local kelp forests has disappeared, so their behaviour cannot be validated with historical data. Nevertheless, they are secondary indicators meant to show the extended effects on the ecosystem and are not directly important for the dynamics of kelp forests.

# 5 Results: Analysis of Simulation Scenarios

My goal with the model, as mentioned under "Research Purpose", is to understand the dynamics of the shifting states between barren grounds and kelp forests. As mentioned, we know that the further the ecosystem is leaning towards one state, the harder it is for it to shift towards the other because of the reinforcing loops that dominates in each of the system states. That is why I am confident, if any useful insight is to be drawn from a conceptual model of the ecosystem, that testing the system under ideal conditions is a good way to learn about the upper levels of human interventions the ecosystem can withstand without collapsing.

I will further in this chapter show the results of different scenarios imposed on the model and analyse the behaviour to better understand what feedback loops in the system that are at work. The feedback loops I will refer to is those in the CLD under "Feedback Story", Fig.1.1.4.

1. Kelp Stable State (Base Run)

When the kelp forest is close to the carrying capacity I regard it as a pristine kelp forest, which constitutes a stable state of the ecosystem. The stocks in the base runs are initialized at levels that are below their CC. The model is simplified in such a way that I look away from environmental factors that contributes to determine the equilibrium in the real-life system, like latitude, temperature changes, storms, light, space, etc. (Sivertsen, 1997, p. 2878) - and rather look at how the system might behave under ideal conditions.

The behaviour of the KPI's of the ecosystem is shown in Fig.1.3.1, below. The indicators for the kelp forest stable state behave as expected when initialized below CC and increases decreasingly to stabilize at their equilibrium. The sea urchins also behave as expected by decreasing decreasingly due to high predation from fish. The *Gadid Fish Biomass* finds equilibrium below its CC because of the constant fishing pressure. All the stocks exhibit goal-seeking behaviour - the exponentially decaying behaviour towards an equilibrium level.
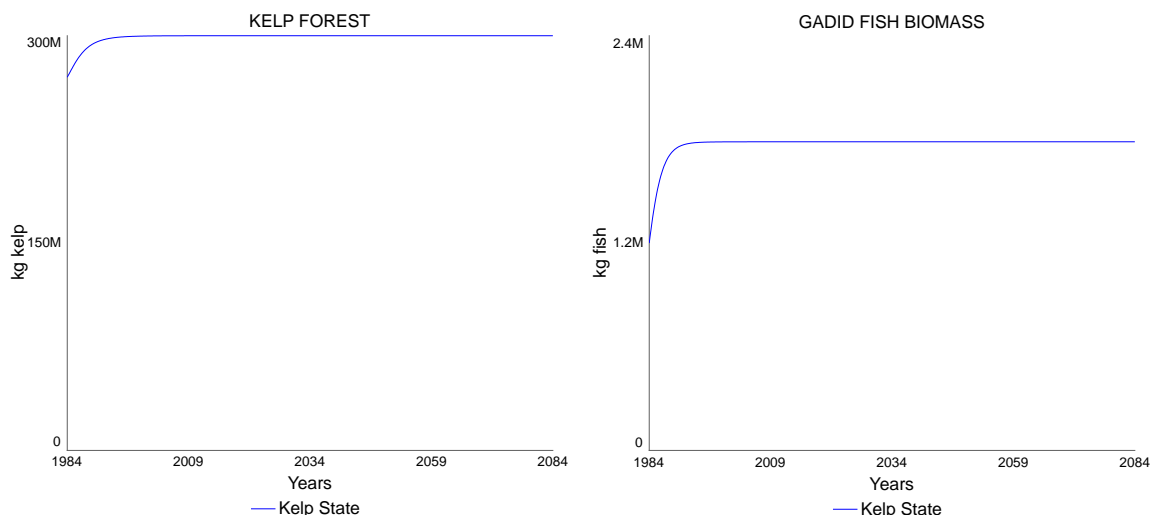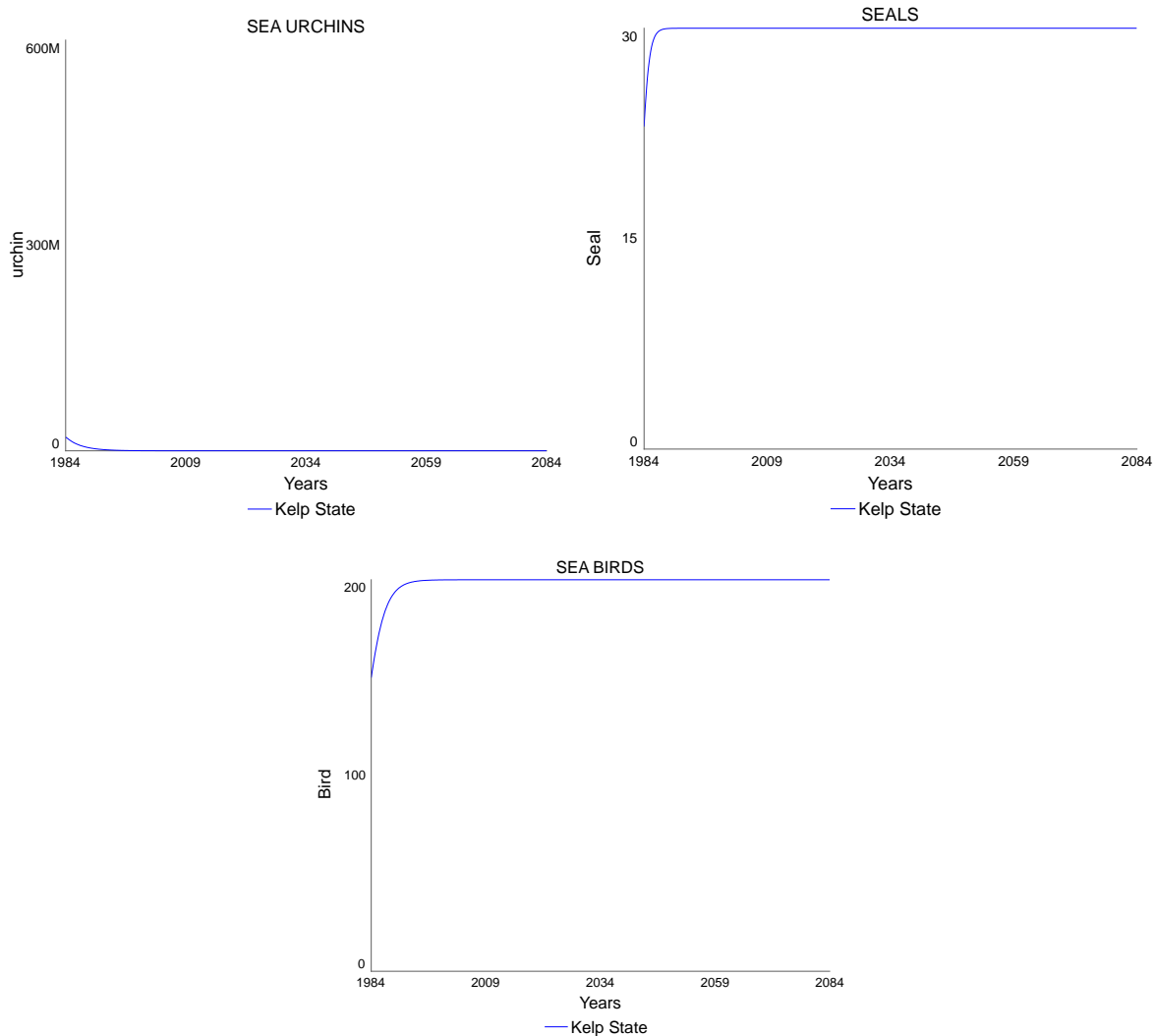
Fig.1.3.1 – Kelp Stable State (Base Run)

When the kelp forest has reached high levels, the system is constantly forced to its maximum by the reinforcing feedbacks loop "Kelp Forest enables Gadid Fish" (R3) and "Kelp Forest enables Other Predation" (R2), by enabling the *Gadid Fish Biomass* to stay high, thus a high predation pressure on *Sea Urchins*. The system also gets help from the reinforcing loop "Drift Kelp" (R1) which increasingly decreases *Kelp Grazed* at high levels of *Kelp Forest*. The decreasingly increase towards their equilibriums is due to the balancing feedback loop that each stock's carrying capacity has on its own growth rate through the logistic function.

Lastly, when the *Gadid Fish Biomass* is high there will be enough food for *Seals* and *Sea Birds* to increase decreasingly towards their equilibrium. Their increase does create an increase in predation on the gadid fish stock (the balancing feedback loops B1 and B2), slightly decreasing the fish's equilibrium level, though its miniscule.

The parameter values of the base run are found in Table.1, under "Behaviour Sensitivity".

Alternative Base Run - with Average Harvest

The base run could also be set with an average amount of trawled kelp without it imposing any instability in the system behaviour. We see dips in the kelp forest each 5th year as 35% of the standing stock is set to be removed at that interval through a PULSE function. These dips are

affecting the gadid fish population, as their carrying capacity decreases with the kelp forest stock, shown in Fig.1.3.2, below.

Input values:
Fraction of Kelp Trawled: **0.35**
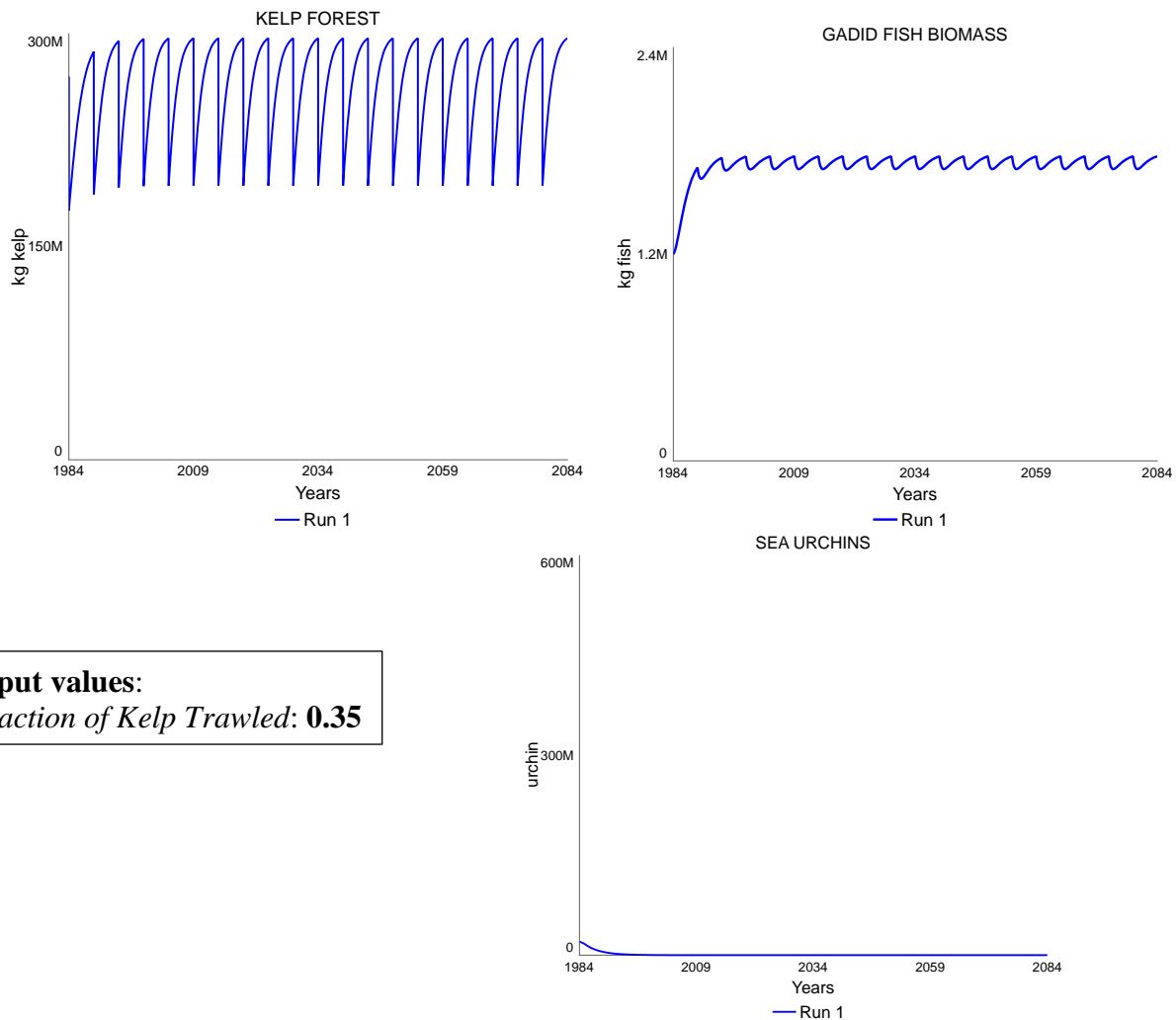
Fig.1.3.2 – Base Run w/ Average Havrest

The seal and sea bird stocks do not notice any change as their desire for food is met throughout this simulation. The sea urchin stock does not change much either, though there is slight prolonging of their decrease, because the reinforcing feedback loop of Kelp Forest supporting Kelp Forest (R2) is weakened by the slight decrease in fish which slightly decreasees the predation on urchins. Further, after trawling the forest composition is being decreased so the reinforcing feeback loop Drift Kelp (R1) is weakened, enabling a slight higher grazing pressure, which slows the regrowth of kelp slightly. Which again slighlty prolongs the increase in *Gadid Fish Biomass*.

2. Barren Stable State

The barren stable state comes about when sea urchins accumulate in greater numbers enabling them to graze down whole forests within few years (Sivertsen, 1997, p. 2880). To show a clear barren state behaviour I initiate the numbers of sea urchins at 20 urchins per square meter, well above the known tipping point. The behaviour is shown by the graphs in Fig.1.3.3, below. The blue line is the kelp stable state, and the red stippled line is the sea urchin barren state. In the graphs, following the red stippled line, we can see how all stocks decreases to their minimum

while urchins go to their maximum and stabilizes there for the rest of the simulation in this barren state scenario.

KELP FOREST

GADID FISH BIOMASS

SEA URCHINS

SEALS

SEA BIRDS
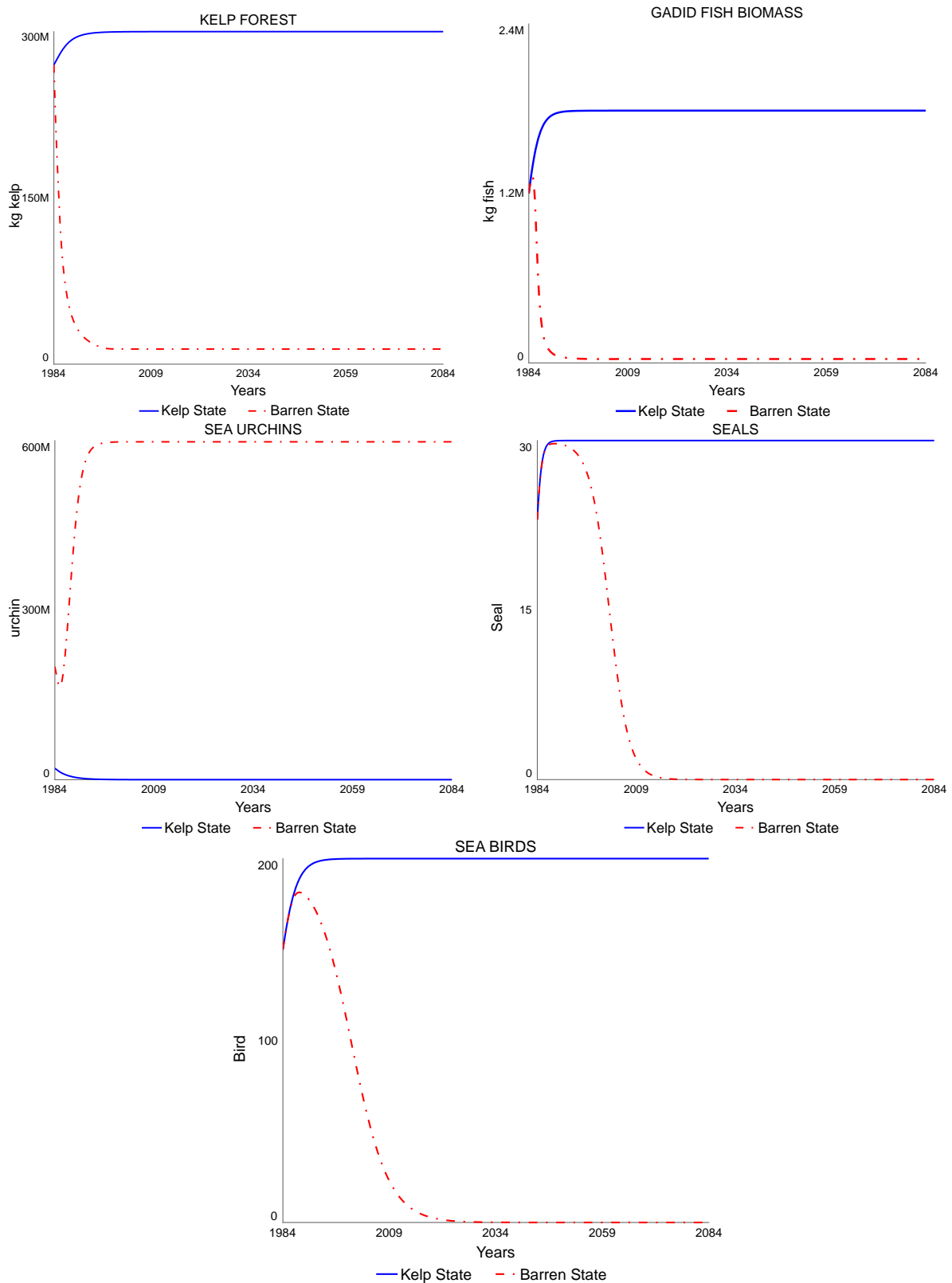
Fig.1.3.3 – Barren Stable State

Following the red line in the *Kelp Forest* and *Gadid Fish Biomass* graphs, we see that the stocks do not go all the way to zero. That is due to the balancing feedback loops B4, 5 and 6, which

decreases the kelp grazed when at low levels through a density effect and that the forest composition in low levels consists of unpreferred food for urchins, which also decreases their grazing. These loops are not that strong if we were to look at a few square meters on a real barren kelp forest but are here to represent adjacent kelp forest's continual effort to regrow in the barren area, explained further under the "Discussion" chapter.

The short-lived increase in *Gadid Fish Biomass* we see in the red line, is due to the high initial level of *Kelp Forest* which rooms more fish than what the fish stock starts with. The fish stock thus firstly increase as there is room for it to grow through the reinforcing feedback loop Shelter & Food for Gadid Fish (R3). The initial level of urchins also makes more of the fish's diet to consist of urchins through the balancing feedback loop Density Effect of Urchin Population (B3), which together with the increase in fish levels creates a dip in the *Sea Urchins* stock. This behaviour is short-lived because the number of initial urchins has already imposed great grazing pressure, and reduced the kelp forest to a level that decreases the fish stock and thus predation pressure on urchins. The system is now dominated by the two reinforcing loops R2 and R3 in sea urchin's favour.

We also see that the seals and sea birds disappear several years after the forest is diminished. Their delayed respones is because their net growth rates does not go to minus before the fish levels are very low. In addition, as there will be a few fish left due to the adjacent kelp forest (when *Kelp Forest* is at its low equilibruim), the *Seals* and *Sea Birds* will not reach their maximum rate of decrease.


3. Kelp to Barren Shift - harvest and fishing

Now, we will examine the tipping points, and how much pressure the kelp forest can sustain before a shift of state occurs.

Change in Kelp Trawling

For a better visual understanding of the urchin threshold, I set the *Area Size* to 1 m^2 (change in area size does not affect behaviour).

Trawling can commonly range from 15% to 75% of the local kelp forest each trawling year in Norway. The average trawling pressure is thus 35%, which is sustainable when trawled in pristine kelp forests. Since there are strong indicators to that the pressure on this resource will increase forward, we can benefit from insights to how much human pressure the forest can sustain before it collapses. In the scenario below, Fig.1.3.4, the kelp trawling is set to take out 60% of the forest each 5th and 6th year. With such a high pressure the forest does not fully regrow with the 5-year interval before it is harvested again. The implication of this is that the output will proportionally get smaller. With the current trawling techniques this is a more plausible behaviour than having a set amount output as the trawl boats movement pattern is relatively random within the set trawling area which will result in less caught kelp when there is less kelp (Dalsgaard et al., 2020, p. 135). The blue line is with a 5-year interval and the red line is with a 6-year interval.
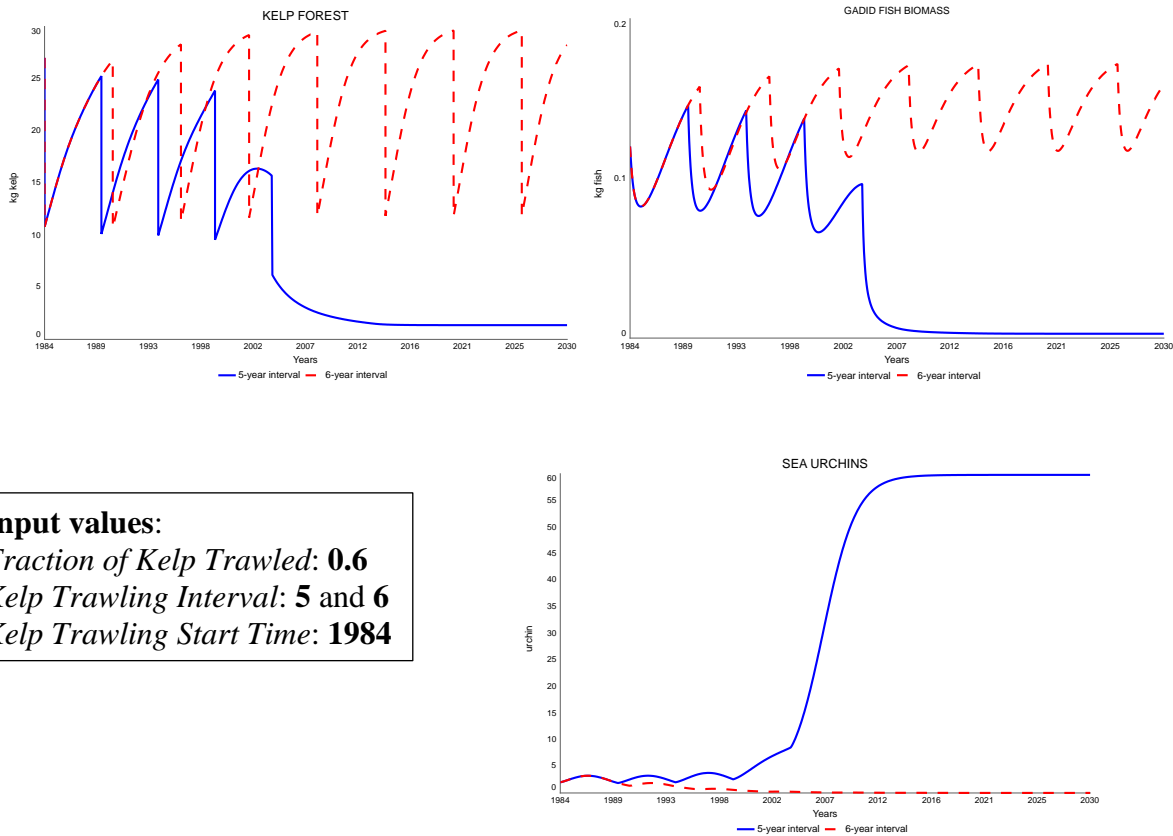
Input values:
Fraction of Kelp Trawled: **0.6**
Kelp Trawling Interval: **5** and **6**
Kelp Trawling Start Time: **1984**

Fig.1.3.4 – Kelp to Barren Shift: Trawling 60%

In both runs, when *Kelp Forest* is trawled at a rate of 60% that starts in 1984, the *Gadid Fish Biomass* reduces at the same time. We see this recurring behaviour in *Kelp Forest* and *Gadid fish biomass* as the trawling continues in pulses throughout the simulation. We also see low hills in *Sea Urchins* coinciding with the trawling incidences, which is a result of the sharp decreases in *Gadid Fish Biomass*, signalling a weakening of the reinforcing loops R3 and R2 which controls the urchin stock through *Predated Urchins*. The red line, representing the 6-year interval policy, shows increasing peaks of kelp and fish before next trawling, which is due to a slowly decreasing grazing pressure on the kelp stock which is a result of the slow decrease in *Sea Urchins*. One could believe that when the amount of fish is at high levels several times within the first 20 years, surely the urchins would be predated quickly to zero. But the number of *Predated Urchins* gets increasingly restricted through the balancing feedback loop "Density Effect of Urchin Population" (B3) the closer *Sea Urchins* are to zero. The real-life explanation is due to high levels of other easier and more abundant prey in higher levels of *Kelp Forest*.

Looking at the blue line, showing a harvest interval of the normal 5 years, the forest might first collapse with a harvest percentage of 60% of the standing stock, but not with any lower values. That is if we initiate the simulation with a few urchins (2 urchin pr m^2). And as we compare both runs, we see that if the harvest interval is only extended by one year the forest manages to recover and keep stable. With the one-year shorter trawling interval the forest reaches a lower peak before it is trawled again. The lines shows a small difference in the peaks of the *Kelp Forest* levels after the first year of trawling. This difference increases markedly after the next two trawling events before the system finally collapses in the blue run. The reason is due to the opportunity for urchins to persist when there is little predation on them until the point where the number of fish can no longer keep the predation pressure above that of the urchin growth rate and the system hits the tipping point and shifts to an urchin barren.

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We learn from this that the threshold of how many urchins a kelp forest can hold before the ecosystem shifts, can change, and that it is lowered when the kelp forest level itself is continually kept lower than its natural possibilities.

The scenarios above show how a small change in a policy variable can change the state of the system when under constant high trawling pressure, and that the presence of just a few urchins makes to system vulnerable to overexploitation. But the system is otherwise a very stable one. To show the stability and resistance to kelp trawling I show in Fig.1.3.5 the *Kelp Forest* tested with random levels of *Fraction of Kelp Trawled* between 15% and 75% output, as kelp trawling can vary between these values. Of the ten runs only two scenarios resulted in the kelp forest to shift to a barren ground.
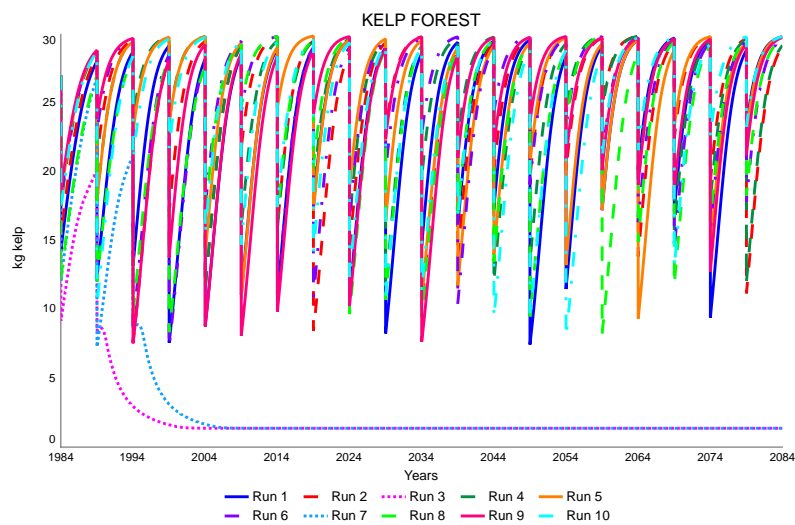
Fig.1.3.5 - Random trawling magnitude (0.15-0.75).

Change in Fish Harvest

If we were to assume the average trawling value of 35% with an interval of 5 years in an area where the fishing pressure increase, we find different thresholds where a shift of state occurs. First, I will show the behaviour of the system with four different fish harvesting levels, 20% - blue line, 40% - red stippled line, 47% pink dotted line, and 50% green dashed line.
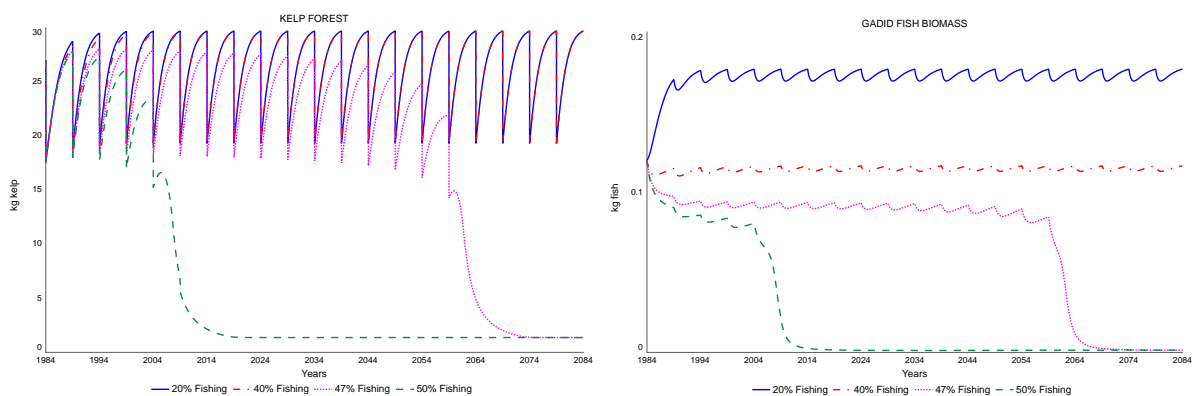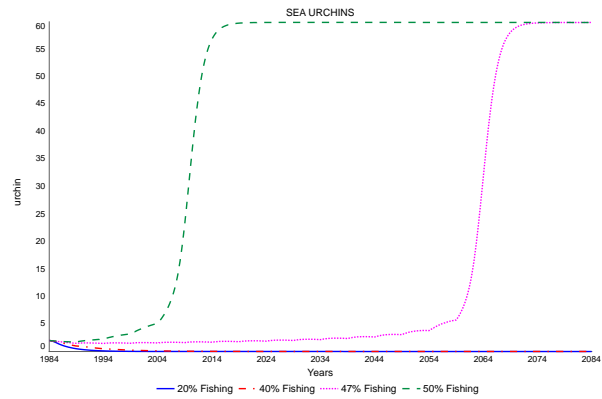
Fig.1.3.6 – Change in Fish Harvest

As shown in Fig.1.3.6 above, the blue line represents the alternative base run as a reference for the other behaviours. The system is stable with a continual 40% fishing pressure (red stippled line) on top of the 35% trawled kelp over the 100 years. Following the pink dotted line with a continual 47% fishing pressure the system collapses after about 80 years. That is because *Harvested Fish* keeps the *Gadid Fish Biomass* stock low enough for urchin's growth rate to slightly out-match the predation pressure on urchins, enabling urchin numbers to grow gradually towards the tipping point. Also, the urchins continually graze on the kelp, which decreases the kelp stock's net increase, disabling the kelp stock from reaching its CC before new trawling event which explained earlier, leads to a continually lower kelp stock after each trawling event. The reduced kelp stock then leads to reduced *Gadid Fish Biomass*, which feedback loop works slowly leading to less predation on urchins to the point where *Sea Urchins* are high enough, in relation to fish, to start an intensive grazing that shifts the state of the system within a few years.

Now, following the green dashed line with 50% fish harvesting, the system starts shifting after only 20 years. That is a 60-year difference with a mere 3% change in fishing, which tells us that the system becomes exponentially fragile towards its tipping point.

Further, if the fishing pressure is to decrease to the normal (20%) any time before the system collapses, the *Kelp Forest* and *Gadid Fish Biomass* will re-grow quickly, depicted in Fig.1.3.7 below, by the orange line (Run 5).
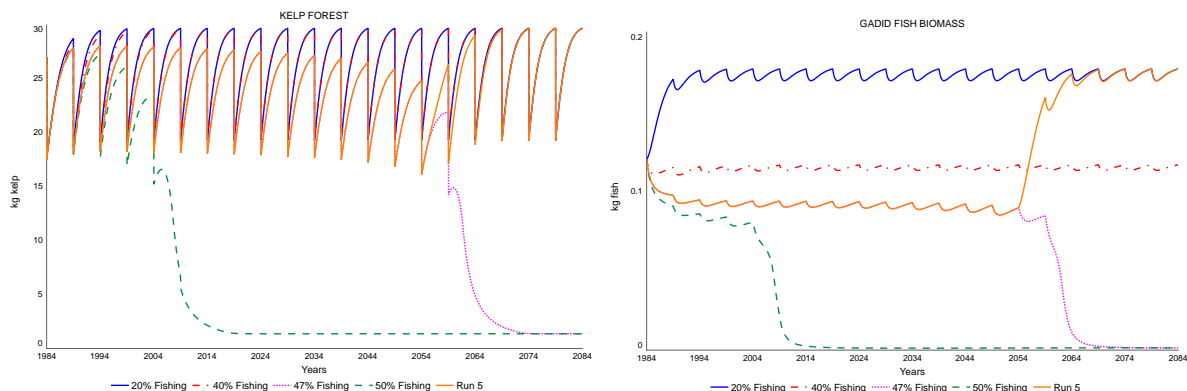

Fig.1.3.7 – Change in Fish Harvest: Reduction from high to normal fishing pressure

Change in Kelp Trawling and Fish Harvest

The below scenarios are with higher kelp trawling as well as higher fishing pressure. The first number in the name of the runs in the graphs is percent output of trawling from the kelp stock, the second number are percent fish harvested of the gadid fish stock (X-X), shown below in Fig.1.3.8. The behaviour and loops working here is the same as explained in the prior scenarios, but with different magnitudes and timing.
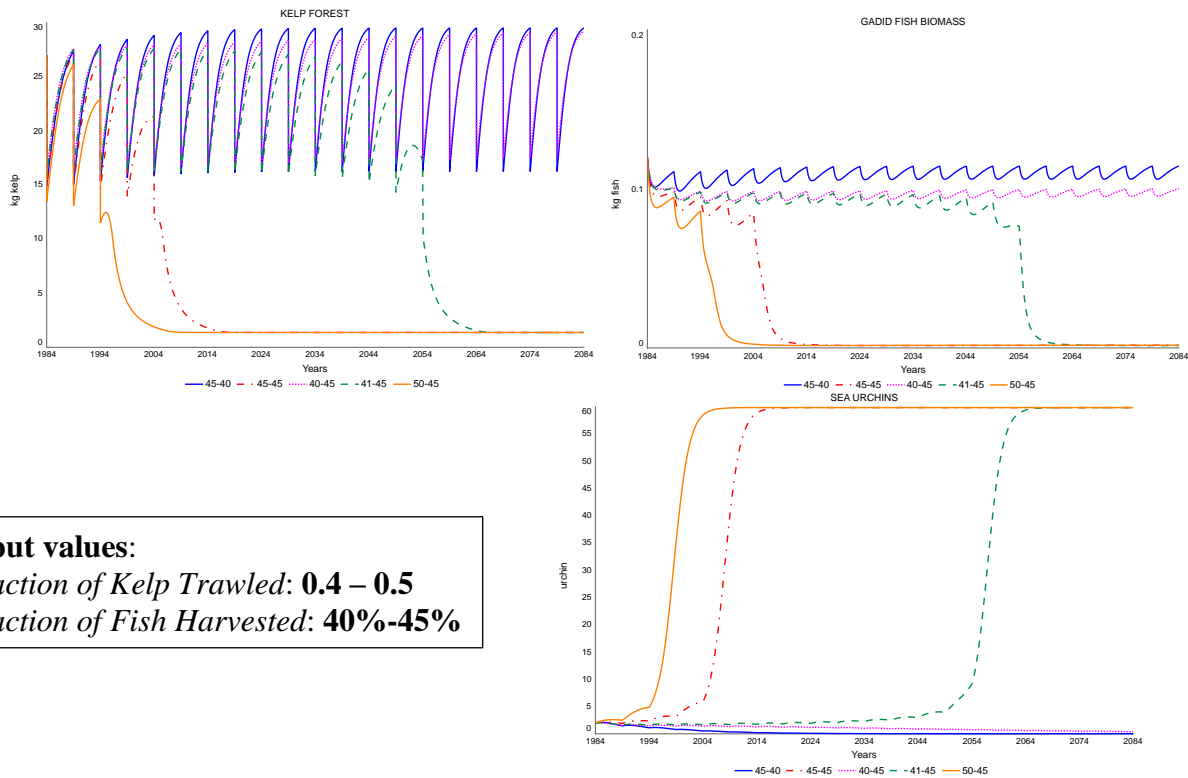
Input values:
Fraction of Kelp Trawled: **0.4 – 0.5**
Fraction of Fish Harvested: **40%-45%**

Fig.1.3.8 – Kelp- and Fish Harvest

The blue lines show the behaviour of the system with 45% *Fraction of Kelp Trawled* and 40% *Fraction of Fish Harvested.* The system keeps stable with this pressure as we see that sea urchins decreases towards zero. The pink dotted line shows the behaviour with 40% & 45% output of the stocks. Comparing the pink line with blue line shows us that the system is more sensitive to fish harvest than kelp trawling as sea urchins decrease slower with 40% & 45% (kelp Trawling & fish Harvest) output. Though with this pressure, only 1%-point increase in *Fraction of Kelp Trawled* (to 41 & 45), makes the system turn to a barren after 70 years, showed by the green dashed line. If we harvest both stocks with a 45% output (another 4% increase in *Fraction of Kelp Trawled*), seen in the red stippled line, the system shifts 50 years earlier. A further increase of trawling by 5%, to 50-45, only advance the shift 10 years which tells us that the system behaviour becomes increasingly less sensitive to increasing trawling and harvest.

In total we see that when the pressure on kelp and fish is more than 40%, the system is close to the tipping point. Again, we see how a very small change to a single variable can tip the system over when its fragile, here the change from 40-45 to 41-45.

4. Barren to Kelp Shift – Urchin Die-off

When the barren state already has become a reality, no change in fishing or trawling can reverse it. The only reasons for re-vegetation in Norway is due to rising temperatures or deadly virus infections in urchin population. For this model I could only include the effect of the virus infections that only affects sea urchins, whereas changes in sea temperature would alter many other aspects of the ecosystem. For this deadly virus infection to happen in the model we set the *Mass Death Event Switch* to 1 (one). I assume there to be no kelp trawling in this area.
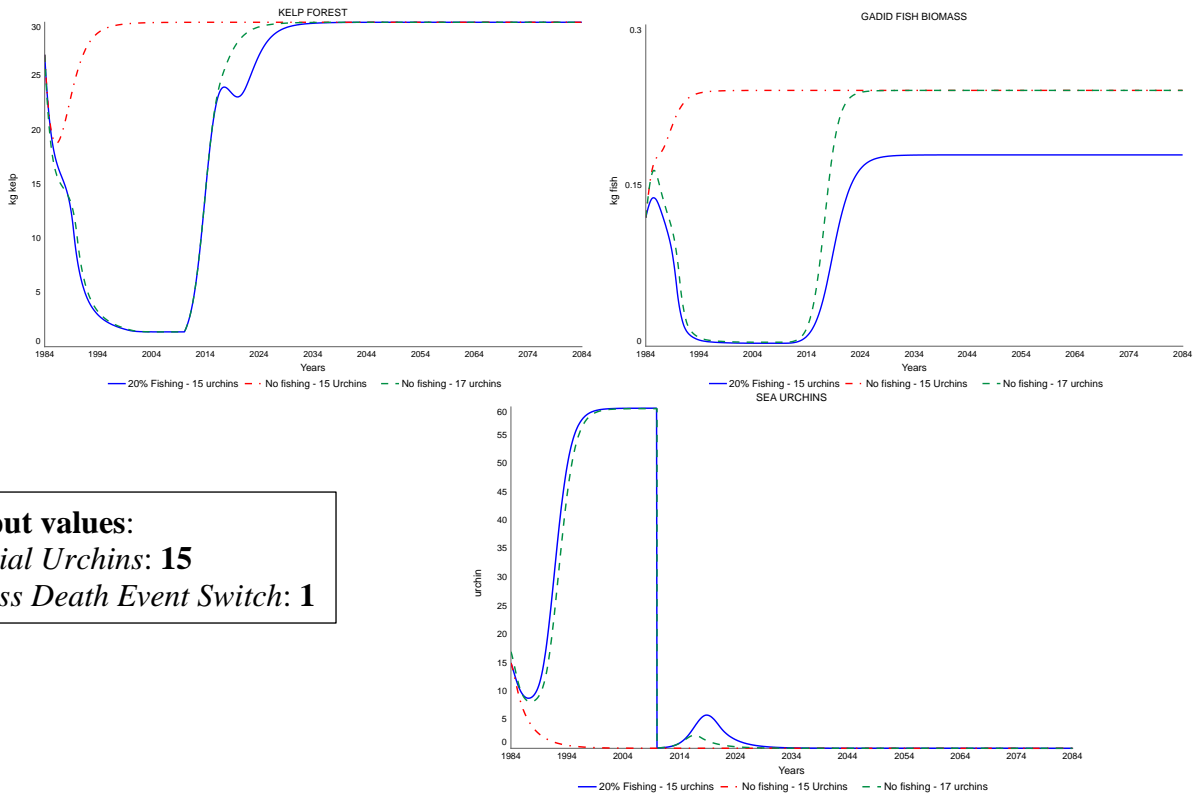
Input values:
Initial Urchins: **15**
Mass Death Event Switch: **1**

Fig.1.3.9 – Barren to Kelp Shift

For the blue line in Fig. 1.3.9, the number of initial urchins is set to 15 as this is the threshold number of urchins for the forest to collapse. When the kelp forest, following the blue line, steeply declines from the beginning of the simulation (when the kelp forest collapses), we see a slight bump in the fall which is because the numbers of urchins meet a high predation pressure when the kelp forest is at a high level with a lot of predators, again a making of the balancing "Density Effect of Urchin Population" loop, B3. Also, the fish is initialized well below its CC, which is high when the kelp forest is high. And since the forest is at a high level at this point as well, the fish growth rate is starting off close to maximum. However, the urchin grazing on the kelp forest still out-do the kelps growth rate, decreasing the kelp forest which then quickly turns the upward behaviour of the fish stock to a rapid decrease.

The green and the red line simulations are scenarios where there are little to no fishing pressure on the local fishes receding in the kelp forest. The red line is initiated with 15 urchins. By reducing *Fish Harvest* with 20 percent points (to zero %) the system does not collapse at the threshold of 15 urchins. Rather, the system now need a few more urchins to collapse, shown by the green line, initiated with 17 urchins (and no fishing). The forest's threshold only increases by 2 urchins, to 17 urchins with the 20%-point reduction in fishing pressure.

Further, the mass death of urchin event is set to year 2010, which occurs after the system has fell into a stable urchin dominated barren state. Since such an event kills of almost all the urchins, the system gets time to again become kelp dominated. Such an event is believed to take about 14 years, explained in the "Behaviour Reproduction Test" chapter. The simulation run showed by the green dashed line is the run that fits most with the conditions which the calculations for the regrowth are based on. Because the "8 or more" years regrowth time is based on kelp regrowth after harvest, which rate is measured from areas without urchins, thus harvesting of fish would not affect it.

The blue line, that includes the 20% fishing pressure, shows that *Kelp Forest* makes a small U-turn when its already a long way into regrowing, before it continues to grow and stabilize at CC. That is because in the beginning of the kelp re-vegetation phase, there are few predators, which allow the urchins to slightly increase to a point when the predation pressure forces them down again. This "backlash"-behaviour is also observed in the real system, explained in the "Behaviour Reproduction Test" chapter.

We can below, in Fig.1.4.1, also see how seals and sea bird's delayed reactions makes them avoid collapses, although sea birds experience a huge dip in population size.
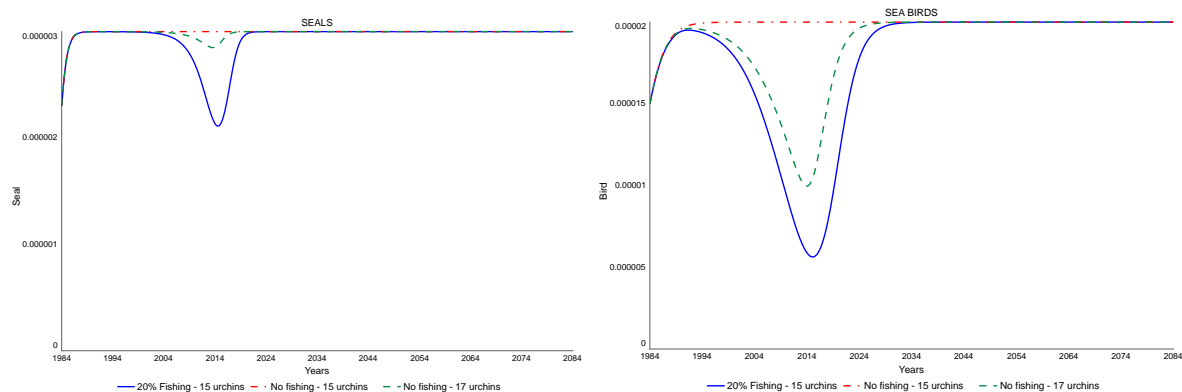

Fig.1.4.1 – Barren to Kelp Shift: Secondary KPI's

5. Recovered and crashed, again…

The timing of restart of kelp trawling and fish harvest could be crucial to avoid a new collapse of the kelp forest leading to another long-lasting, hard to reverse, barren state.

The graphs in Fig.1.4.2 below, show different start years of kelp trawling and fish harvest after the sea urchin die-off at year 2010. Both trawling and harvest is set at higher-than-normal levels, with 40% each.
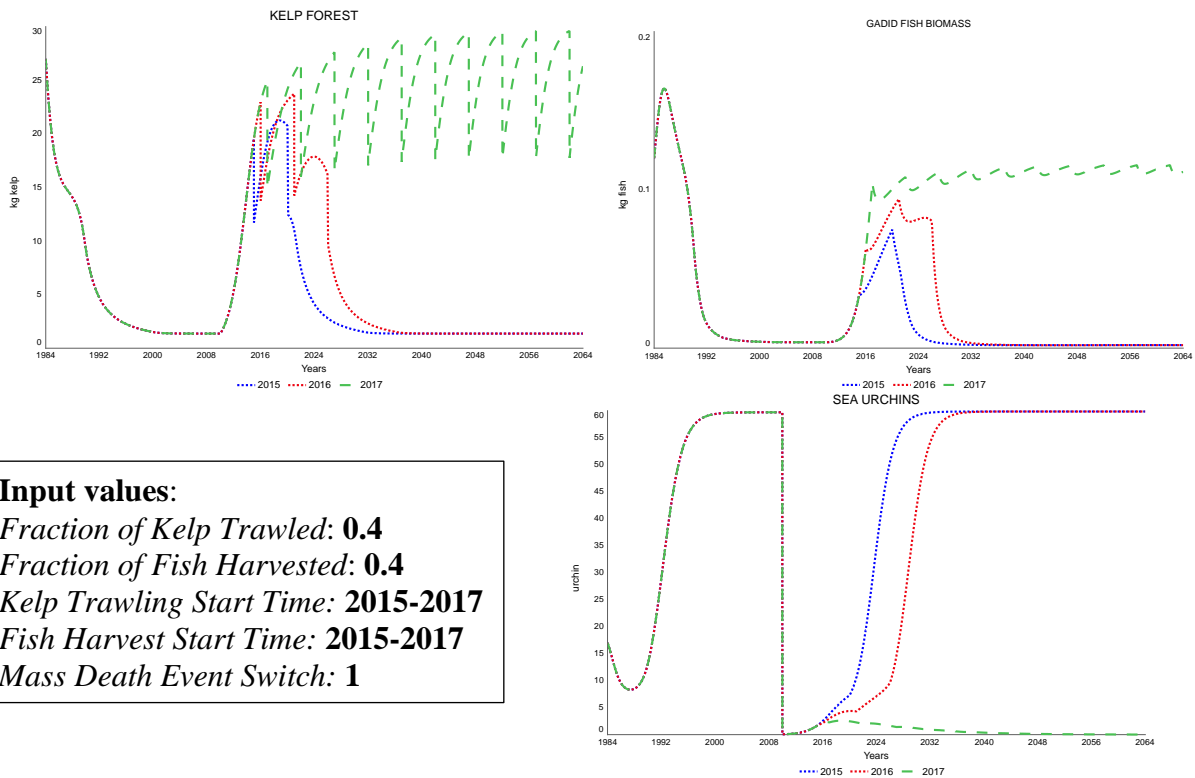
Fig.1.4.2 – Recovered and Crashed: Main KPI's

5 years after the urchin die-off the kelp forest is at 19 kg pr m^2, which could visually look like a healthy forest and give good amount of trawled kelp. The blue line shows the behaviour of the system if exploitation, through trawling and harvesting, starts in 2015. After two trawling periods the system collapses again because the low levels of kelp keeps the net growth of fish too low for them to grow any further than a short peak before the next trawling period, enabling *Sea Urchins* to increase. The red line shows the behaviour from starting trawling and harvesting at year 2016. In that one-year difference the *Kelp Forest* level has increased from 19 to 23 kg pr m^2 (which is a lot when looking at bigger areas), and the *Gadid Fish Biomass* has almost doubled (from 0.034 to 0.062 pr m^2). It is more likely that 2016 (6 years after the urchin die-off) could be deemed as a good year to start harvesting and trawling, but if not done with caution the forest might very well collapse again, as we see following the red line. The re-collapse happens approximately six years later if the exploitation starts in 2016, compared to starting it in 2015 (blue line). Again, following the red line we see that the kelp forest seems to follow an upward trend before the second trawling, at year 2021. The fish increases to a level that can predate higher than the growth rate of the sea urchins. But as the second trawling hits, the amount of fish is decreased to a level, just below the level they need to keep the urchins in check, which we see in the more stable increase in *Sea Urchins* which quickly after shoots up by shifting the dominance of the reinforcing loops "Kelp Forest enables Other Predation" (R2) and "Kelp Forest enables Gadid Fish" (R3) in *Sea Urchins* favour.
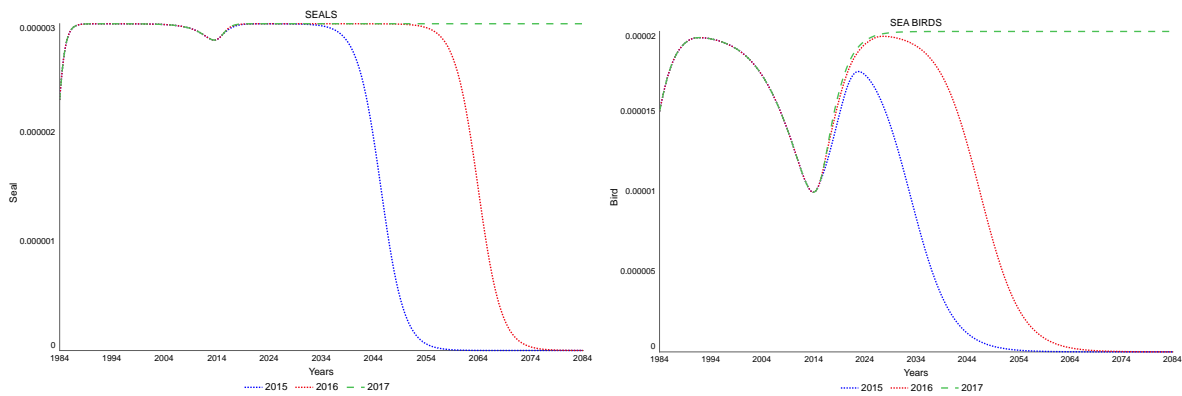
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Fig.1.4.3 – Recovered and Crashed: Secondary KPI's

When the kelp forest is regrowing after a sea urchin die-off in 2010, the seal and sea bird population experience a turn from negative to positive growth trend. The *Seals* stock experience only a mild bump during the years of barren state up to 2010. Following the blue line, when the forest collapses again around 2024, the collapse of *Seals* happens more than 20 years later. That is because the link between *Gadid Fish Biomass* and *Seals* are weak, due to the diversity of foraging ground by the Norwegian coast seals. In the red run, we see that the seals collapse 20 years later, even though the difference of the time of the kelp forest collapses is only 10 years. That is because the level of *Gadid Fish Biomass*, in the 2015 run (blue line), consist of a much lower level of prey in total during the period between 2010 and 2030, compared to the red line. The level of seabirds is governed by the same dynamics but are much more sensitive to the prey availability than seals, making the population change with higher magnitudes, and it reacts quicker. In the years 2015 and 2016 the level of *Sea Birds* is fairly close to the initial level, and as it is in a growing trend one might regard that as a sign of a healthy kelp forest. But as we see, if kelp trawling and fish harvesting starts in these years the system is fragile and might collapse, again…

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6 Discussion

I will here discuss the main results from the simulation scenarios to see what we can learn about the feedback loops in the system and to reveal our possible leverage points.

Kelp to Barren shift

From the simulation analysis we found that the two main reinforcing feedback loops of the system is "Kelp Forest Enables Other Predation" (R2) and "Kelp Forest enables Gadid Fish" (R3), which both are reliant on the *Kelp Forest* to then govern the predation pressure on *Sea Urchins* in the same way, to the extent that they could be argued to be one and the same but stronger reinforcing loop. We see that these reinforcing feedback loops are important drivers to keeping the system in its current state, which supports the belief that coastal cod is the main controller of sea urchin population (Enoksen & Reiss, 2018; Lorentsen et al., 2010, p. 2055; Norderhaug et al., 2020; Teagle et al., 2017, p. 93). Whenever the *Kelp Forest* is reduced these two reinforcing loops are getting closer to tip in *Sea Urchins* favour. If the system is under high pressure, a very small increase in pressure can tip the R2 & R3 loops to the urchin's favour, which gives the system a steep goal seeking behaviour towards a stable urchin barren state. And the other way, if the pressure where to cease the kelp forest would quickly increase. Even though fish levels are relatively high, urchins can avoid decimation because low urchin density leads to a decreased predation pressure through the balancing feedback loop "Pressure on Urchin Population" (B3). In the kelp forest state when the force of the R2 & R3 reinforcing feedback loops are reduced, the system will be more fragile to changes in other influence like, fishing or local sea temperature.

Also, the re-establishment of the forest is reliant on sporelings that drift in from nearby forests (Fagerli et al., 2015, p. 1220; Sivertsen, 1997, p. 2883). These nearby forests are established in areas with higher wave activity, often further from the coast. High wave activity poses a threat for urchin settlement, so these more wave exposed parts are seldom affected by urchin down grazing that happens nearby (Sivertsen, 1997, p. 2879). That is why we see the kelp forest to stabilize at a low level above 0. This dynamic relationship is important to capture in the model to enable the behaviour where the kelp forest can re-establish as quick as in real-life after an urchin die-off. In this model, these dynamics is preserved through an aggregate and simplified structural relationship that is mean to include all the main dynamics of the ecosystem, which is often represented within one trawling sector. When the kelp forest is low, its composition will in reality be of other kelp and algae that could be represented by a separate stock, which reduces urchin grazing and not produce new kelp, the L.Hyperborea, which constitutes the big three-dimensional habitats of the pristine kelp forests. Rather than representing the other vegetation in an own stock, the *Kelp Forest* stock at low levels represents the adjacent kelp forest in the more wave exposed areas that ensures a continues effort of the kelp forest to regrow. The effect of the changing forest composition is ensured by a separate effect variable (*Effect of Forest Composition on Urchin Grazing*) that reduces urchin grazing when kelp is at low levels creating the balancing feedback loop called Unpalatable Kelp & Algae (B6). So, what is technically happening is that when urchins are at CC the grazing is reduced to a level where the kelp forest net growth rate matches the grazing pressure and creates an equilibrium. Modelling it this way gives us a simplified representation of any sized area of kelp forest where the main dynamics always are included by including both inner and outer coast, as most kelp trawling sections do.

Further, I found that *Fraction Fish Harvested a Year* has a stronger influence on the main reinforcing feedback loops (R2 & R3) than *Fraction of Kelp Trawled*. That is because the effect from change in kelp is not linear or instantaneous on the number of *Predated Urchins*, as the change of *Gadid Fish Biomass* is.

The ecosystem is increasingly sensitive to increases in harvest and trawling. So, in areas where there is done both kelp trawling and harvesting of fish, the ecosystem might be just a few percentages in increased outtake away from collapsing, thus also a short way from keeping stable with decreased pressure. If there has been a declining trend of total biomass after several trawling periods one can be sure that the system is getting increasingly fragile and might even be close to a collapse and should quickly reduce the pressure which then could prevent the collapse.

Barren to Kelp Shift

The threshold number of *Sea Urchins* that the kelp forest can hold increases with decreasing pressure. With other words, the less kelp forest the less urchins are needed for a state shift. This finding supports the findings by Filbee-Dexter & Scheibling that the biomass of kelp directly the threshold urchin biomass for a shift to barren (Filbee-Dexter & Scheibling, 2014, p. 15). But, I found that change in pressure and the urchin threshold does not move linearly, rather it is needed exponentially less change in pressure the closer the system are to the tipping point. For instance, reducing the fishing pressure from 20% a year to zero, only increased the urchin threshold from 15 urchins to 17. Whilst under high pressure, the number of urchins needed to tip the system can be as 5 urchins, where only a 1%-point change can spur it. This is an important dynamic to understand because, if the relationship is believed to be linear, a big increase in pressure on the system from very health levels seem not to affect the instability of the system at all, where then a doubling of that increase can push the system well beyond its limits, resulting in a shift from kelp forest to barren state.

Even though the kelp state is thought to be very resilient, my findings says that it is needed a bigger reduction in sea urchins to return the barren to a kelp forest than reduction in kelp forest for a turn to barren state. This phenomenon is also found by Filbee-Dexter (Filbee-Dexter & Scheibling, 2014, p. 4). Though that is only if there are some urchins present in the forest. Also, the only way that urchin levels reduce from a barren state in Norway is through variables which we do not have any (known) direct influence on, yet.

The behaviour of urchins produced by the model fits with what is known about their behaviour as barren stable state, when the environment allows it. These urchin-barrens is found to last for hundreds of years (Sivertsen, 1997, p. 2880). And as mentioned, the ability of sea urchin populations to persist on barren grounds is due to great phenotypic plasticity in response to low food availability (Norderhaug & Christie, 2009, p. 515), meaning individuals are good at altering their biological functions to benefit the populations survival when food is scarce. Since this model is meant to catch the change in state, I do not model but are aware of the fact that there has been observed barrens with urchin levels that we can expect kelp recovery from which did not recover due to too big distance to other kelp forests, an effect of a limited inflow of sporelings to the barren area (Fagerli et al., 2015, p. 1220).

Recovered and crashed

The timing of starting trawling or fishing in an area that are recovering from a barren is crucial to avoid a rebound to the barren state. The forest is more fragile when regrowing because there might be a small backlash of sea urchin occurrence as the predation pressure is low at first after the urchin die-off.

Lastly, the smaller balancing loops between *Kelp Forest* and *Sea Urchins* (R1, B4, B5, B6) contributes to nuancing the tipping points as they get stronger towards the equilibriums of the system (CLD with loops is seen in Fig.1.1.4). But they will always be dominated by the main reinforcing loops, R2 and R3.

The system affects the top predators with a delayed response in stock behaviour due to low sensitivity to decrease in gadid fish. I found that the seals and sea birds disappear several years after the forest is diminished. This is a good insight to the ecosystem telling us that measures of apex predators in the system, as sea birds and seals, is not a good measure for policy making aimed at saving the ecosystem. Low observations of sea birds and seals is rather a sign of that the system has already collapsed. Thus also, an increase in seals and seabirds should not be used to make decisions of kelp trawling and fish harvest. If using the level of seabirds as an indicator for a healthy kelp forest, one might start fishing and trawling too early. A concern based on that seabird levels are speculated to be a useful monitor of the kelp forest (Lorentsen et al., 2004, p. 168; Lorentsen et al., 2010, p. 2055). Especially, as there are little knowledge of how the state of the kelp ecosystem is relevant for higher species in the food web (Dalsgaard et al., 2020, p. 135). Or, if the start time of the exploitation of the forest is based on approximate visual measures of the kelp re-vegetation, or test trawling driven purely by economic incentives like CPUE (Catch per Unit Effort), the level of kelp forest might seem healthy or profitable enough to start exploiting, which drive is otherwise known to be unsustainable (Mac Monagail et al., 2017, p. 378).

7   Conclusions

In this chapter, will discuss to what extent I answered my research questions and lay forth the concluding remarks of this thesis. And lastly, I will discuss limitations of this work and the future directions of this research.

To recall the objective of this thesis, I have used a conceptual modelling approach to identify the main driving loops of the two stable states of the kelp forest ecosystem with the goal of gaining knowledge on how human activity might impact the ecosystem. The model is operationalized with estimated parameter values averaged from the literature from mid-Norway, where we find the best growth conditions for big and dense kelp forests. In mid-Norway, the standing biomass of kelp and growth values, as well as harvesting activity is higher than further north or south. It is also an area with more literature on the coastal ecosystems. With this in mind, we consider the research questions posed at the start of this thesis:

1. *Can a simple model be derived from existing literature about the kelp ecosystem in Norway that captures the main dynamics of the shifting stable state behaviour from kelp forest to sea urchin barren ground?*

Through the system dynamics approach, I mapped out the main structures in the system that are in play when the system changes state between a kelp forest state and a sea urchin barren state. This was possible as there was enough research available about the system to create a simple, and conceptual in nature, model based on the ecosystem of kelp of the Norwegian coast, supplemented with literature for the more generic parts. The model structure was then validated through a verification process following standard guidelines for the system dynamics approach. The main model boundary is that its values are based on stable and ideal conditions for ecological growth, without environmental fluctuations. Further, all parameter values were tested to assess if their effect on the systems behaviour conformed with what could be expected. The behaviour was justifiable even under extreme conditions. Even though the model is a very simplified version of the real system, I found that it does replicate what we know of historical behaviour through the "Behaviour Reproduction Test" (with a small exception addressed under Limitations). This indicates that the explanatory model, though conceptual, is able to adequately represent the complexity of the kelp ecosystem.

2. *What are the key feedback mechanisms that are active in driving the system to a shift in state?*

The model was then tested with different value inputs that represents different realistic scenarios to examine the model's behaviour and learn about which mechanisms that drives the feedback loops in the system.

The most important mechanism in driving the system away from the tipping point is the reinforcing feedback loops that comes from the effect that the kelp forest has on the coastal fishes' possibility to reside in the area. I have divided the effect into two feedback loops: (1)

the effect the kelp forest has on the coastal gadid fish and (2) the effect kelp forest has on other animals that also predate on urchins, which together decides the level of predation on sea urchins. As the model is created to analyse system behaviour under ideal and stable environmental conditions, the only endogenous outflow from urchins is predation (there is also the outflow of *Mass Death Urchin* that we can infringed on the sea urchin population exogenously by the urchin die-off switch). That means that the urchins will be able to persist indefinitely if there is no predation. When the urchin levels reach above a threshold of which the kelp forest can sustain, the reinforcing feedback loops works to decrease the kelp forest and increase urchins. When the urchin level is below the threshold the loops will work to increase kelp forest and decrease urchins. In addition to these two main loops, the weaker reinforcing loop of drift kelp also contributes to driving the system one way. Besides that, the rest of the loops are balancing, meaning they will work to keep the system in one of the equilibriums. Thus, this system will not experience a shift in stable state unless it is affected by exogenous factors.

3. *What are the leverage points in the system that have the potential to affect the state shift of the system?*

As mentioned, the main reinforcing feedback loops are those that goes from *Kelp Forest* and *Gadid Fish Biomass* to *Sea Urchins*. In these loops, the only realistic leverage points that we currently can influence in Norway is trawling of kelp and harvesting of fish. Both interventions alone have the possibility to affect the systems with such a magnitude that it will provoke a shift of state in the ecosystem. When combining them their magnitude of effect can be much lower and still provoke a shift. The system showed more sensitivity to changes in fish harvesting than that of kelp trawling, though only a slight change of either can tip the system if the system already is under enough pressure. This supports the hypothesis of Norderhaug that it was the modernization of the fishing fleet in the 70's which lead to a decrease in the coastal fish, that lead to the urchin blooms that laid the long coast from mid Norway to the Russian border barre (Norderhaug, 2021, p. 6; Norderhaug & Christie, 2009, p. 515).

4. *Can the insights gained from a simplified ecosystem model be useful for policy design?*

We gained the knowledge of the importance in controlling the kelp forest for occurrence of sea urchins as they are the only factor that enables the possibility of a shift in the otherwise stable kelp forest ecosystem. If the ecosystem is under both fishing and trawling pressure, the system can tip with the slightest of changes in these leverage points, thus a coordination between the two activities will be crucial when operating in the same area. Also, the urchin threshold which a kelp forest can hold before it collapses changes exponentially with increasing pressure from human exploitation of the kelp forest. This means that if fishing or/and trawling is started in a pristine kelp forest, it can seem close to unaffected where a decision to increase the pressure relative to the small effects observed can suddenly have devastating effects on the system.

In addition, the model showed us that when a shift of the feedback dominance occurs, the favoured stock(s) will quickly (within a few years) reach high levels, and the unfavoured stock(s) deplete just as quick. If the tipping point is reached, there is nothing we can do to stop it. If there has been high pressure on the forest for a longer time and the kelp forest and/or gadid fish biomass shows a declining trend we know that the system is in a very fragile state and might collapse very soon. If the tipping point is not already reached the system can easily be saved by slightly reducing the pressure, but if there is witnessed increases in sea urchins their

numbers should play a role in how much we should decrease the pressure on the kelp forest and the fish. In the real system, there will be natural fluctuation that would have to be accounted for in such calculations.

Since the only two leverage points to affect the state of the system is trawling and fishing, we can imagine a reversal of these practices; that artificially repopulating the area with coastal gadid fish could at least increase the fragility of the barren state. And since we also know that the gadid fish is reliant on the kelp forest for carrying capacity to sustain growth rates, a simultaneous effort in artificially revegetating the area with kelp would increase the success chance of that sort of repopulation effort. Further insights for possible policy design are that we know that drifting algae reduces the grazing rate on the growing kelp, so it is not far-fetched to believe that dumping of shredded kelp (from e.g. the massive leftovers from the alginate production) in the same area could even further increase the chances of a revegetation. Dumping of shredded kelp could also be believed to decrease grazing of kelp in forests that are in a transition phase. Since the system is more fragile in a transition phase, as it is closer to the threshold, the weaker reinforcing loop of drift kelp might be enough alone to reverse the shift. But there is higher probability that releasing predators of the urchins will have a stronger effect as the predation on urchins is the main driver of the main reinforcing loops of the system.

To assess when trawling and fishing can begin after a revegetation from a more detailed model is recommended. That is based on the findings from this model, where we see that there is a short-lived increase in sea urchins after a die-off, which indicates that the system is more fragile than usual before the forest has reached its equilibrium.

My results also find support for existing recommendation that trawling intervals should be more than 5 years (Christie et al., 1998, p. 57; Steen, 2019). In the scenario "Kelp to Barren Shift", I found that with a high trawling pressure on the kelp forest, a year difference in trawling cycle can determine if the system is driven past the tipping point or not. As will be mentioned in Limitations and Improvements, my model shows a bit faster regrowth of kelp after harvesting of less than 100%. Thus, in reality the kelp forest's regrowth time is a bit slower, which further underlines that today's trawling intervals can put the system in a very fragile state when the trawling output of a local area is high.

Limitations and Improvements

I will here lay forth the limitations of the model, discuss possible improvements, and what further research can be done on the topic to contribute to an even better understanding of the ecosystem.

The model is an aggregate representation of the coastal ecosystem of the kelp forests along the Norwegian coast. The model boundaries I have set for this paper excludes several interesting and important system parts that should be added if the model were to create more detailed behaviour.

When creating the model there were a lot of possible system parts I considered to include before deciding on the outcome. For instance, there are several articles that addresses predator-prey systems and the ecosystem of kelp with adult- and juvenile- kelp, urchins, and fish, and adding more predators (Hagen, 1983, p. 187; Norderhaug & Christie, 2009, p. 521; Wang & Chen, 1997, p. 83). A very common part in the kelp ecosystem literature, which was left out of my

model boundary, is that for invertebrates (Norderhaug & Christie, 2009, p. 521). These small animals are a big part of the kelp community, but which composition are very complex as it can entail all from small crustaceans to juvenile urchins (Norderhaug & Christie, 2009, p. 519). To properly address the properties of the invertebrates, how it affects kelp, and how it effects fish, would need a specialist on coastal or marine biology. Further, if I were to find an easy way to add the invertebrates, their impact on the other stocks would need to be addresses through adding the other "sub"-stocks. Including these structures in the model would then have doubled its size and scope. The nature of such a model would have leaned much more towards an empirical model, where the numerical accuracy would play a bigger part. That would be beyond the purpose of this model, as this model is not meant to predict numbers for decision-making, but rather to get insight in how the system works and that there are leverage points humans can affect that needs further research before the system is put under more pressure.

Further, the model does not include environmental factors which are known to affect the dynamics of the system both short- and long-term. One such factor is latitude, which entails factors as temperature and lighting (Sivertsen, 1997, pp. 2872, 2878). Temperature is believed to be an important factor for urchin reproduction and survival, it affects fish production, as well as the carrying capacity of kelp and its ability to grow (Norderhaug & Christie, 2009, p. 518; Skadsheim, 1995, p. 205). E.g. sea urchins spawn between -1 to 10 degrees (Hagen, 1983, p. 186), and kelp growth decreases below 4 degrees and above 20 degrees (Rinde & Sjøtun, 2005, p. 1052). I did try to find a not too complicated way to add a parameter effect of the latitudal gradient, but it seemed to need a higher complexity of the model as other models with a latitude effect are at a marine biology level, not suited for this model. I mention this because the carrying capacity (CC) can be changed in the model. If done, I expect the model behaviour to become increasingly less accurate with increasing change in the carrying capacity away from 30 kg kelp pr m^2, as changing it would in real life mean changing the area that is modelled, which would need specified relational changes in several other variables. The effect of latitude on the different parts of the ecosystem is definitely an important aspect to address in more detailed and flexible models. It is also a focus that needs more research if it were to be used in more elaborate models. The aggregate and conceptual goal of this model does not need such detailed complexity. The model, as is, creates interesting behaviour within the frame of keeping the system in a possible ideal state in mid-Norwegian standards where the CC of kelp is close to 30 kg.

In reality, the way kelp grows back is different after it is grazed by urchins compared to being harvested by trawlers. After trawling, the revegetation is often quick because of the sub-canopy kelps and juvenile kelp that kickstarts the regrowth helped by fast improved lighting conditions. It takes longer time for a down grazed forest because of the lack of smaller kelps to kick-start the process. This leads me to address a difference between model behaviour and known historical data from the real life system, which I mentioned in the conclusion. As established, it takes about 14 years for the kelp forest to regrow from a sea urchin barren, and more than 8 years to fully recover after trawling. The model behaviour fits well with the historical data on regrowth time after trawling when kelp forest regrows from very low levels (with no urchins). But if the kelp stock is only reduced to medium levels after trawling the regrowth time becomes less than 8 years. Further research or more complex models is needed to understand this difference in behaviour and to represent it through a System Dynamics model.

During the process of writing the theses I found interesting indicators for further investigation around the leverage point of trawling. I have found no research on that kelp trawling is actually observed to contribute to a down grazing or to make the kelp forest more vulnerable. Usually

there are found no urchins in harvested areas, e.g Sivertsen's Fig.5 (Sivertsen, 1997, p. 2880). Either such events have not yet been recorded, or the kelp trawlers have always been very careful in choice of harvesting site. But I have to speculate that there might be other reasons. One might be that sea urchins need the juvenile kelp that is found on the ocean floor underneath pristine kelp forests, which is found to be consumed first (Sivertsen, 1997, p. 2879), to individually get big enough to be able to graze through the thicker stipes. Because, after a trawling it is the juvenile kelp that spurs the quick regrowth of the forest. In continual trawled areas it might be lesser juveniles on standby to regrow than in a kelp forest, which might make the areas unattractive for urchins to graze. Or, if a few urchins where to start an aggregation in a newly trawled area, they might either be dispersed physically by the whipping of the blades of the kelps close to the ocean floor (Filbee-Dexter & Scheibling, 2014, p. 16), or the trawl itself or, or the opening of the kelp forest close to them might enable more underwater currents to reach the bottom of the forest which can disturb urchin reproduction processes (Sivertsen, 1997, p. 2879). Also, the reduced epiphyte volumes on stipes in trawled areas might make it harder for urchins to climb the otherwise smooth and slippery kelp stems. In addition, the less preferred kelp, L.Saccharina, is found to increase significantly in recently trawled tracks. This is just a theory based on a review of literature and could very well be an interesting focus to research further as it has the potential to give us a leverage in avoiding down-grazing of the forests.

Finally, the goal has not been to replicate the system as detailed and accurate as possible, but to build systems understanding which is believed to be best done through simple models (Moxnes, 2000, p. 341). Moxnes found that understanding of the system alone might not be so effective to make decision-makers, in this case kelp and fish harvesters, make good choices. Rather, their choices were more easily altered with direct forecasts of an important contributor (or indicator) for the possible stock development of the primary resource. Moxnes supports this with that humans tend to not be able to take into account huge systems when making decisions, thus we are selective in the momentums that affects our decisions (Moxnes, 2000, p. 338). And as Sterman himself wrote:

"...modeling is the art of simplification"

(J. Sterman, 2000, p. 166).

Therefore, for further work, this model can be the basis of an interactive learning environment (ILE) targeted at decision-makers, which are known to teach important general concepts of sustainability to the user (Sterman, 2014, p. 92). We learn better when we are actively experimenting with a system, than only studying it theoretically. An ILE of a system dynamics model is a good tool to explore and learn about the consequences of our actions within a system, which wisdom would be too time-consuming or with a to high risk to learn from a real system (Sterman, 2014, p. 90). The ecosystem of kelp is definitely a time-consuming system to draw knowledge from by real life experimentations, with great risk of devastating results.

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Appendix A – Sensitivity analysis

Here, I present the complete model sensitivity analysis as part of the model testing and validation. The model's sensitivity was tested against the Base Scenario. It was done by using the model analysis tool in the Stella Architect software which generates random numbers between a max and min input that I have set based on the realistic upper and lower values that each parameter is thought to hold in real-life. The results are showed by sector.

Kelp Forest Sector constant

- *Maximum Growth Fraction Kelp (Test range: 0.425-1.225)*
Test range is based on the observations by Steen (Greenhill, 2021, p.2), saying it takes more than 8 years for a kelp forest to regrow which with calibration through the logistic equation gives a value of 0.8 maximum growth fraction of the kelp forest. The range of value tested is 50% up and down from the fraction of 0.8.

SEA BIRDS
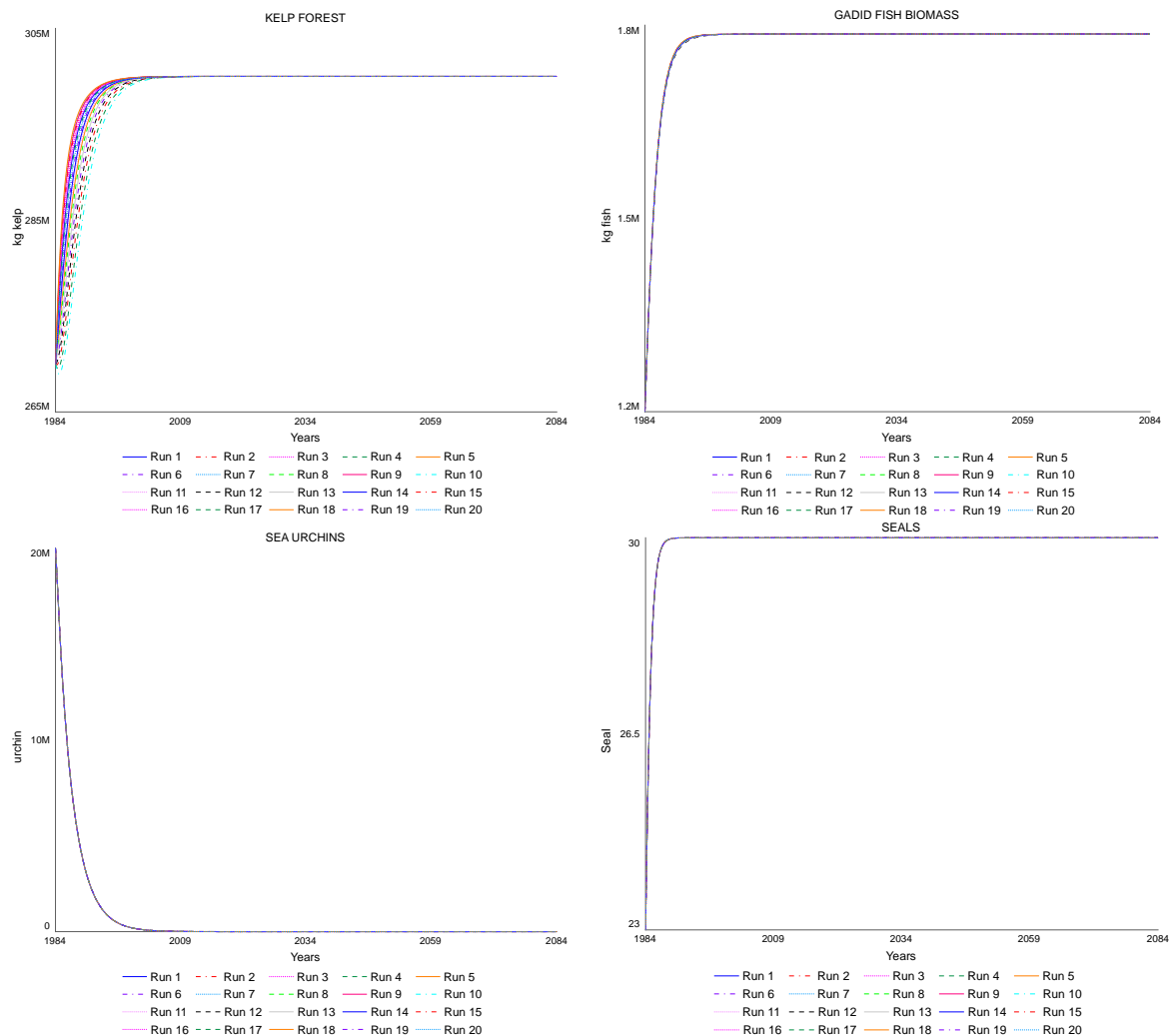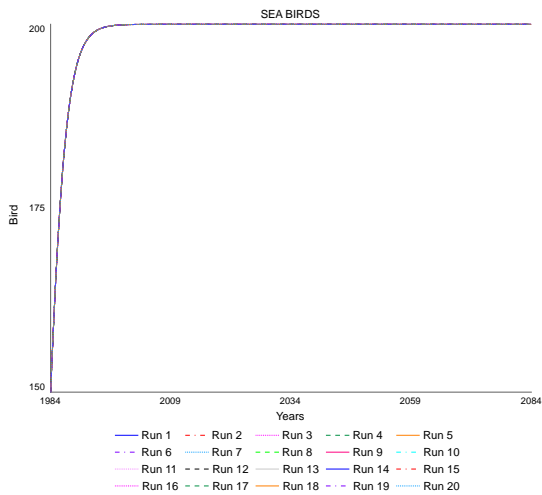
The model is not very sensitive to changes in *Maximum Growth Fraction Kelp*. The only noticeable change in behaviour is in the Kelp Forest stock where the stock decreases slightly. It is expected because the growth rate of kelp goes below the grazing pressure from urchins before the urchins are predated away, which lets the kelp grow back.

- *Fraction of Kelp Harvested (Test range: 0-0.75)*

Base run is zero, average is 0.35 (35%). The test range is based on percentage output found across Norway (Rinde et al., 2006, p. 5), (Steen, 2019, p. 4), (Sivertsen, 1991, p. 29).

Behaviour:

KELP FOREST

GADID FISH BIOMASS
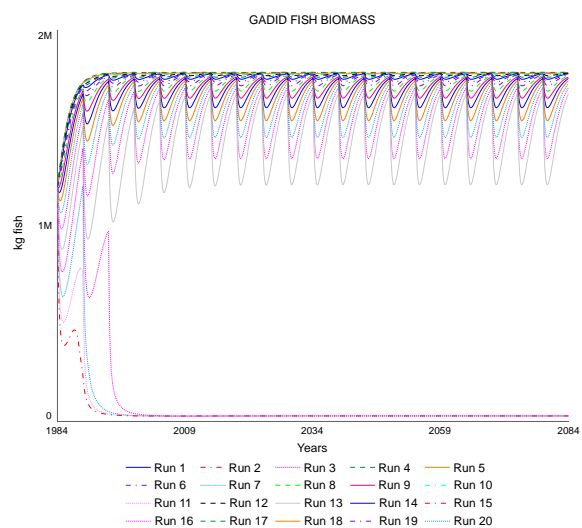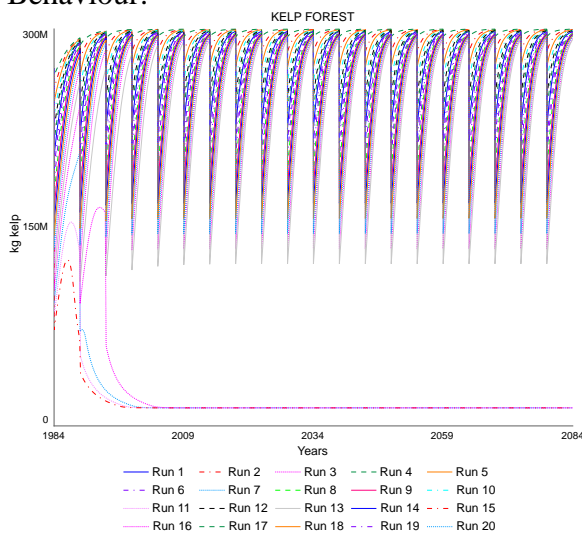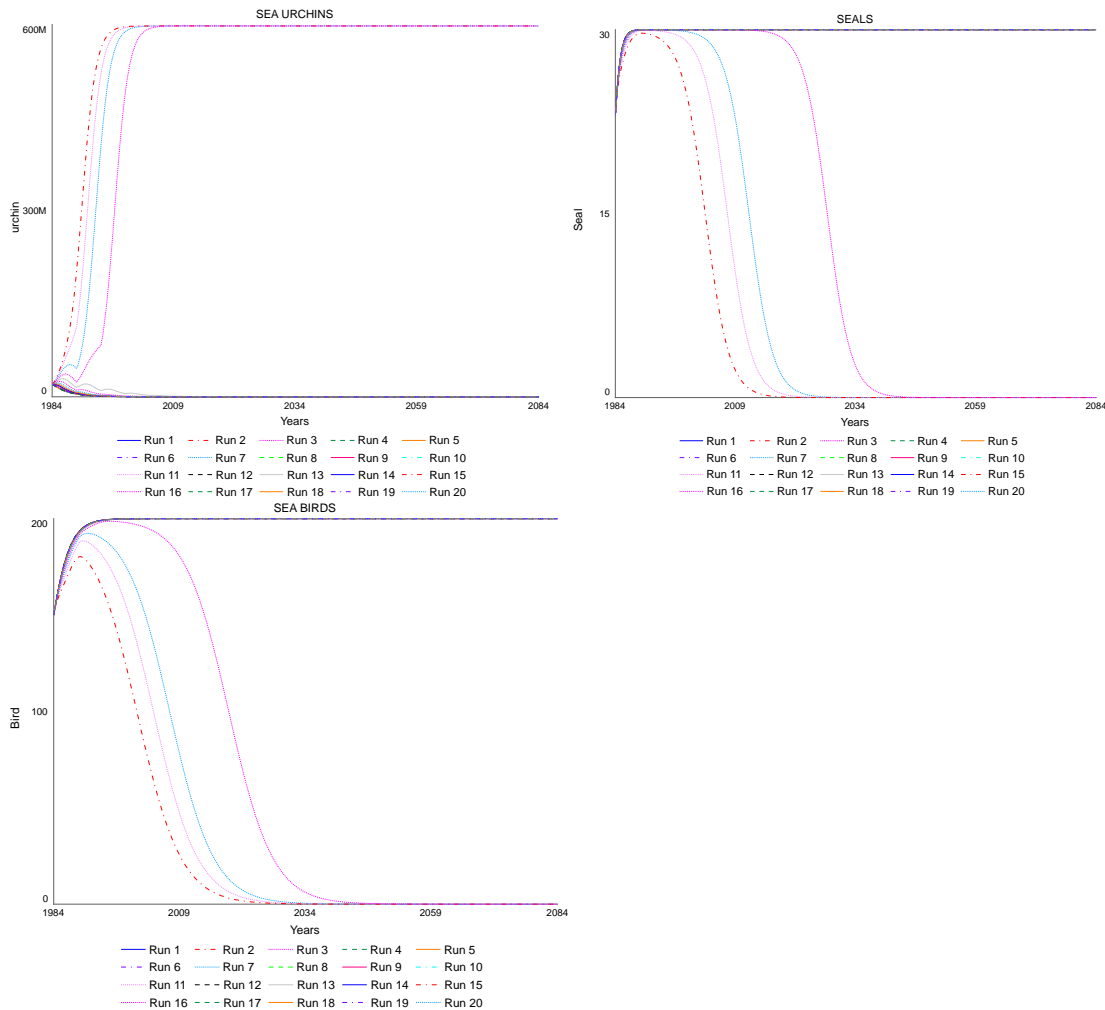
The model behaviour is sensitive to changes in *Fraction of Kelp Harvested*. The kelp stock is very sensitive, as expected, as a direct extraction of the stock will be noticed immediately, which quickly will be felt by the fish as their carrying capacity is directly dependent on the kelp forest. Sea Urchins also changes behaviour with several of the harvesting values, which is an expected result from the changes to their predator. The behaviour of Sea Birds and Seals are only sensitive to very high values of harvest. The amount of kelp and fish is largely sufficient to keep the system in a kelp dominated state and is only altered in four of the twenty values tested. These three values are above 0.63 which is within the upper 16% of the values tested and change the kelp dominance to a barren state which changes the behaviour of the whole system significantly. This is expected if the kelp forest gets too low to support a higher growth fraction than kelp grazed by urchins.

Further, changes in *Kelp Harvest Interval*, the interval between each harvest, does nothing if the harvest is zero. But with harvesting, it reduces the incidences of shifting state. If run with 8 years intervals (minimum regrowth time of a forest) the times of state change goes to only two, and if set to the shortest harvesting frequency allowed in Norway, 4 years (Steen, 2005, p.54), the number of state-changing scenarios increases to five, seen in the graphs below.

KELP FOREST

KELP FOREST
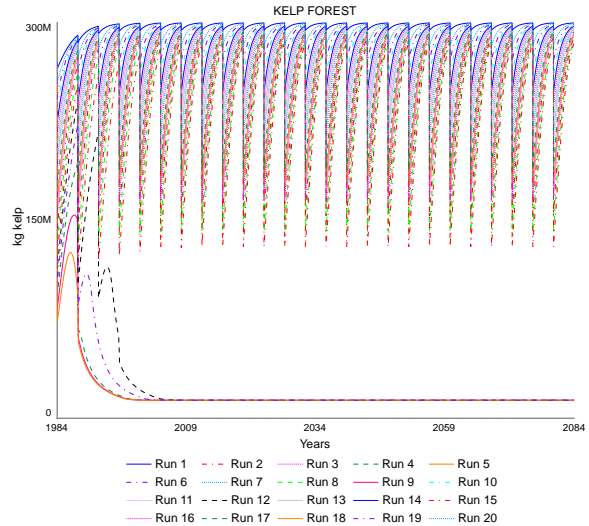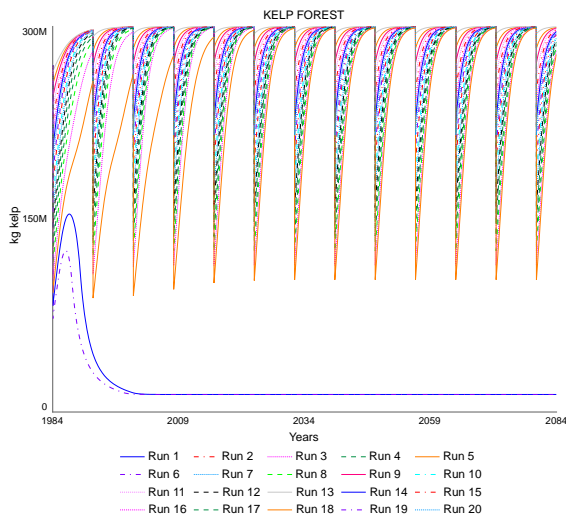
These changes in behaviour are expected because less time between each harvest gives the forest less time to recover before the next harvest, as well as decreasing predation pressure on urchin more often giving their grazing room to exceed kelp growth and finally increase in numbers.

- *Initial KELP sqm (15-41 kg)*

The base run value is 27 kg/m2, set to be below the CC of 30 (Rinde, 2007, p. 69).
The test run is set from 15 kg to 41 kg (Rinde & Sjøtun, 2005, p.1060; Sivertsen, 1991, p.1).
To see the meaning full changes in behaviour from the test of this parameter I set the *Initial Urchins* to 16.

KELP FOREST

GADID FISH BIOMASS

SEA URCHINS

urchin

600M

300M

0

1984 2009 2034 2059 2084

Years

Run 1 — Run 2 — Run 3 — Run 4 — Run 5
Run 6 — Run 7 — Run 8 — Run 9 — Run 10
Run 11 — Run 12 — Run 13 — Run 14 — Run 15
Run 16 — Run 17 — Run 18 — Run 19 — Run 20

SEALS

Seal

30

15

0

1984 2009 2034 2059 2084

Years

Run 1 — Run 2 — Run 3 — Run 4 — Run 5
Run 6 — Run 7 — Run 8 — Run 9 — Run 10
Run 11 — Run 12 — Run 13 — Run 14 — Run 15
Run 16 — Run 17 — Run 18 — Run 19 — Run 20

SEA BIRDS

Bird

200

100

0

1984 2009 2034 2059 2084

Years

Run 1 — Run 2 — Run 3 — Run 4 — Run 5
Run 6 — Run 7 — Run 8 — Run 9 — Run 10
Run 11 — Run 12 — Run 13 — Run 14 — Run 15
Run 16 — Run 17 — Run 18 — Run 19 — Run 20

This parameter is sensitive to changes when urchins are high, but not from the base run. That is because when the kelp forest is initiated low enough, there will be less fish and the grazing from urchins that start of in the forest will in exceed the kelp growth, as well as their reproduction will exceed the predation pressure.

- *Kelp CC pr sqm (15-41)*

The base run value is 30 kg/m2 (Rinde, 2007, p.77).

The test run is set from 15 kg to 41 kg (Rinde & Sjøtun, 2005, p.1060; Sivertsen, 1991, p.1).

KELP FOREST

GADID FISH BIOMASS

SEA URCHINS

SEALS

SEA BIRDS

Changes in Kelp CC does not show behavioural sensitivity in the model, except numerical change in the kelp stock itself, as expected because it's still a high level of kelp forest which is known to be a sturdy stable state. The CC is though not meant to be changed in this model because I am looking for behaviour in a system under ideal growth conditions.

Sea Urchin Sector

- *Maximum Growth Fraction Urchin (Test range: 0.35-1.05)*

The range is set to 50% up and down from the normal value of 0.7, found from model calibrations based on observed behaviour (Hagen, 1983, p. 185; Sivertsen, 1997, p. 2880).

Behaviour:
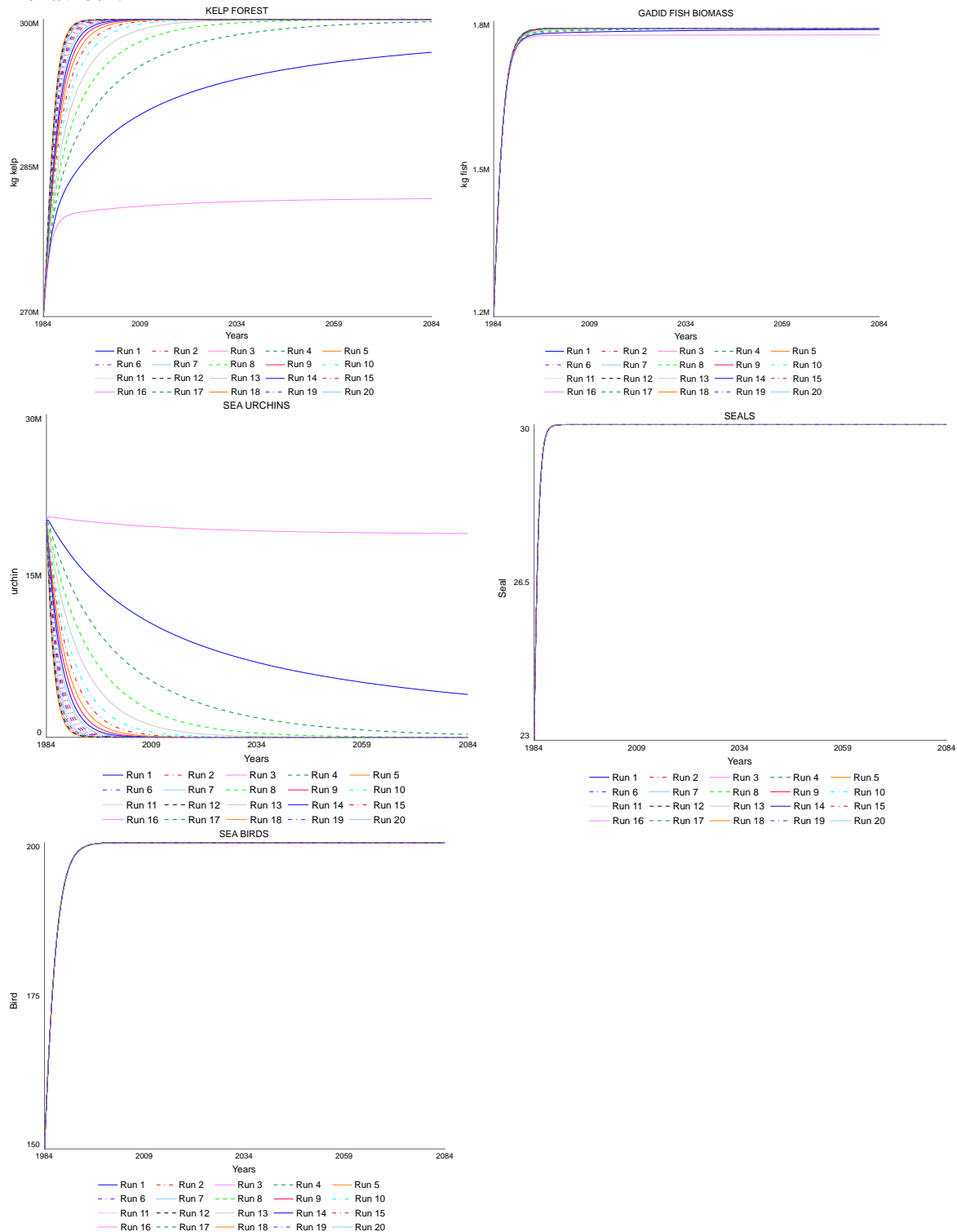
The model behaviour is sensitive to changes in the urchin growth fraction.

- *Average Grazing per Urchin (Test range: 0.365-0.912)*

The test range is based on the observed upper and lower grazing rates, where the normal rate is 0.56 (Scheibling & Anthony 2001, p.144).

Behaviour:
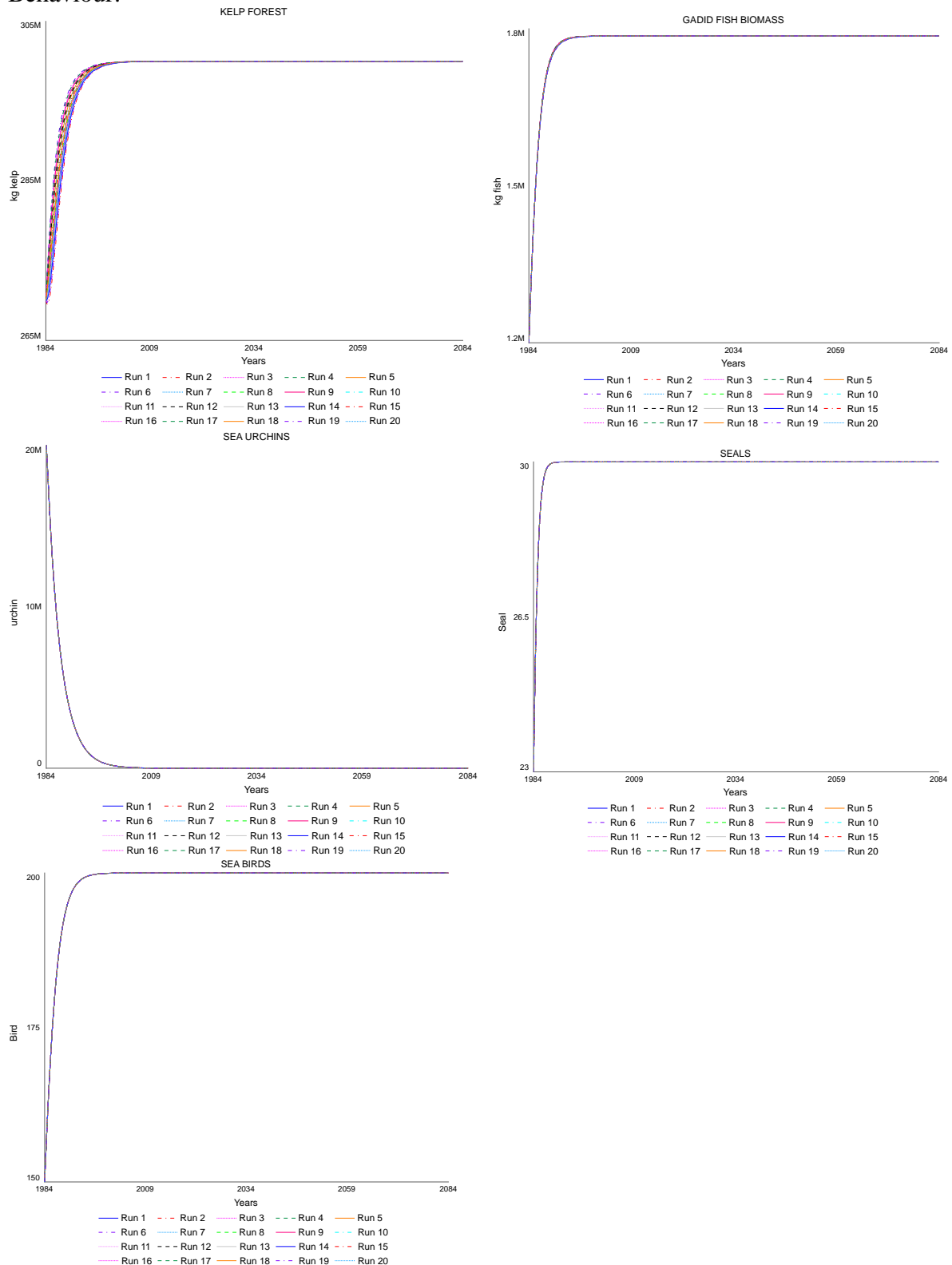
The model behaviour is not sensitive to changes in average grazing per urchin.

- *Effect of Kelp Availability on Actual Grazing (Test range: Graphical behaviours below)*
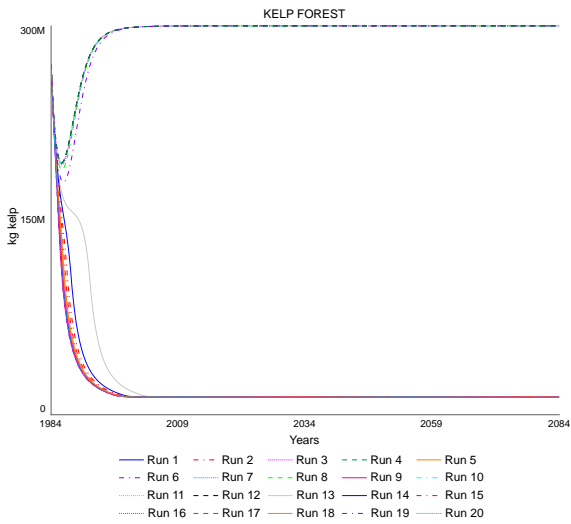
The base run is the first picture of the graphical functions tested:
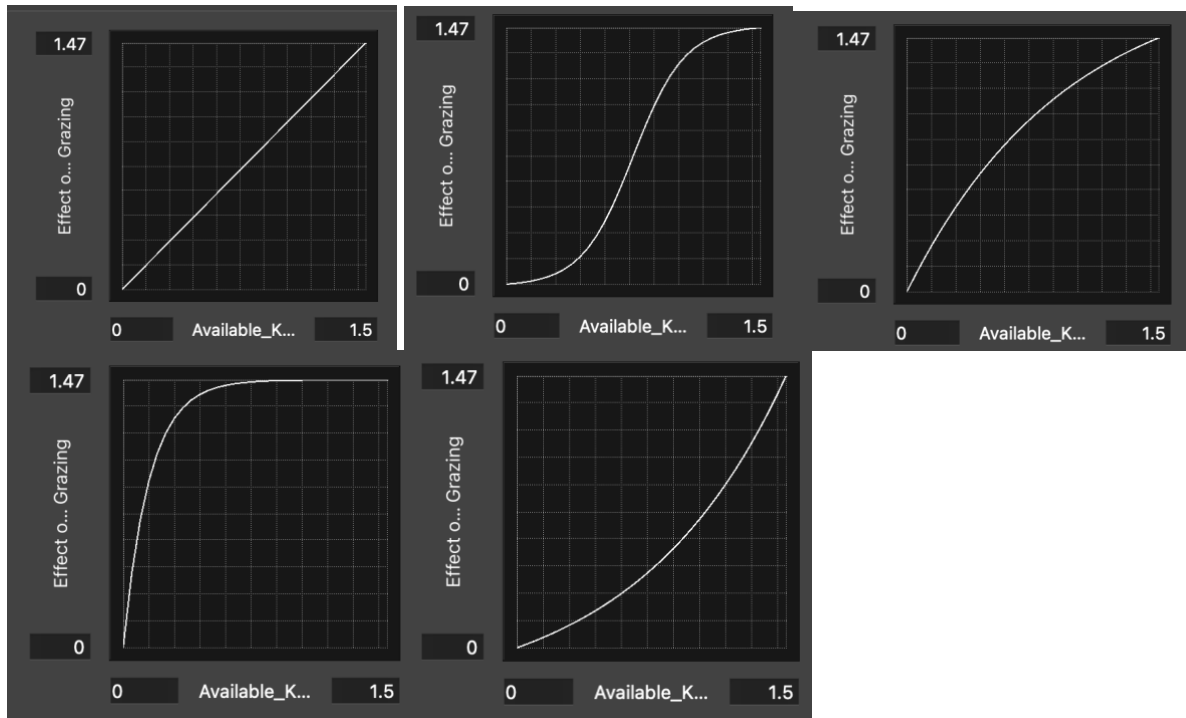
To see the effect of the different shapes in this graphical function I again set the scenario with initial urchins from 2 to 16, which is slightly above the tipping point for urchins to make the kelp forest barren. The different graphical shapes are based on other shapes used in predator-prey models (Swart, p.95: Noy-Meir, p.461).

Behaviour:
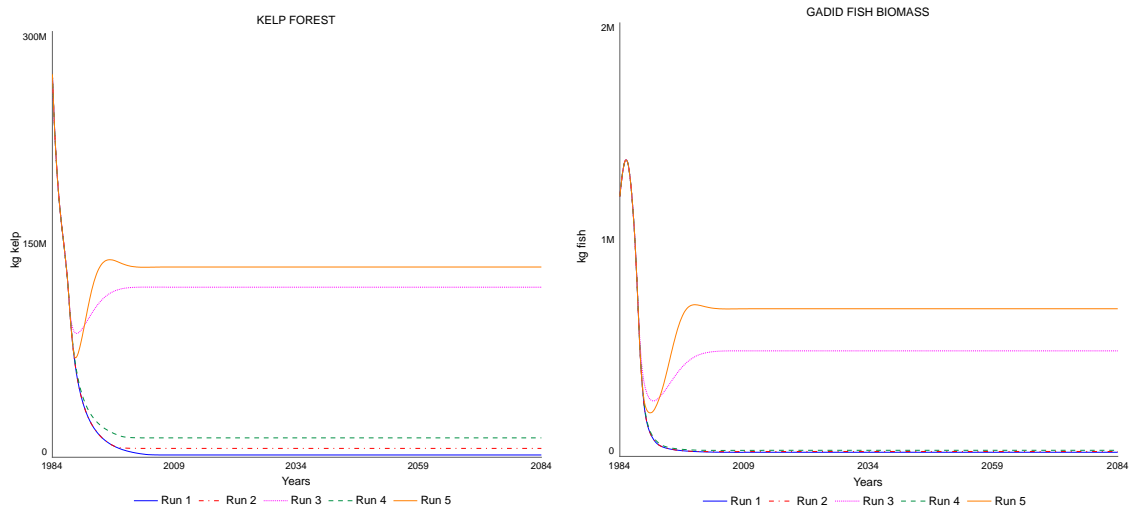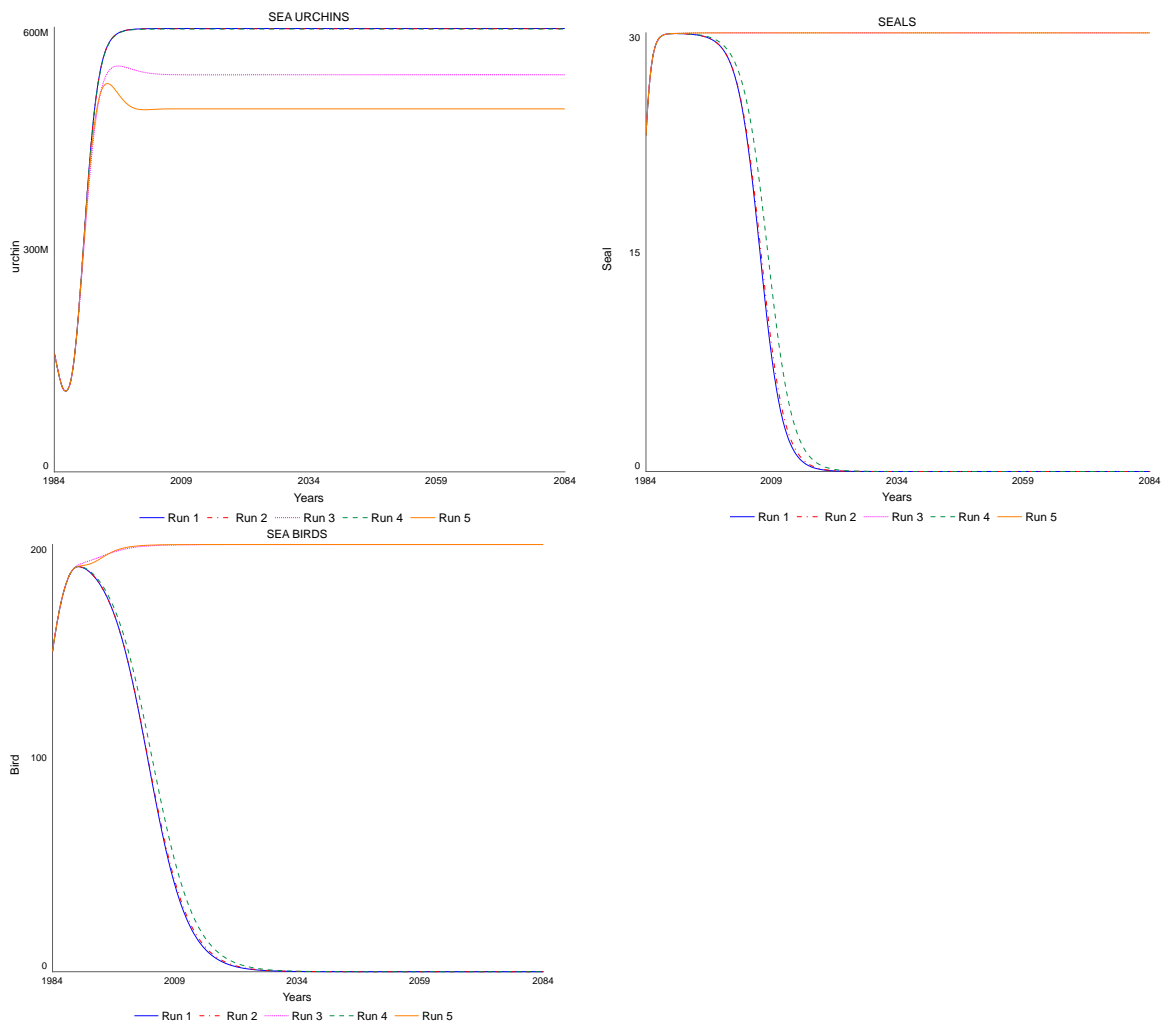
The model behaviour is sensitive to changes in the effect shape of kelp availability on kelp grazing in the scenario where there should be enough urchins to graze down the kelp forest to a barren. The three behaviours where kelp, fish, seal, and bird populations collapses can be expected from a steeper increase in grazing on kelp. From the slower increases, S-Shape and slow exponential, the grazing pressure on kelp is not initially big enough to throw the kelp forest low enough that the predation pressure of fish would decrease below urchin's growth. These two scenarios and behaviours are the least likely as predation pressure usually keeps at a high level before it decreases increasingly or linearly. What these shapes also do is dampen the stable states to far off the cc or zero which this system in real life is portraying (Swart, 1990; Dexter & Scheibling 2014). It is not sensitive in the base run.

- *Effect of forest composition on urchin grazing (Test range: Graphical)*
Again, it is not sensitive to changes when tested in the base run. To see the behavioural changes from altering of the effect of forest composition parameter we set the system to an unstable point, with *Initial Urchin Sqm* at 16.

The base run is the first picture of the graphical functions tested:

Behaviour:

SEA URCHINS
SEALS
SEA BIRDS
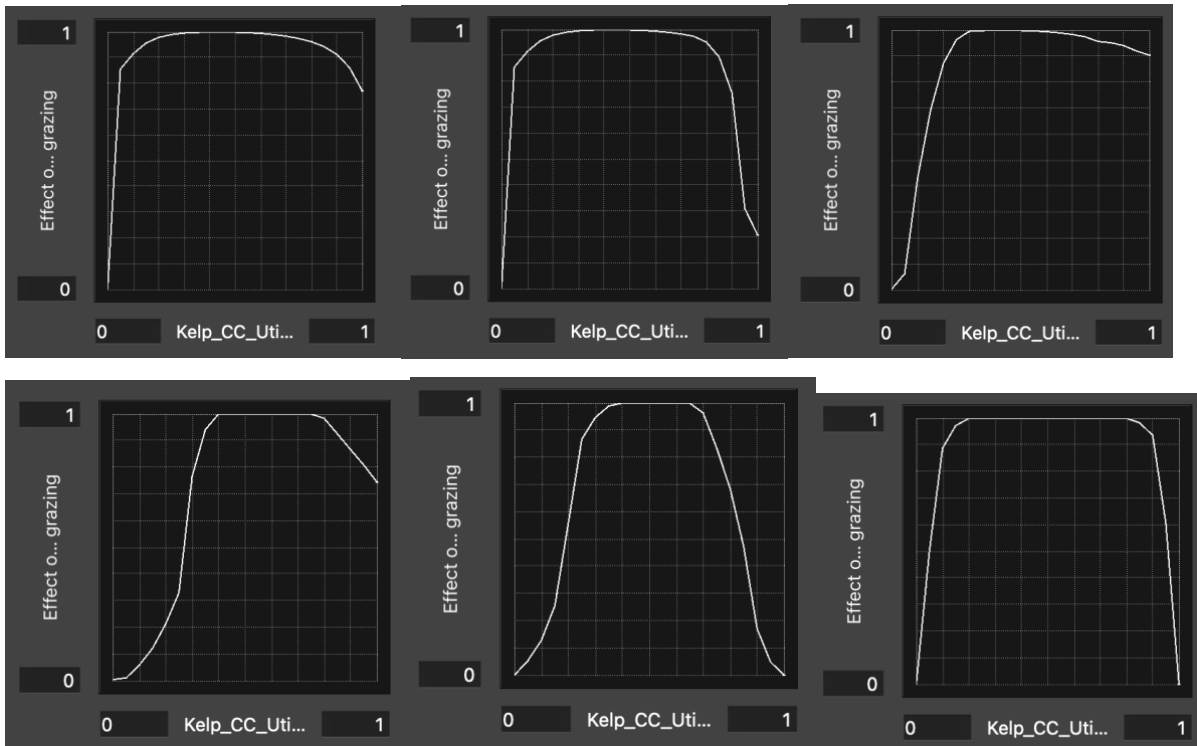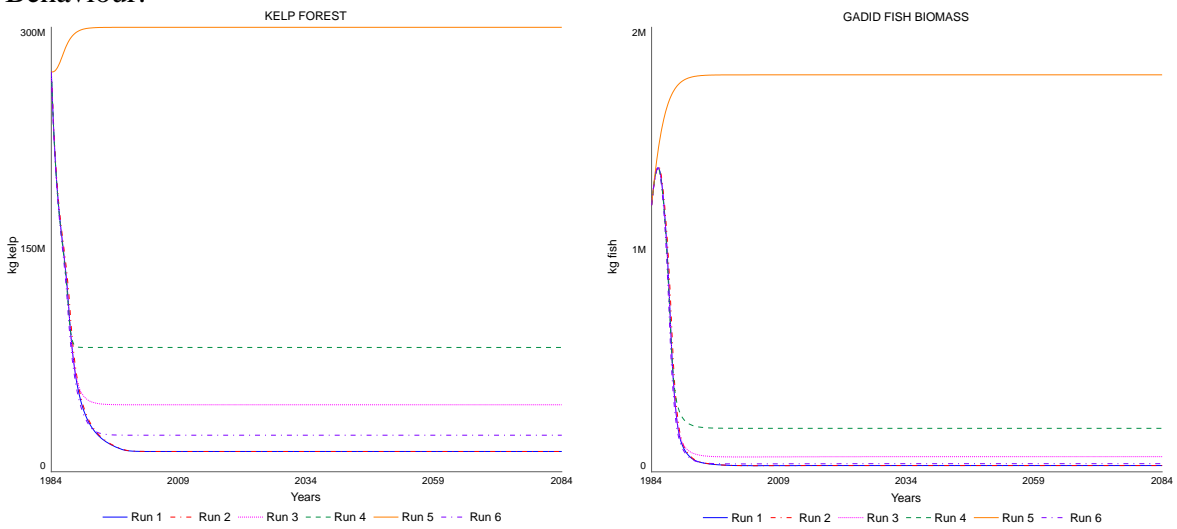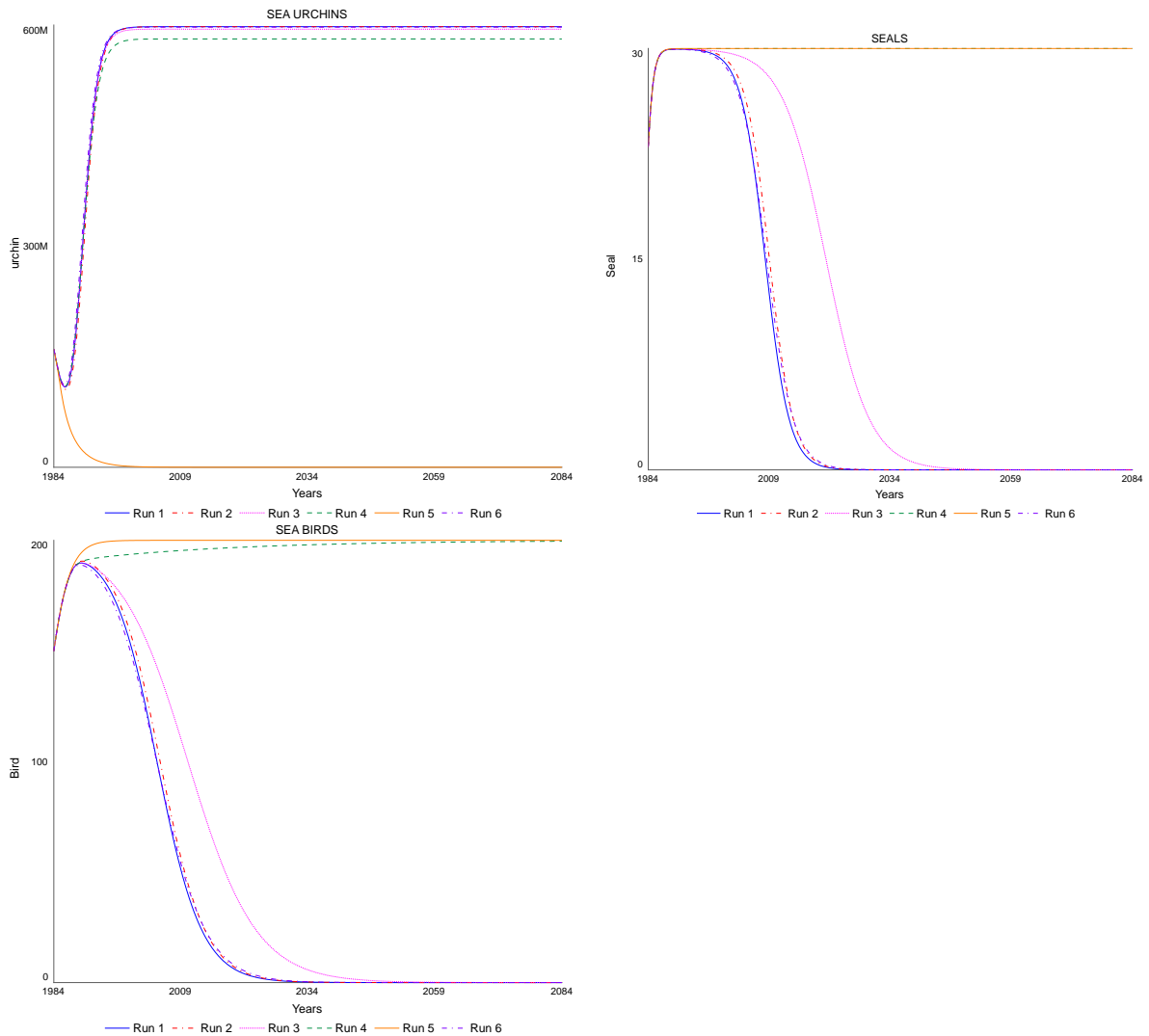
In that scenario, changes in the graphical shapes creates mainly two different behaviours, one that hits the tipping point to barren state and one that don't, otherwise the differences is mainly numerical, as expected.

- *Weight pr Urchin (0.01-0.03g)*

Small urchins weigh on average 10 g (Michelsen, 2022, p.11), commercial urchins size weigh about 20 g (Michelsen, 2022, p.12), so a high average would be 30g.

KELP FOREST

SEA URCHINS

Legend (Kelp Forest, top left): Run 1, Run 2, Run 3, Run 4, Run 5, Run 6, Run 7, Run 8, Run 9, Run 10, Run 11, Run 12, Run 13, Run 14, Run 15, Run 16, Run 17, Run 18, Run 19, Run 20

Legend (Sea Urchins, top right): Run 1, Run 2, Run 3, Run 4, Run 5, Run 6, Run 7, Run 8, Run 9, Run 10, Run 11, Run 12, Run 13, Run 14, Run 15, Run 16, Run 17, Run 18, Run 19, Run 20
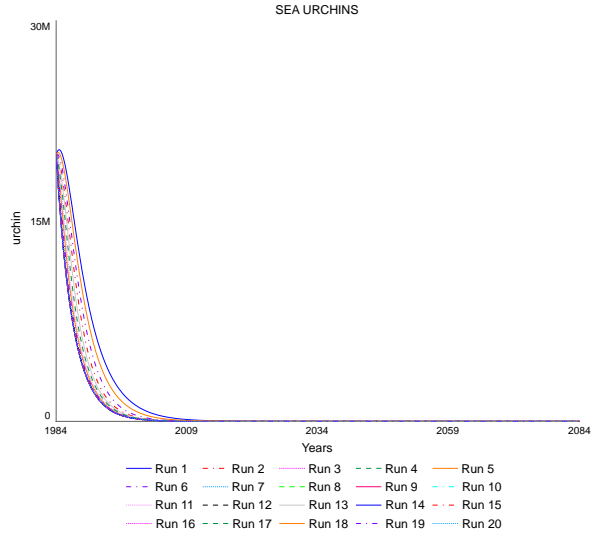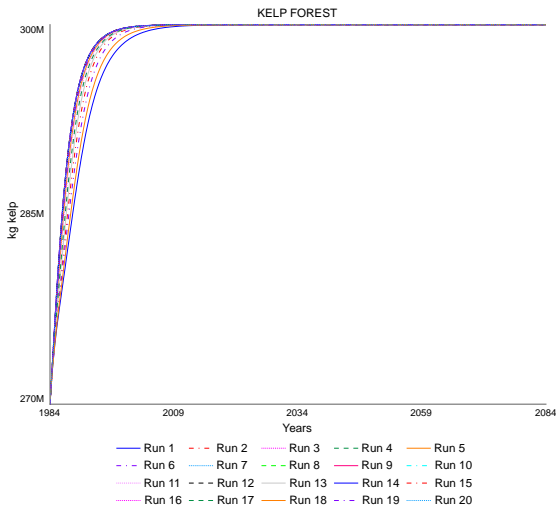
Base run results, above, show little sensitivity. Run with initial urchins at 16, shows greater sensitivity, below.

KELP FOREST

GADID FISH BIOMASS

Legend (Kelp Forest, bottom left): Run 1, Run 2, Run 3, Run 4, Run 5, Run 6, Run 7, Run 8, Run 9, Run 10, Run 11, Run 12, Run 13, Run 14, Run 15, Run 16, Run 17, Run 18, Run 19, Run 20

Legend (Gadid Fish Biomass, bottom right): Run 1, Run 2, Run 3, Run 4, Run 5, Run 6, Run 7, Run 8, Run 9, Run 10, Run 11, Run 12, Run 13, Run 14, Run 15, Run 16, Run 17, Run 18, Run 19, Run 20

SEA URCHINS

SEALS

SEA BIRDS
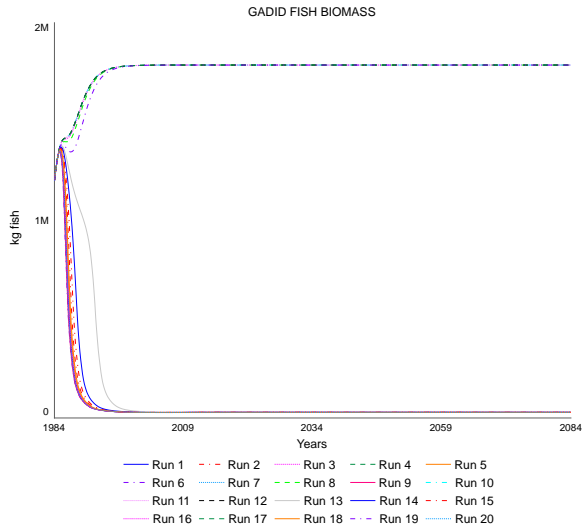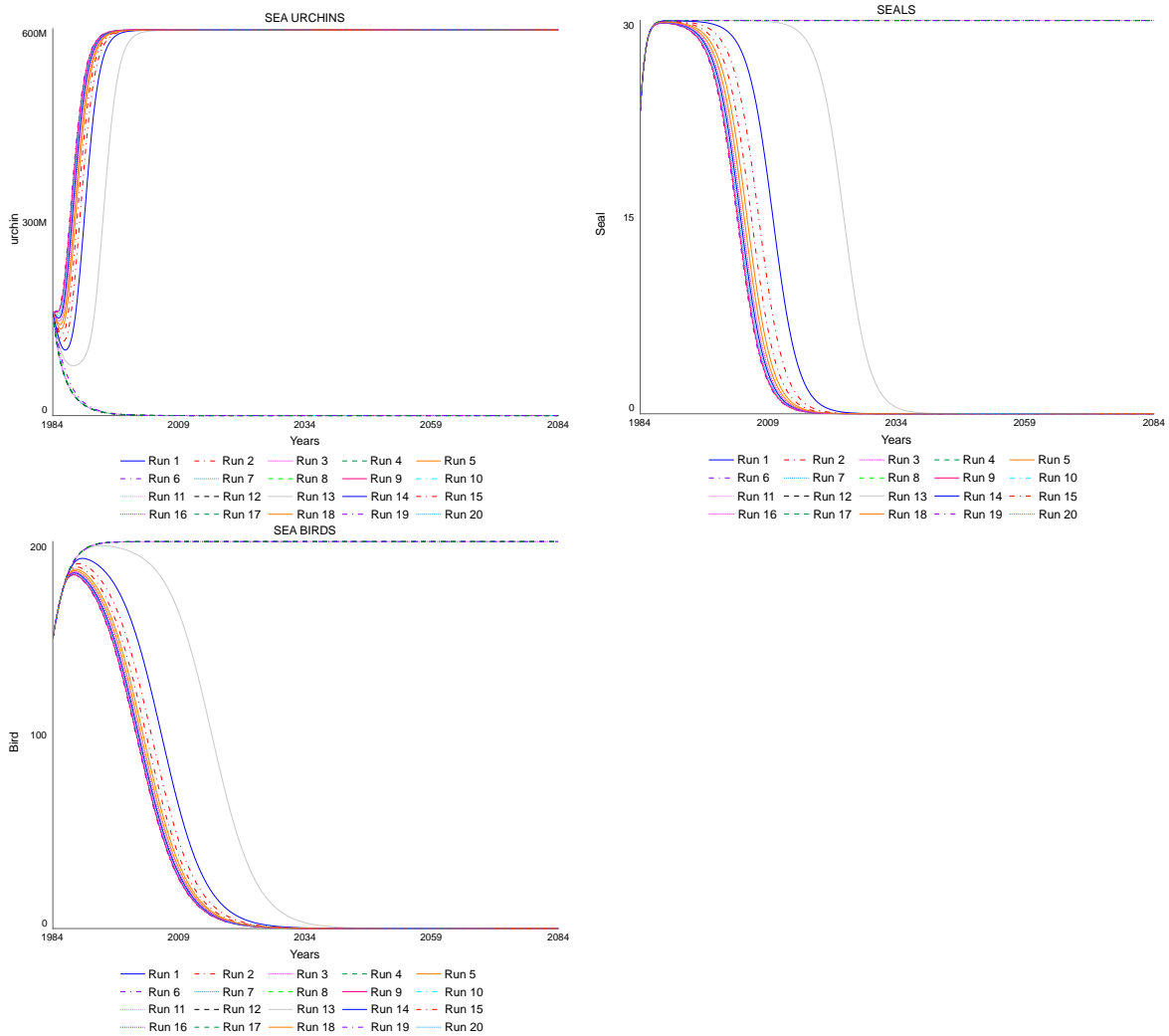
The average weight of urchins does is not sensitive unless the system are close to a tippingpoint. That tells us that small numerical differences in the estimates of sea urchins can alter when the tipping point happens in the model, but will not have any other great effect on the behaviour of the system.

- *Initial Urchin sqm (0-20)*

The base run value is 2 urchins (Sivertsen, 1997, p.2876; Fagerli, 2013, p.124). The test run range is from 0-20, based on the lowest and highest number of urchins found in kelp forests that is still regarded as a kelp forest (Fagerli, 2013, p.124).

KELP FOREST

GADID FISH BIOMASS

SEA URCHINS

SEALS

SEA BIRDS
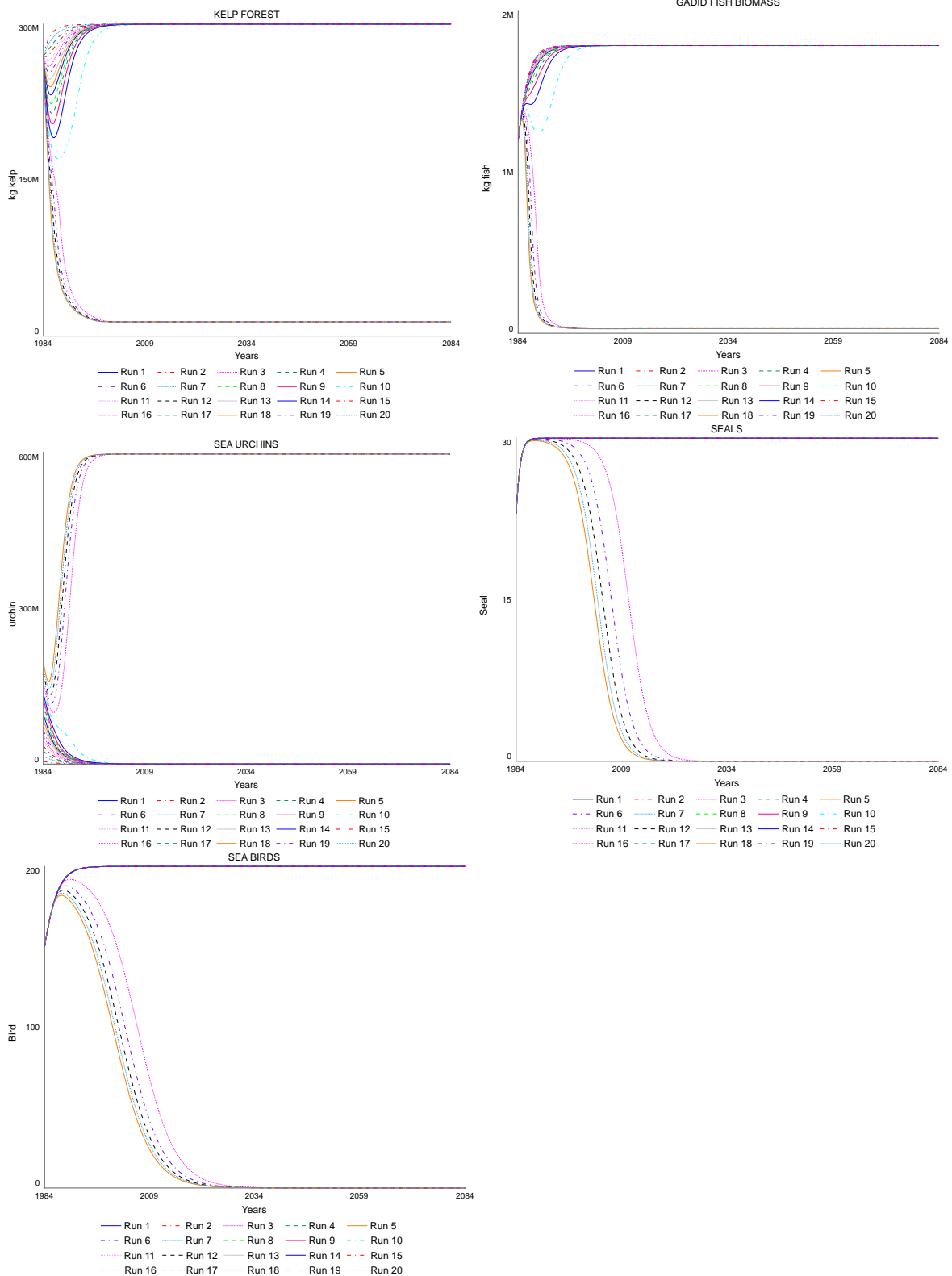
The parameter shows high sensitivity with the confident value range of initial urchins. When the number of urchins in the kelp forest exceeds a certain level (more than 15 urchins) the system changes from kelp dominant to urchin dominant. That is because with enough initial urchins, the grazing pressure on kelp will be enough to push the kelp forest down before enough urchins are eaten by fish to be counteracted. When this threshold is hit, the

number of fish in the forest will decrease with the kelp forest, ending up with a complete collapse of the system's stocks, expect the urchin stock.

The reason why the stocks increase in the first place is because they are not initiated in their carrying capacity, but fairly close to the CC, which gives them a fairly high growth rate. For those runs in Kelp Forest and Gadid Fish Biomass that collapses, the reason is that the stocks get closer to CC which decreases the growth rates quickly, giving grazing from the amount of urchins left an opportunity to exceed the growth of kelp. Further, the runs that shows a recovery of the fall, is due to the number of urchins is low enough to feel the decreasing growth rates that comes with a low population giving the predation on urchins room to exceed the urchin growth.

- *Urchin CC pr sqm (30-60)*

The base run is 60 Urchins pr m^2, which seems to be the maximum urchin CC (Sivertsen, 1997, p. 2877; Fagerli, 2013, p.125). 30 urchins pr m^2 is also found to be an upper limit (Skadsheim, 1995, p.202). To see the behavioural effect we set the initial urchins to 16.

SEA BIRDS
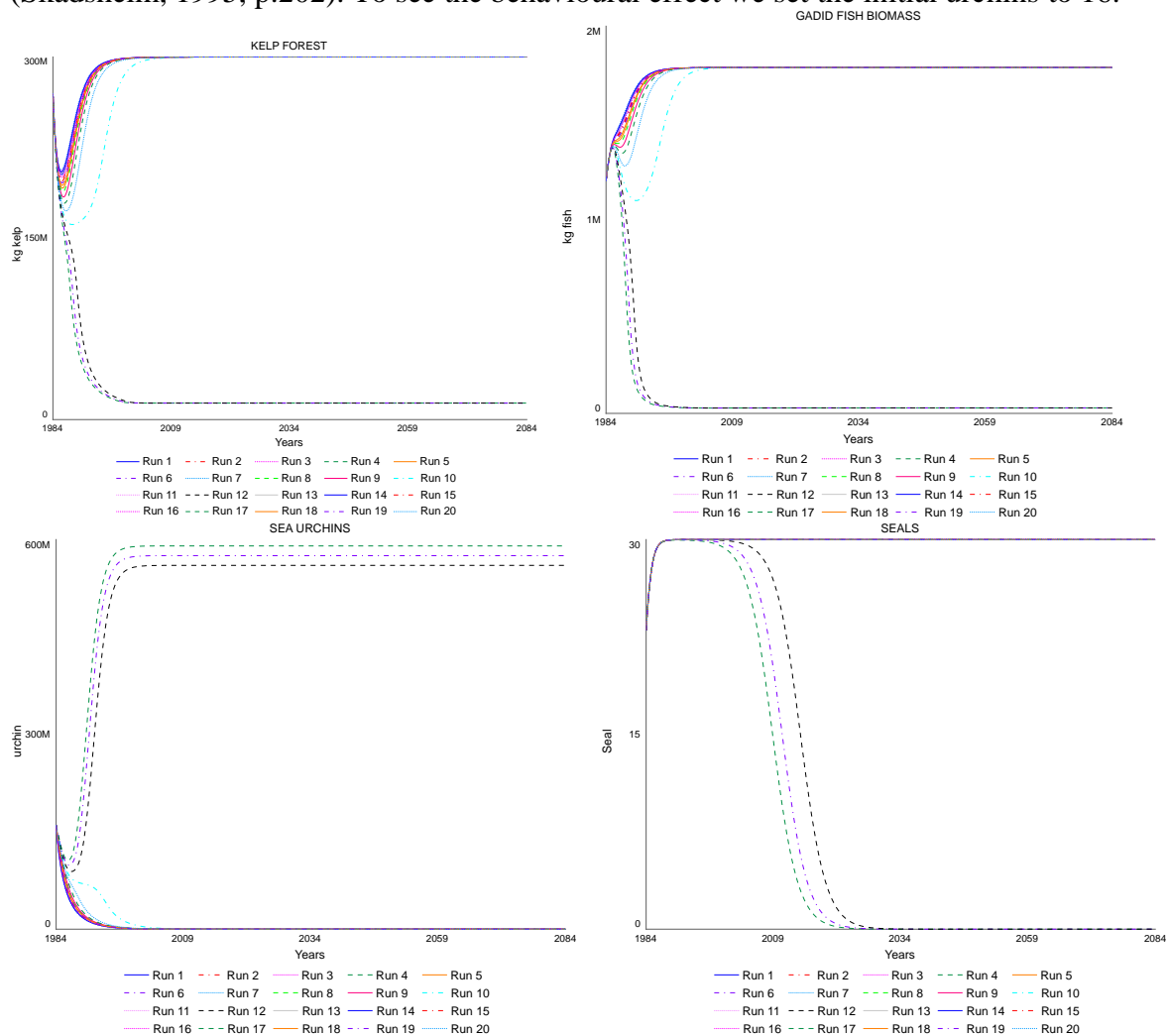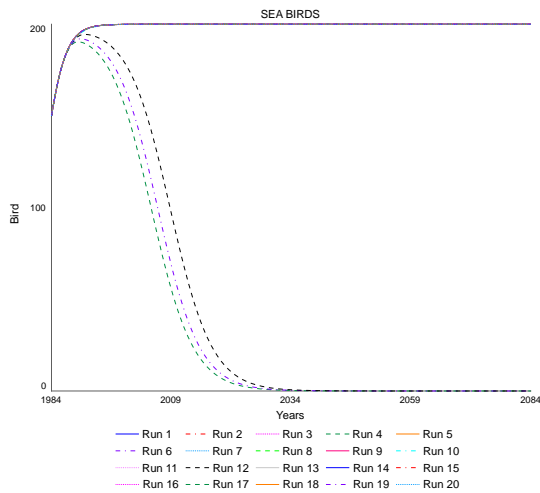
The parameter is sensitive when initial urchins is set to 16 (which I must remind you is beyond the tipping point in the base run). The CC is though not meant to be changed in this model because I am looking for behaviour in a system under ideal growth conditions.

Fish in Kelp Forest Sector

- *Maximum Growth Fraction Fish (0.4-0.9)*

The low growth fraction is set a bit higher than found by Vondolia, as she underestimates the growth, the base Max growth rate is already on the upper scale, so the highest test value is slightly above what I use in the base run (Vondolia, 2019, p. 39). Base run fraction is 0.8.

Behaviour:

KELP FOREST
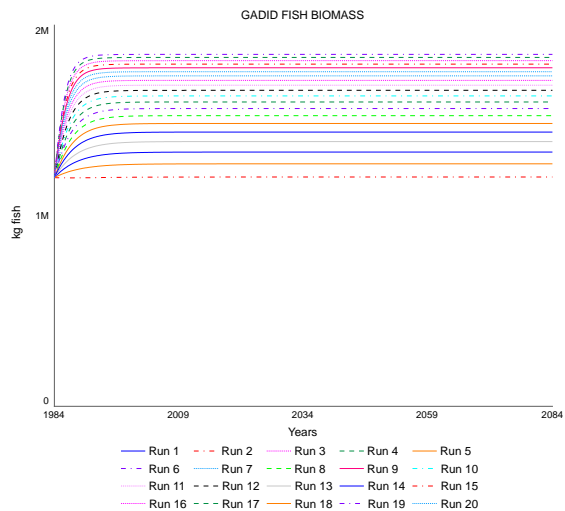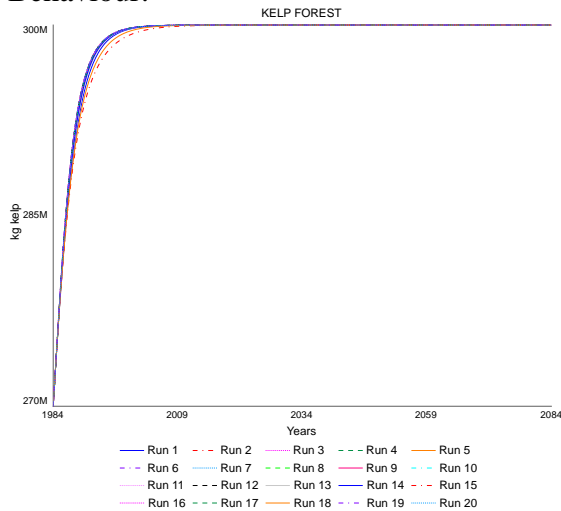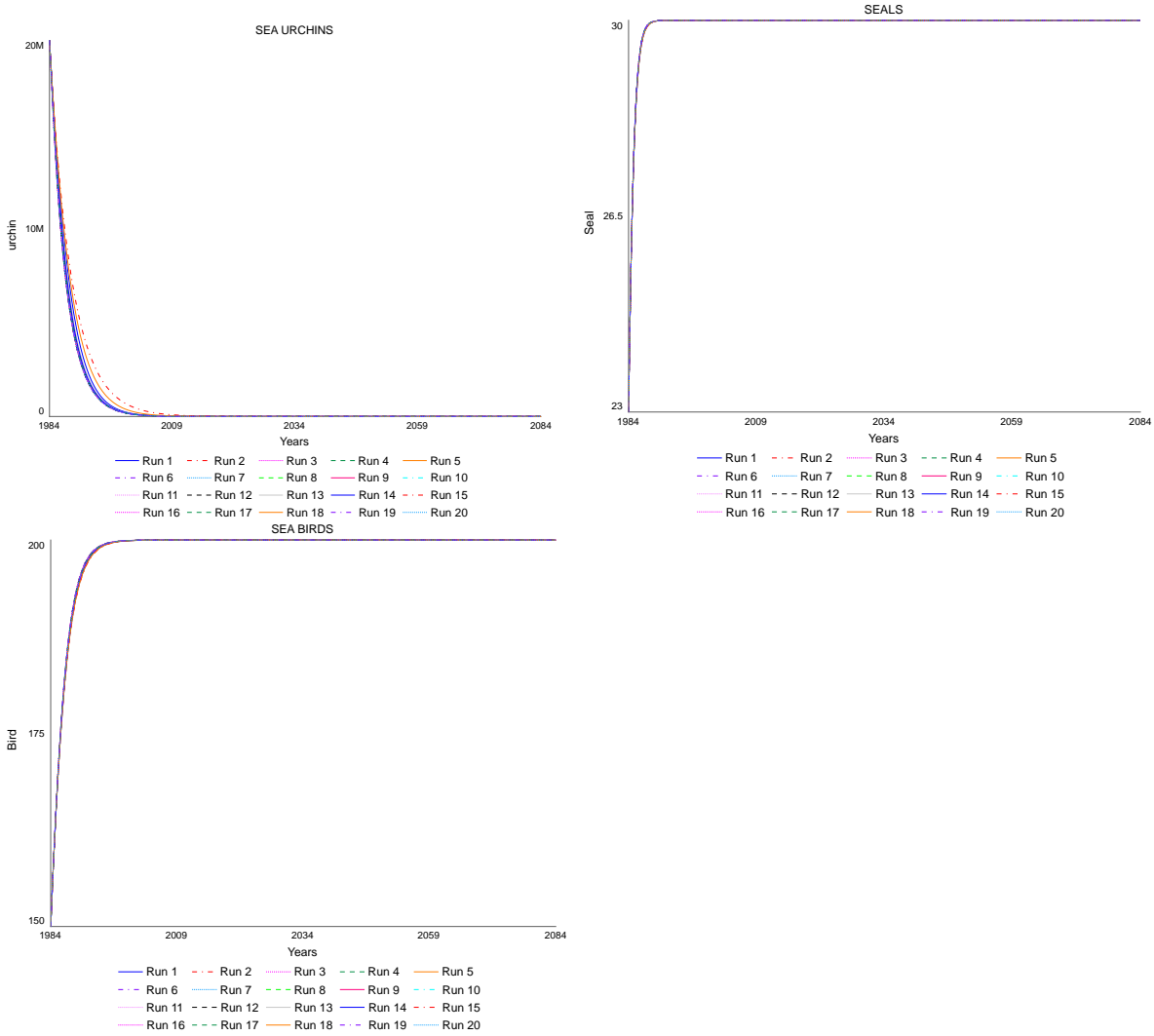
GADID FISH BIOMASS

The behaviour of the model is not very sensitive to changes in the Maximum growth fraction of fish, expect a noticeable numerical change in gadid fish biomass, which is expected due to the fishing pressure that counters the lower growth rates.

- *Habitat Effect on Fish CC (Graphical)*

The base run value of this parameter is represented by the first picture of the graphical shapes that is tested, shown below:
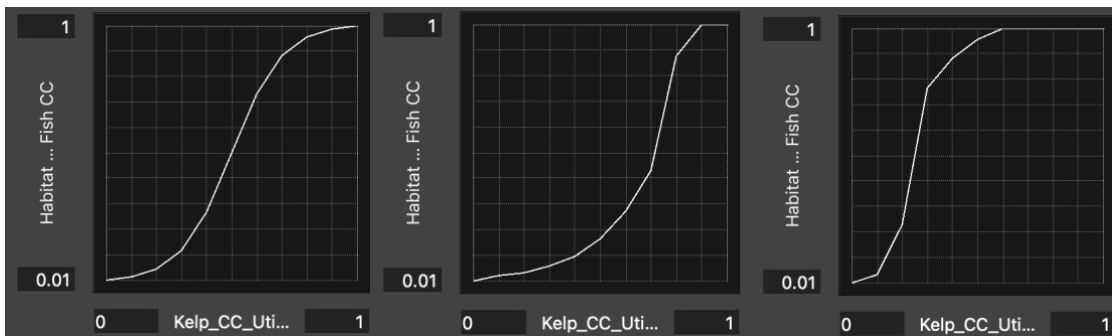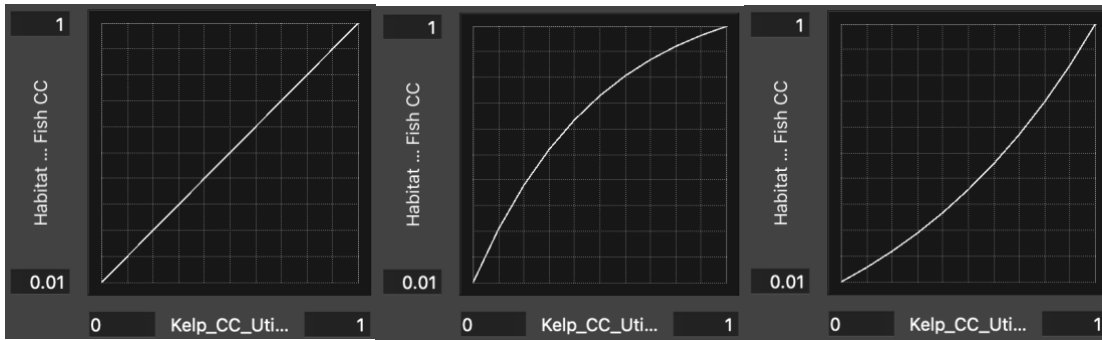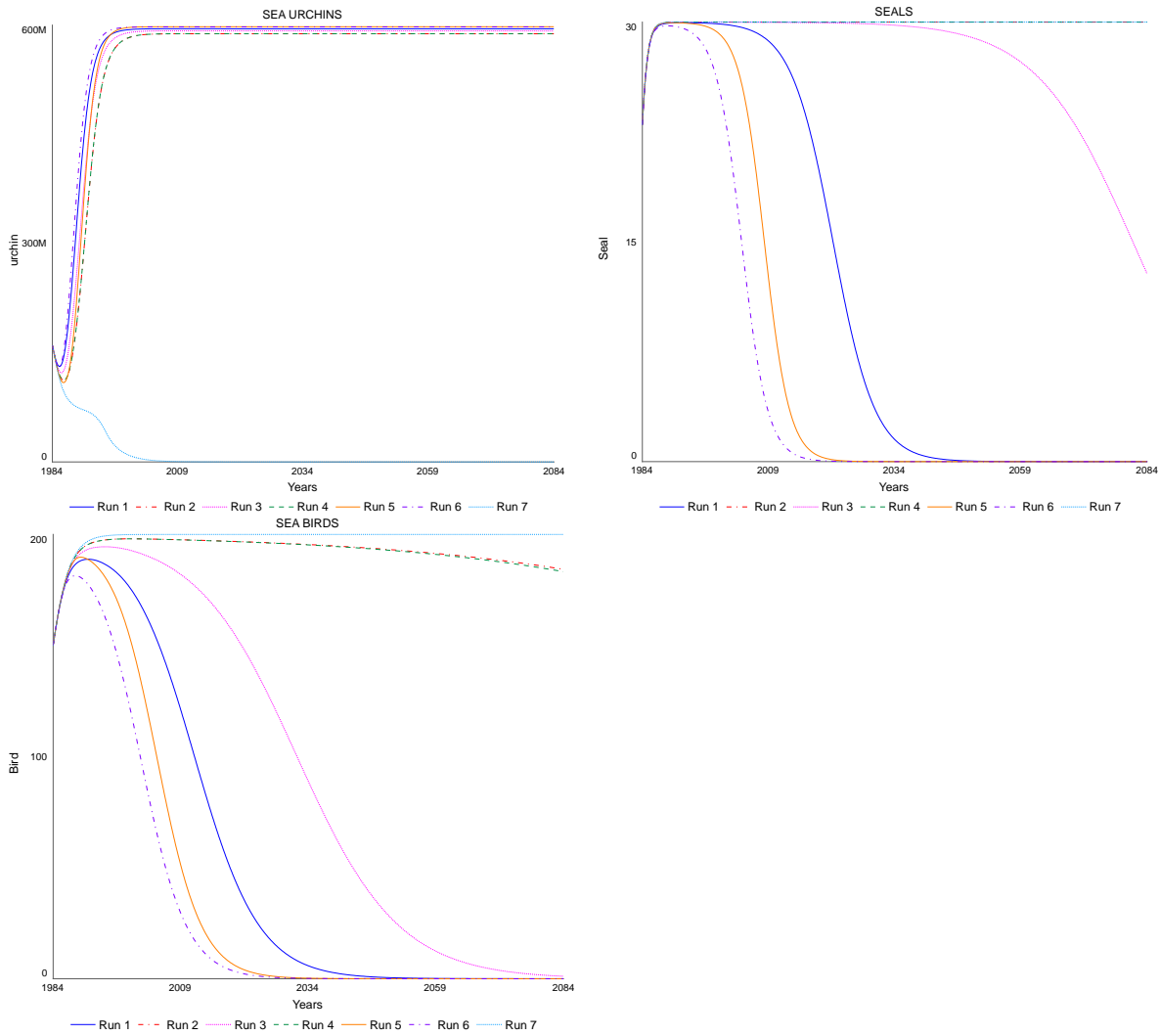
Behaviour:
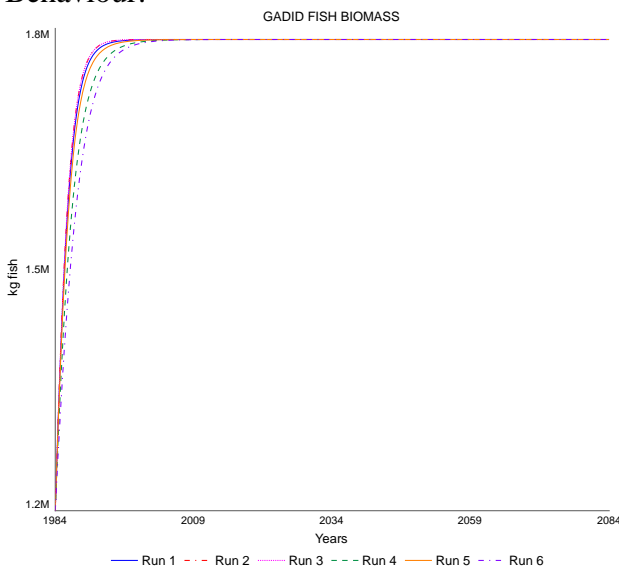
GADID FISH BIOMASS

Only slight numerical effect of changes in habitat effect was on the gadid fish biomass in the base run, no other numerical or behavioural sensitivity were observed. More sensitivity was shown in the alternative fragile state scenario initiated with 16 urchins:

KELP FOREST

GADID FISH BIOMASS
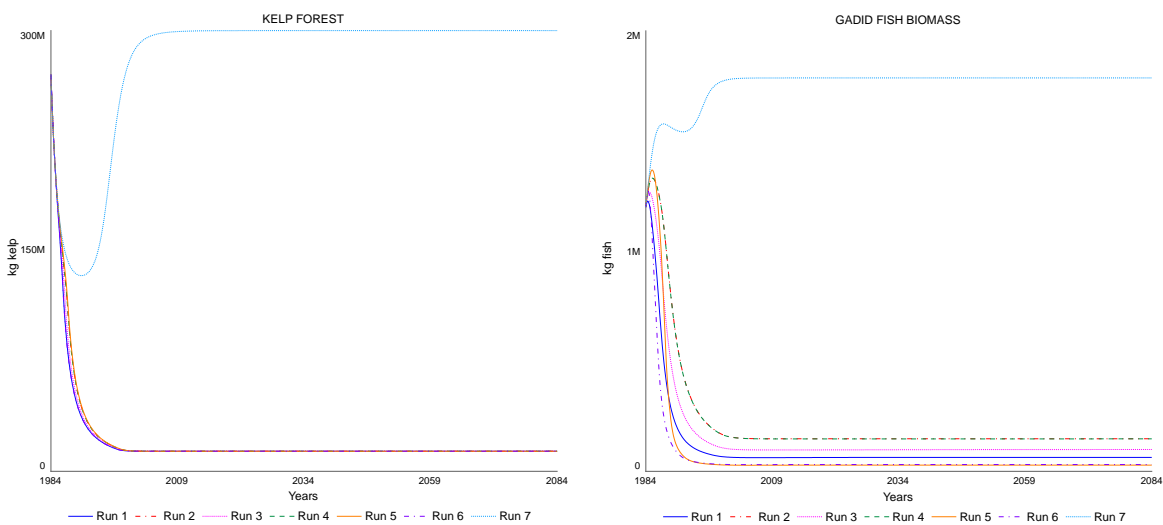
Behavioural sensitivity is observed when Initial Urchin Sqm is set to 16. As the habitat effect changes the CC of fish, we expect those smaller values in the effect variable to decrease fish CC, creating less pressure on urchins, thus making the system more likely to shift in favour of urchins, and vice versa.

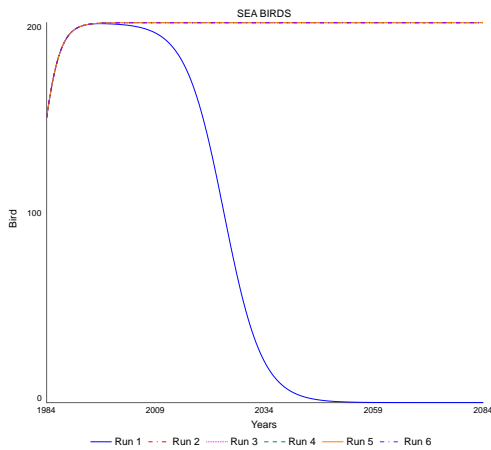- *Other Predators Multiplier (Graphical)*

The first of the graphical shapes tested below is the base run:
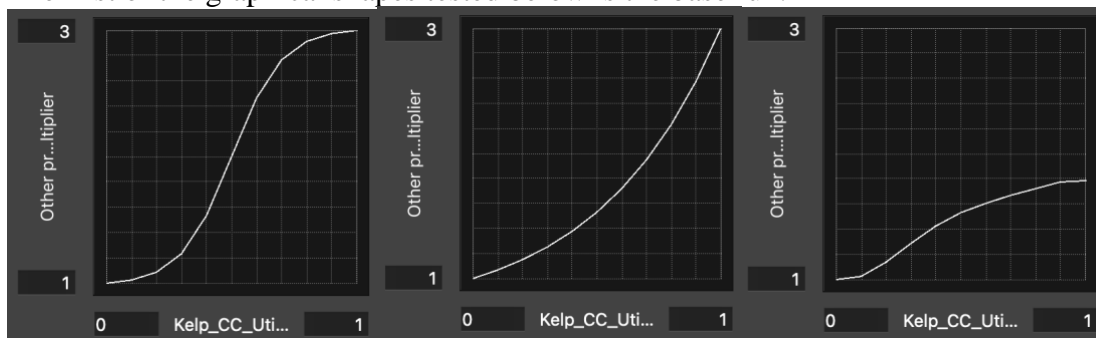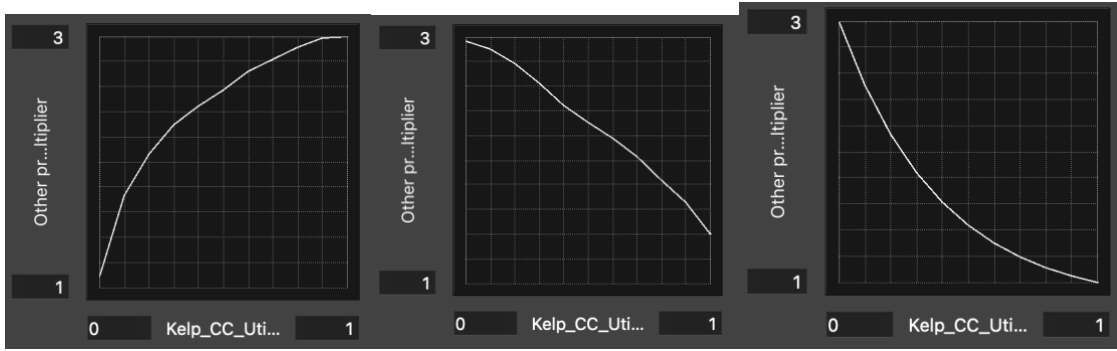
After the test runs with the values above, we get the behaviour of the KPI's shown below:

SEA BIRDS
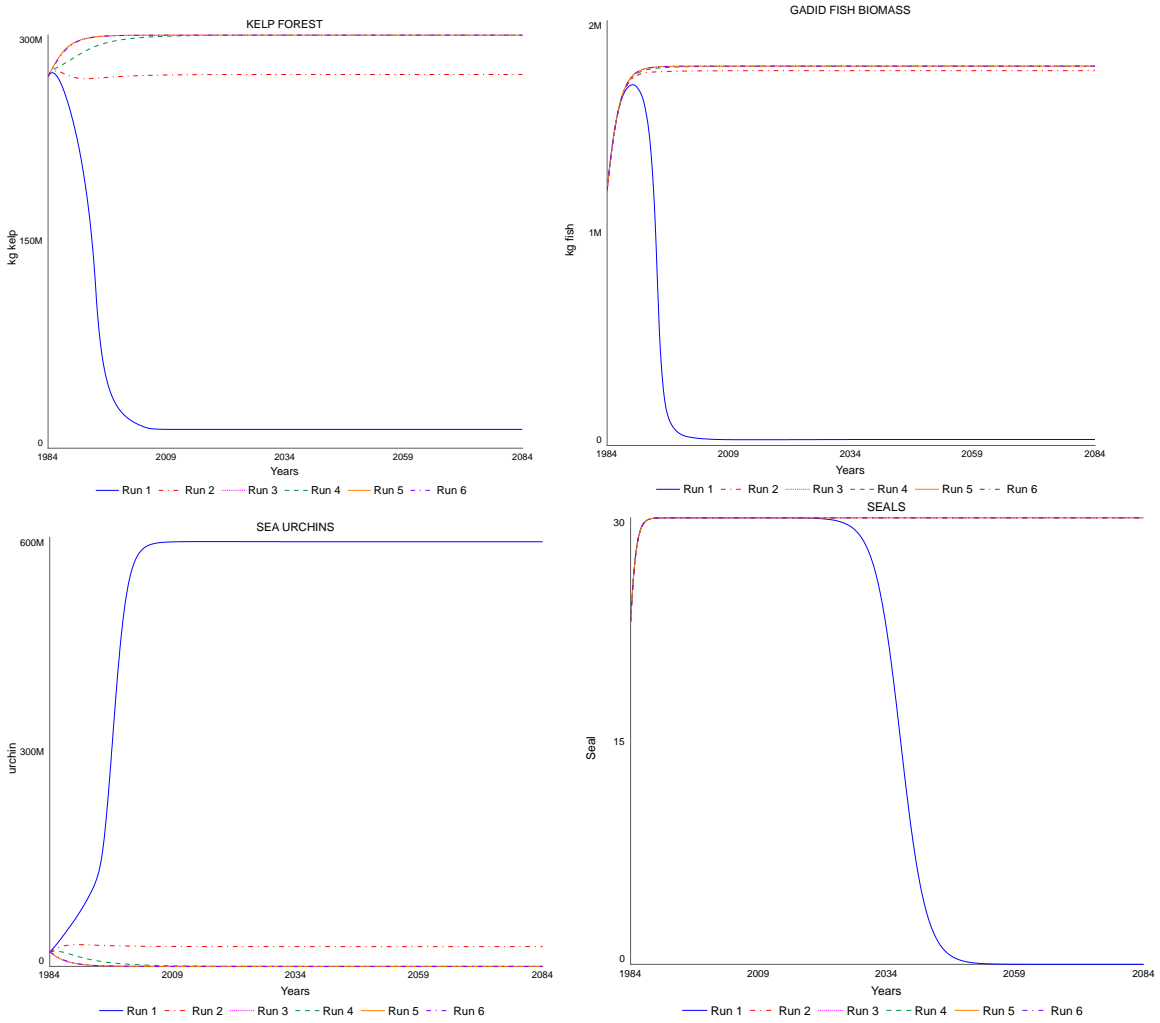
The predator mulitplier shows low sensitivity from the base run. In the run when the system changes to be urchin dominated the multiplier is reversed, so its low when the kelp forest is high and, high when the kelp forest is low. Since its a multipler the effect will be much bigger when the forest is at high levels as there will be more fish and thus a bigger predation pressure to multiply. Meaning that when the kelp forest is high, in this scenario, we lose a lot of the initial predation pressure, which then goes below the grazing pressure from urchin. Further, when the forest decreases, so does the effect of the multipler as the value it is multiplying decreases towards 1. This reversed graphical is not likley to appare since the fauna is dependent on the kelp forest, and that gadid fish is oppurtinistic and can even specialise on urchin hunting meaning its not likley that there will be higher parts of other predators on the urchin when the kelp forest is low, but the opposite (Norderhaug et.al., 2020, p.166). Due to no hard evidence on this effect variable the test is still valid even though im confident of the base shape in this parameter, and I say the paramter is not sensitive.
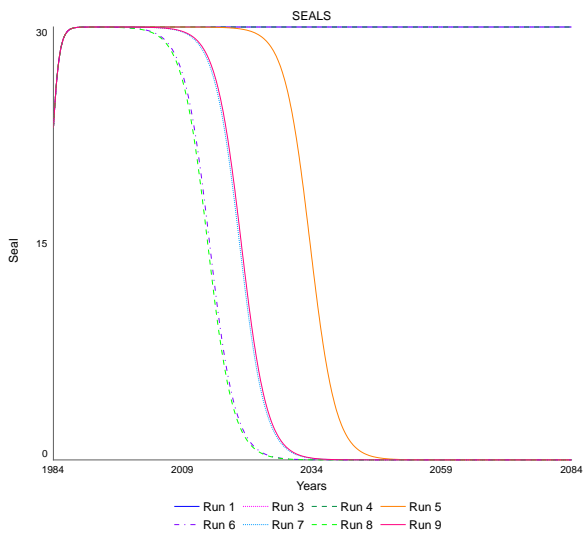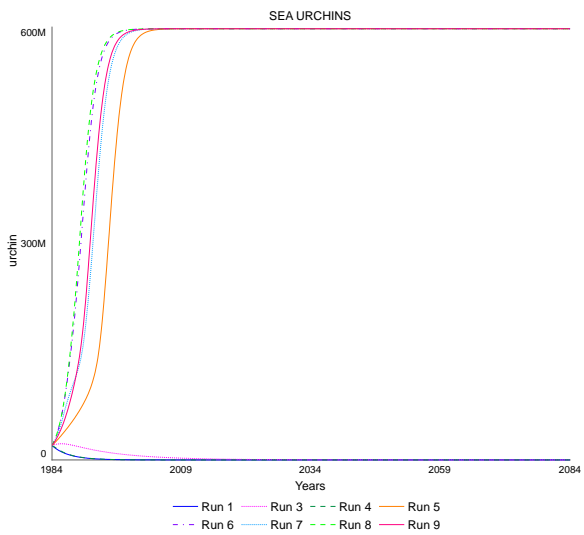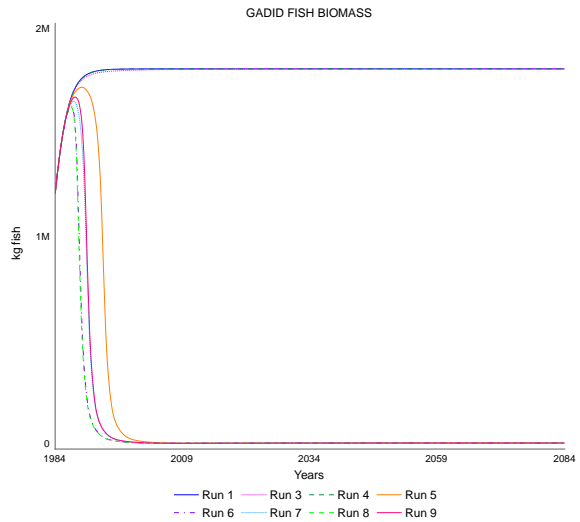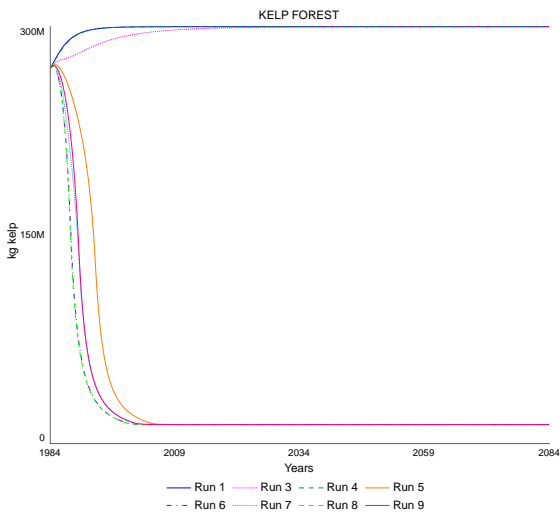
- *Fraction of Urchin as Prey (Graphical)*

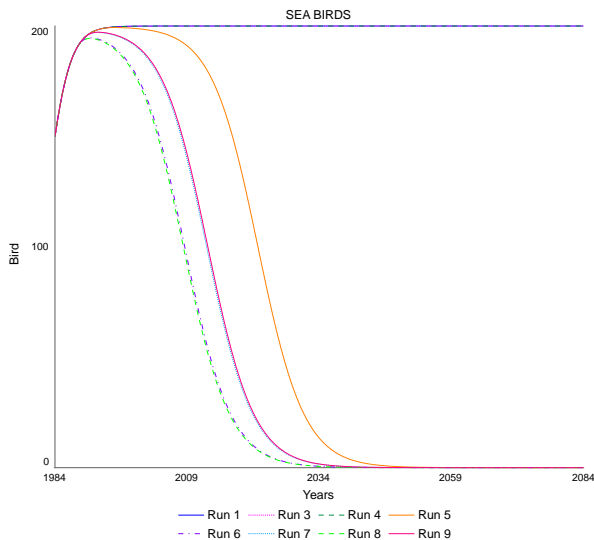The base run is the first graphical of the tested below:
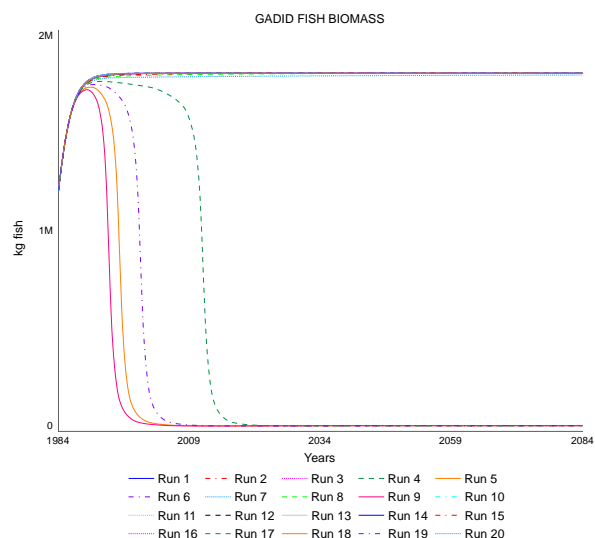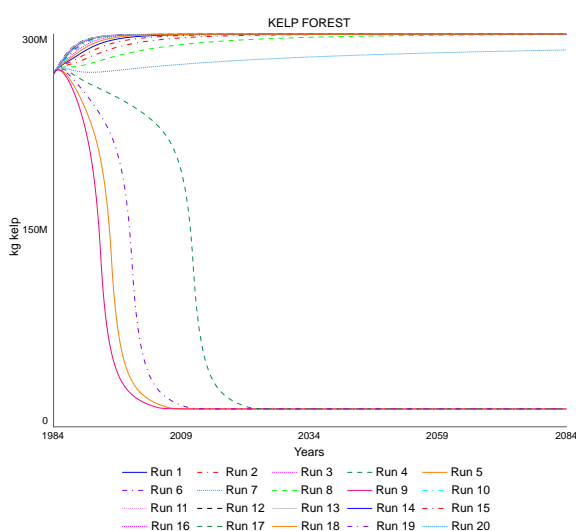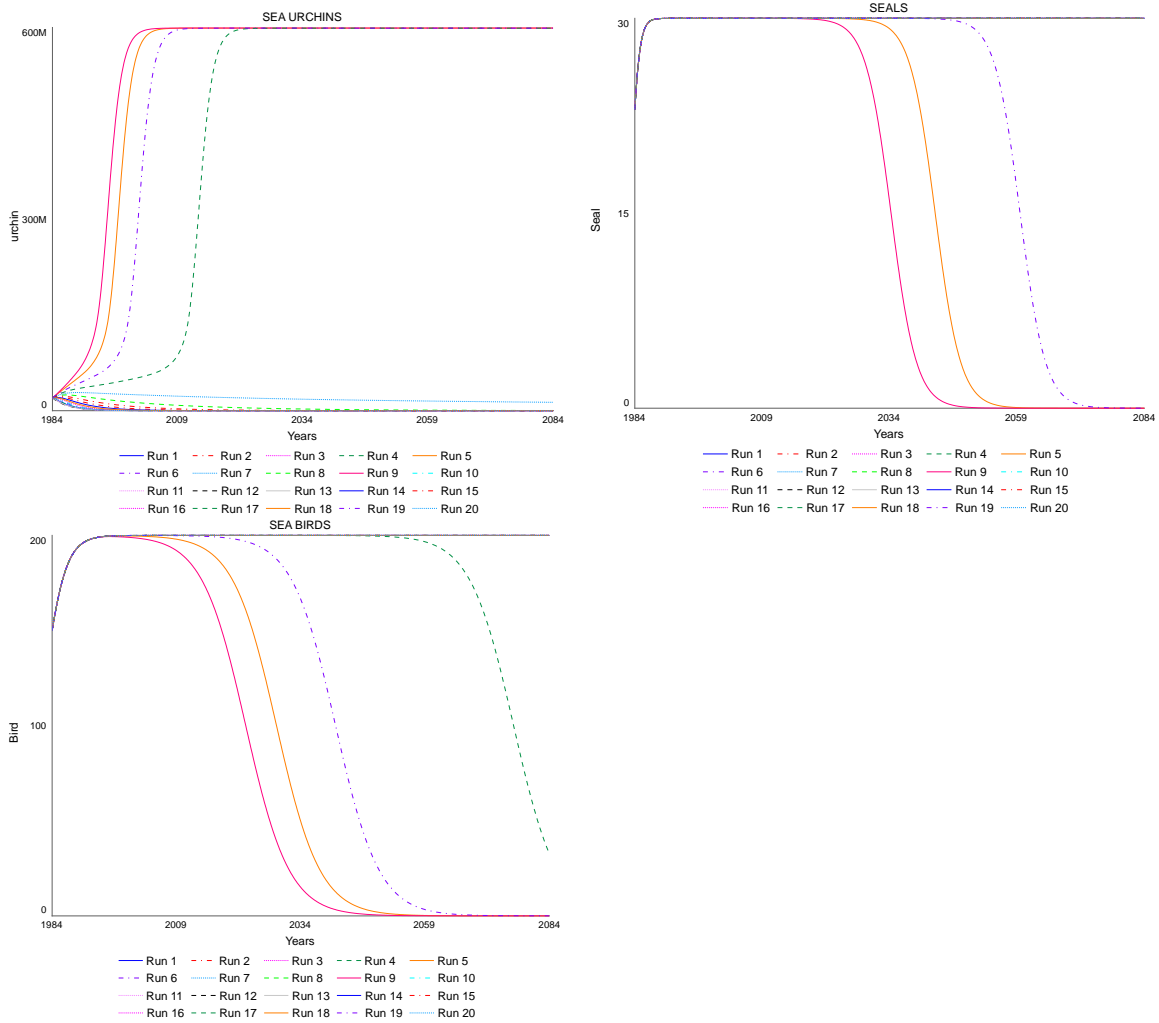
Behaviour:

SEA BIRDS
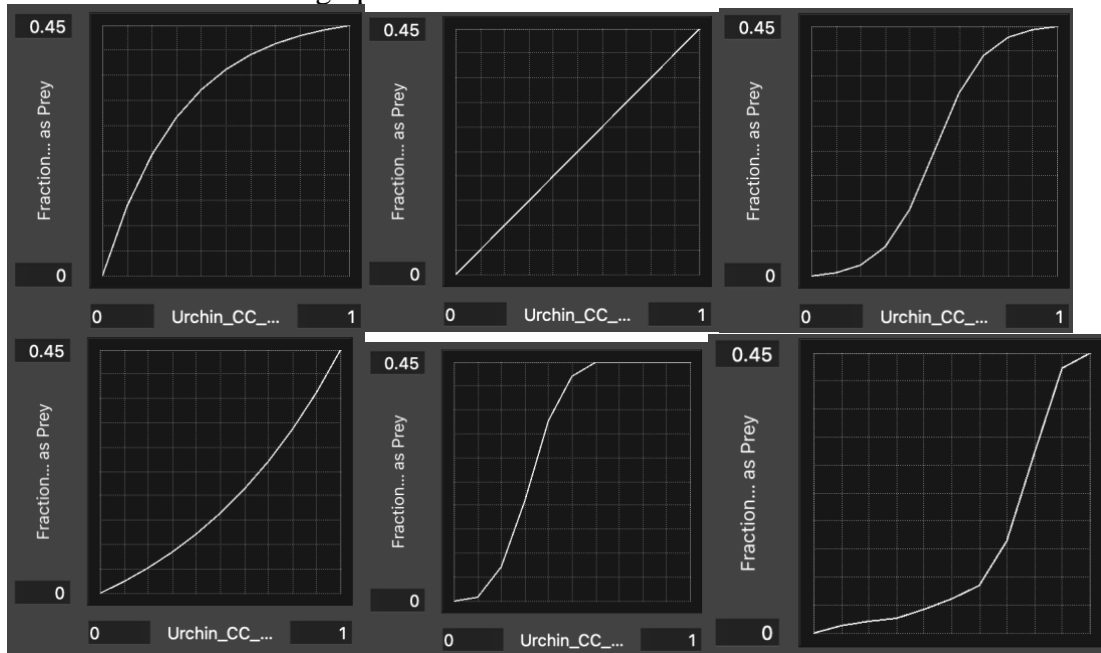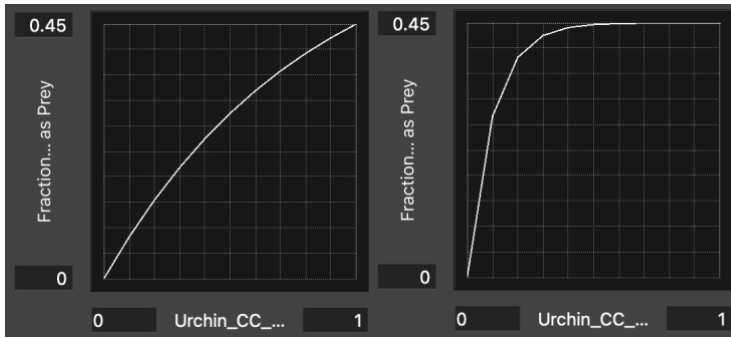
The model is sensitive to changes in the fraction of urchins that fish will prey on because the amount of urchins change. It resembles a density effect. The base run, with an upwards curve is a normal way to explain density effect of prey on predation and the percentage of urchin in diet which is 45% is an underestimation where the max could be closer to 70% which makes me confident on the base behaviour (Salvanes, p.13, 18; Norderhaug, et.al., 2020, p.166; Hagen, p.186; Morecroft, 2015, p.22; Swart, 1990, p.95).

- *Normal Kg Food pr Fish (0.425-0.9)*

The normal food consumption of the fish in the kelp forest is based on an average age of 3 y/o fish (the mean age is smaller), eating 850 g a year (Waiwood & Majkowski, 1984, p. 68). I do a 50% decrease for the sensitivity test, and for the increase I cap it at 9000 g because a bigger increase is unlikely as the average fish age will not be closer to 4 y/o than 3 and that the smaller age classes feed more on the benthic animals, based on the findings in Waiwood's paper at page 68 and Salvanes (Salvanes, 1992, p.19).

Behaviour:

KELP FOREST

GADID FISH BIOMASS

SEA URCHINS

SEALS

SEA BIRDS

The system is sensitive to changes in Normal kg Food for Fish because it is an almost direct controller of how much urchin that will be eaten. If the parameter value is low we see the expected behaviour of an increase in urchins and a decrease of the other stocks.

- *Avg Weight pr Fish (0.2-0.6)*

Base values are 0.35 kg. The range is based on weight finds of small gadid fish from 0.2 kg to 0.8 kg, where 0.6 kg is chosen due to any higher of that would not be representable as a possible average (Salvanes, 2004, p.245).

Behaviour:

KELP FOREST

GADID FISH BIOMASS

SEA URCHINS

SEALS

SEA BIRDS
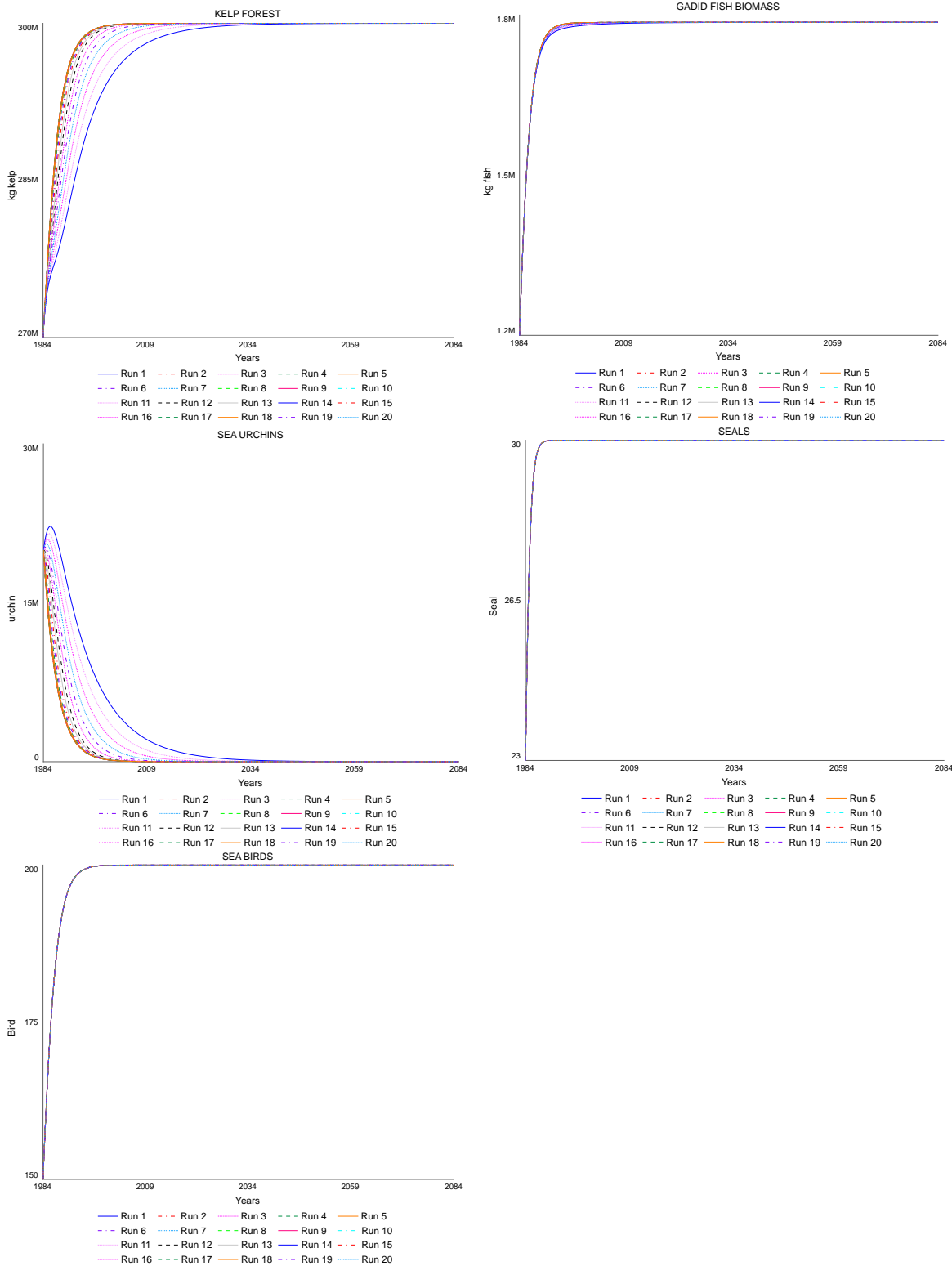
The parameter is slightly sensitive. If the average weight of fish is decreased there will be a higher number of fish with the same consumption habit per fish which increases the predation pressure. The reason why we see a slight increase in urchins is because the average weight is increased, thus the predation pressure is decreased, which is counteracted by the increase in kelp forest, thus predators and predation.

- *Fraction of Fish Harvested a Year (0.1-0.5)*

The normal percentage harvest of coastal cod is 20%. I have not found good estimations on local variations, but I think it is safe to assume that a 50% harvest of the stock has occurred, and that it will occur at some point. The lower fraction is set to 10%.

Behaviour:
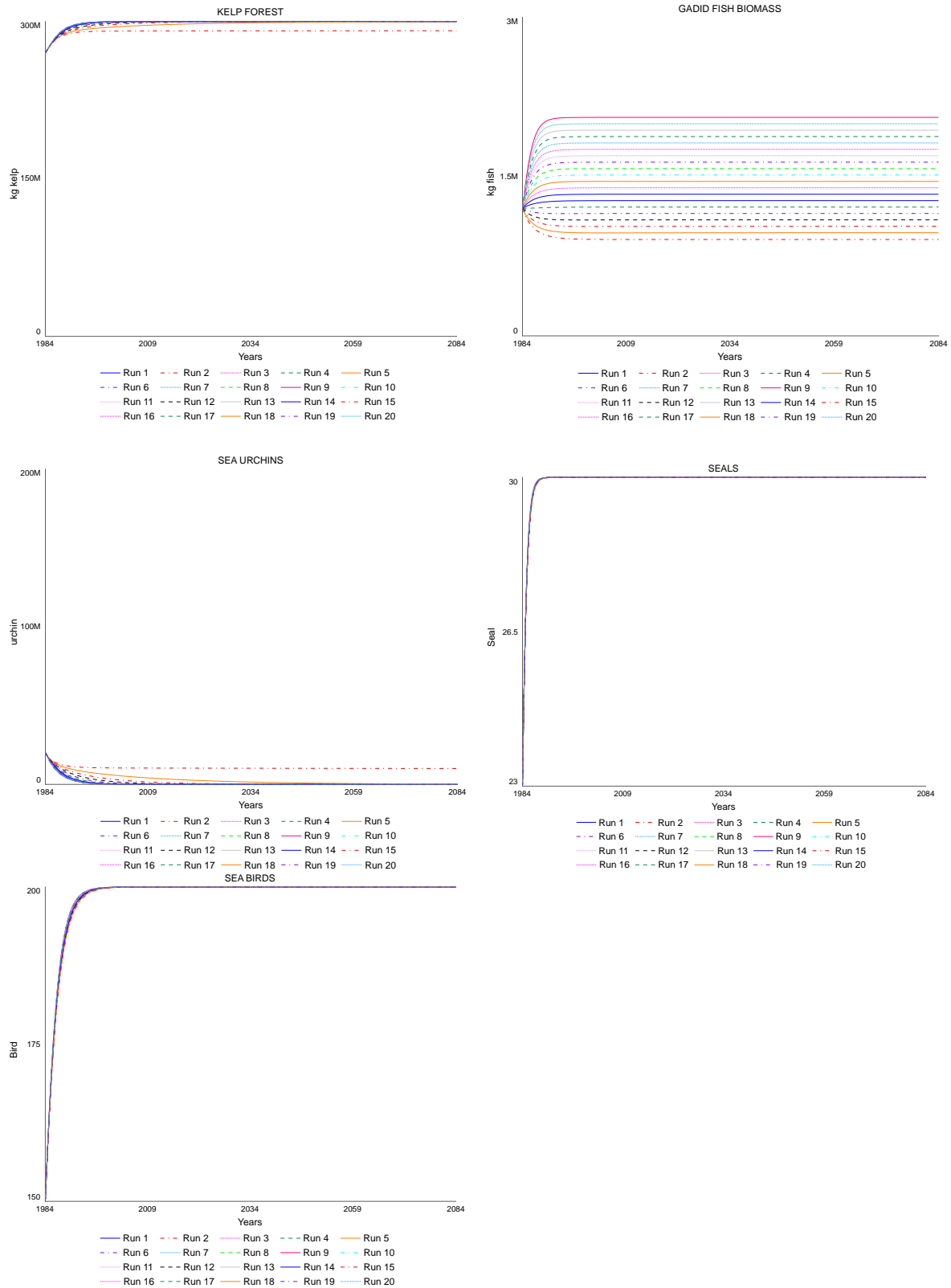
The model behaviour is not very sensitive to changes in the harvest of fish. Though the fish stock naturally will be sensitive, there are no noticeable changes elsewhere.

- *Initial FISH sqm (0.1-0.35)*

The base run is 0.12 fish per m^2 (Lorentsen et al., 2010, p. 2058). I set a slight lower number for the minimum test range and the upper to 0.35 from estimates from Vondolia (Vondolia et al., 2019, p. 39).
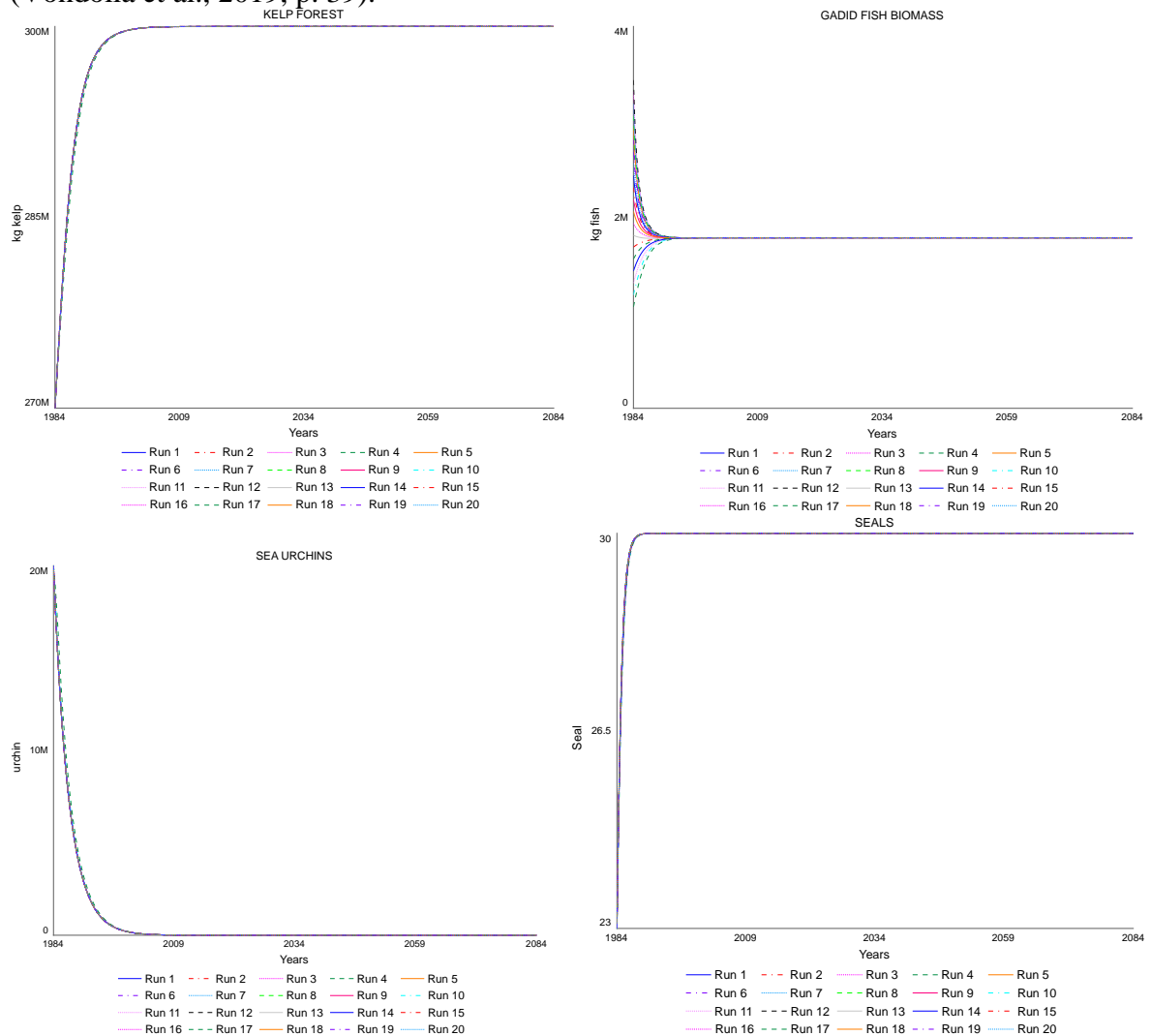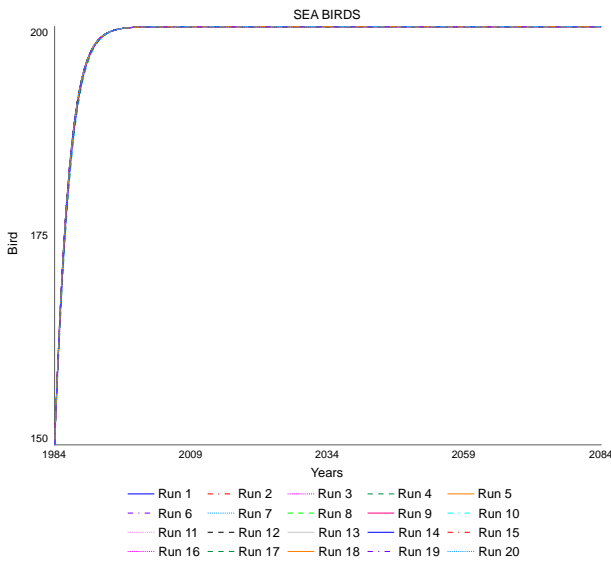
The parameter is not sensitive, unless we increase initial urchins close to the tipping point.

- *Fish CC pr sqm*

The base run value is 0.24 (see model validation of the parameter for the estimations). The range is 0.2-0.35 (Vondolia, 2019, p. 30, 39).

SEA BIRDS
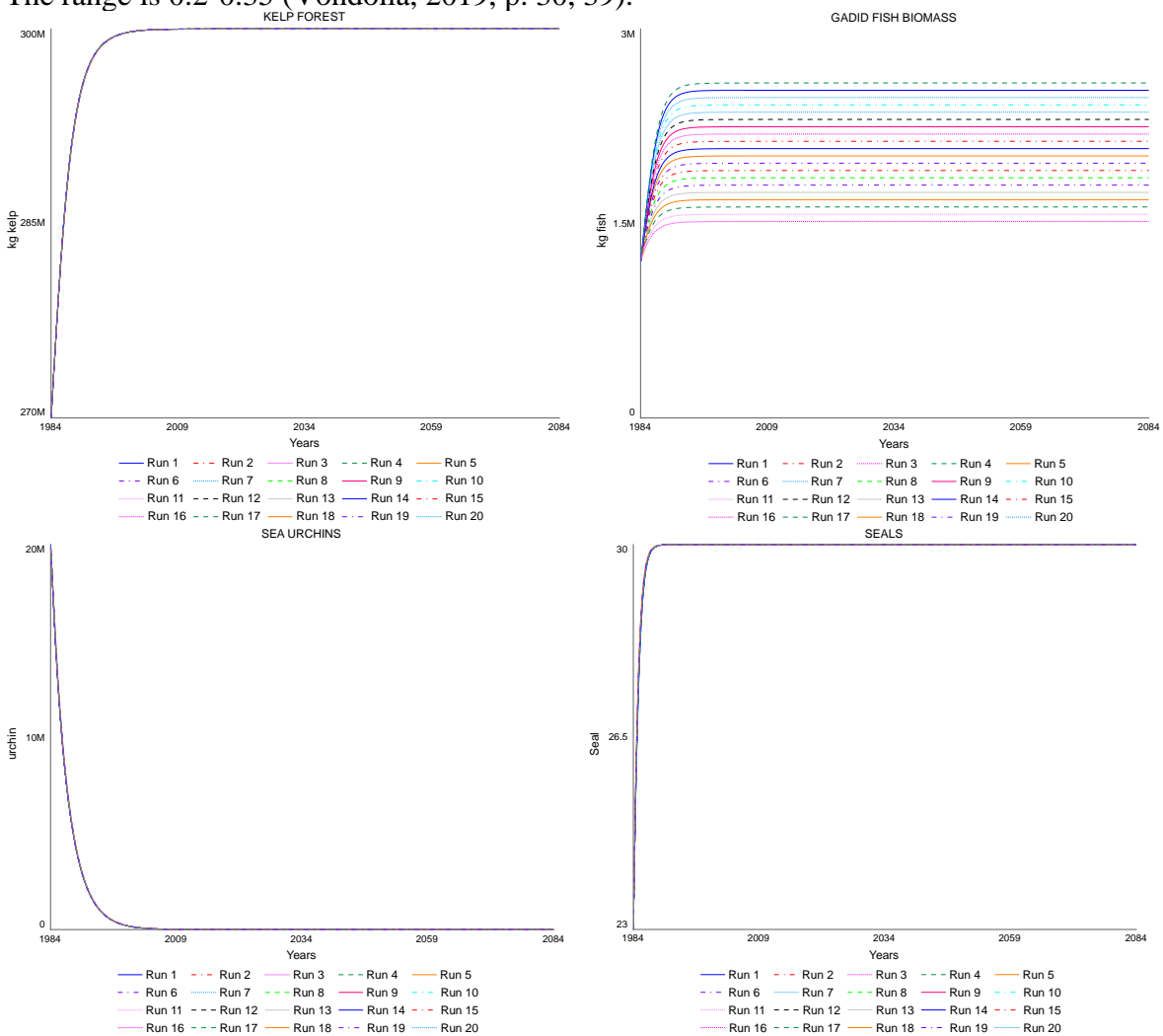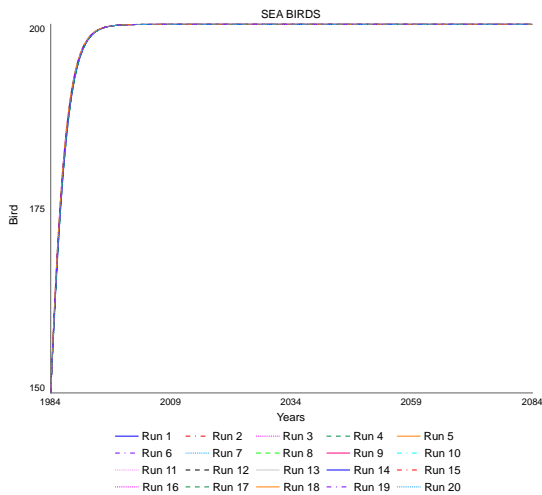
This parameter is not sensitive. The numerical changes in gadid fish is a natural cause of capping their maximum possible amount.

Apex Predators Sector: Seals

- *Local Seal Net Growth Fraction (Graphical)*

The first of the tested graphical shapes below is the base run:
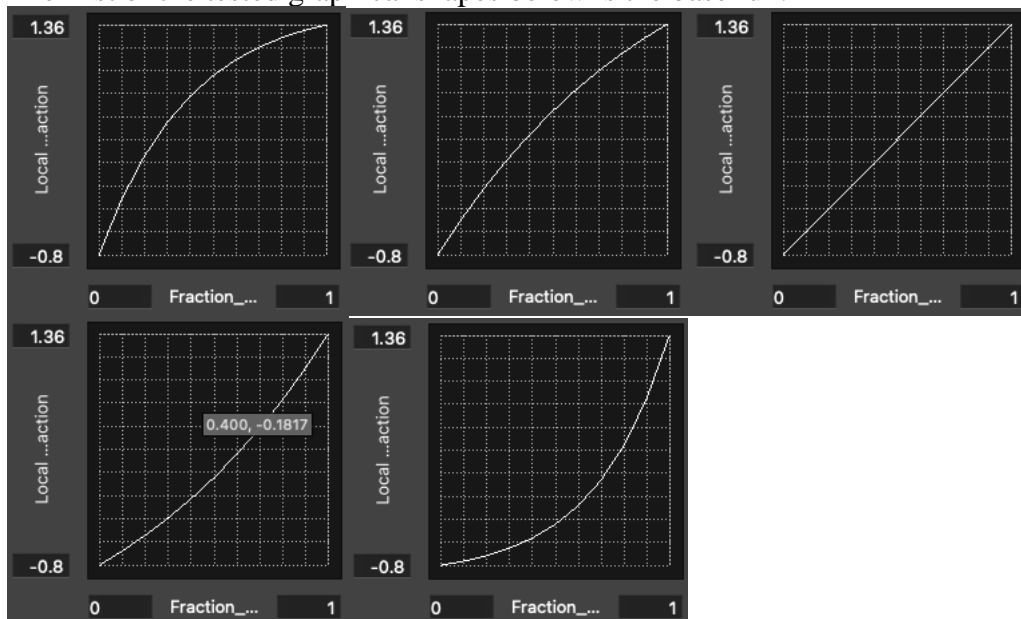
Behaviour:
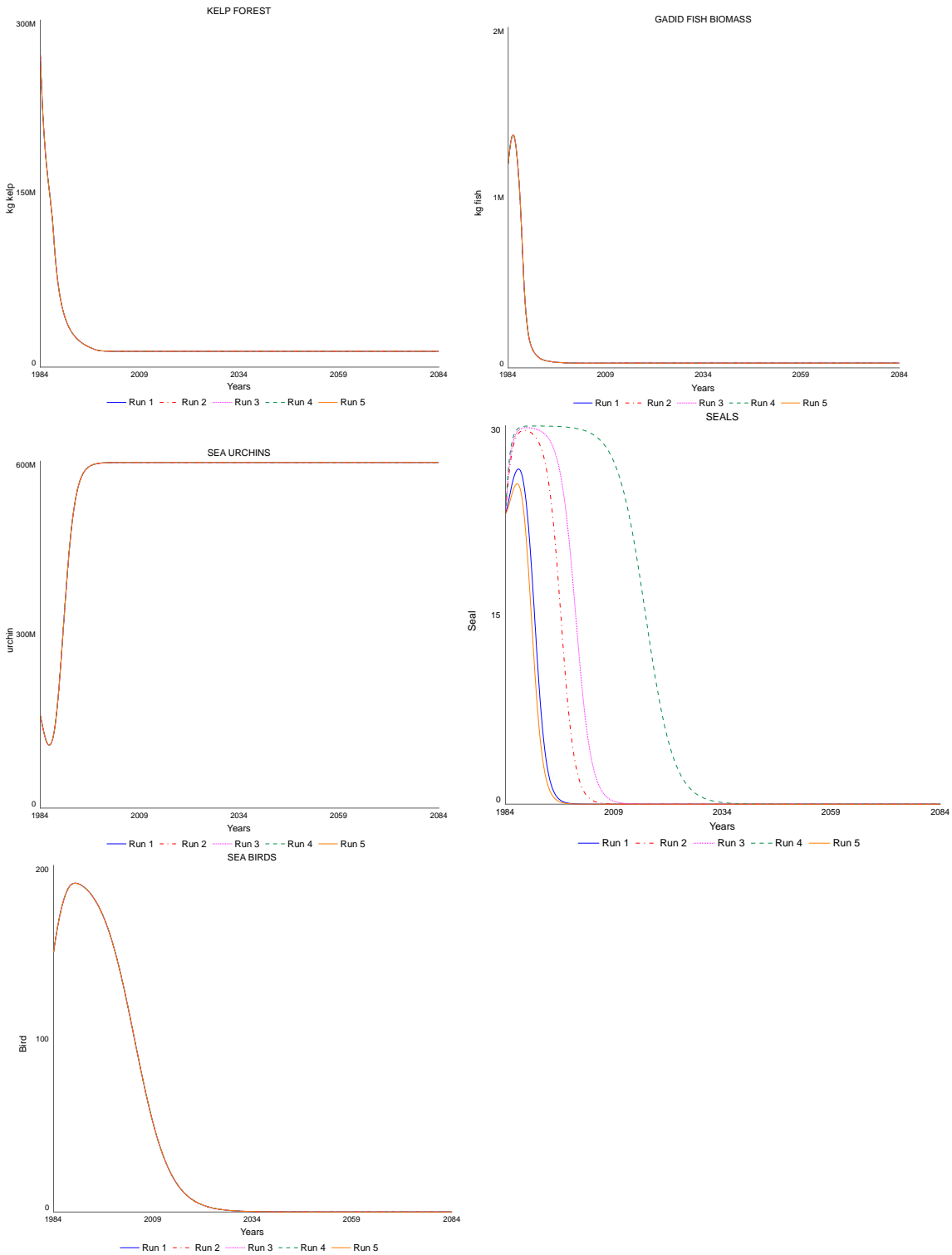
The systems behaviour is not sensitive to changes in seals growth fraction in base run. So, the results shown are with *Initial Urchin Sqm* set to 16. Where the only difference is seen in the Seal stock and is numerical not behavioural. It is expected that the seal stock does not affect the rest of the system because of their low predation pressure on fish, but that low fish stock will affect the seals. The base curved is based on other predator prey models with graphical effects on growth, which gives a fair confidence. The actual rate range is poorer documented, especially since the model does not consider a whole seal population, but those that forage in the kelp forest.

- *Effect of Fish Abundance on Seal feeding in kelp forest (Graphical)*

The tested shapes in the graphical function us below, where the first one is the base run (highest upward curve).

Behaviour:

SEA URCHINS

SEALS

SEA BIRDS
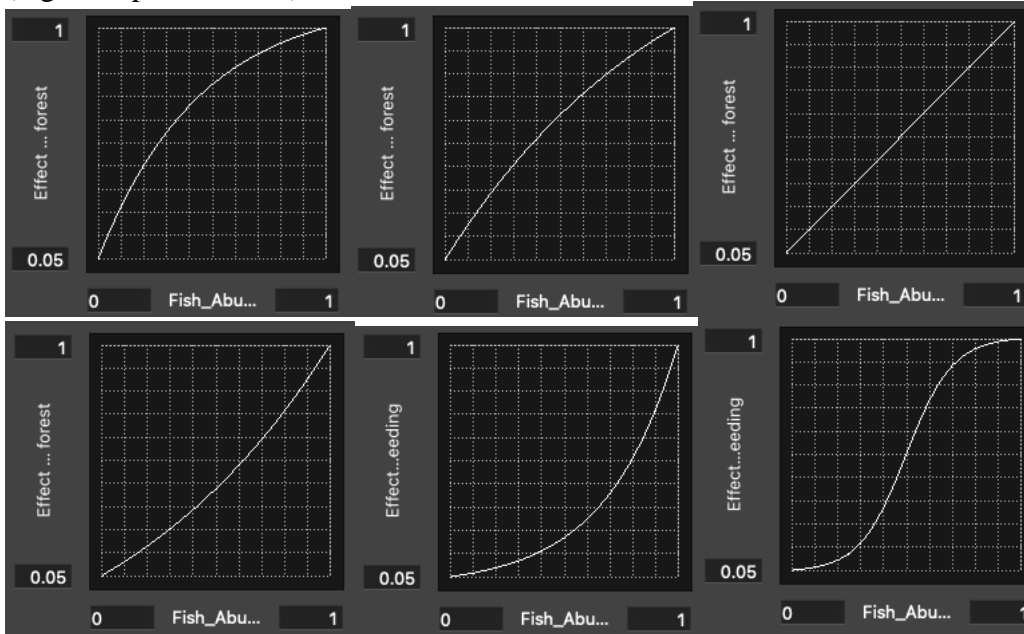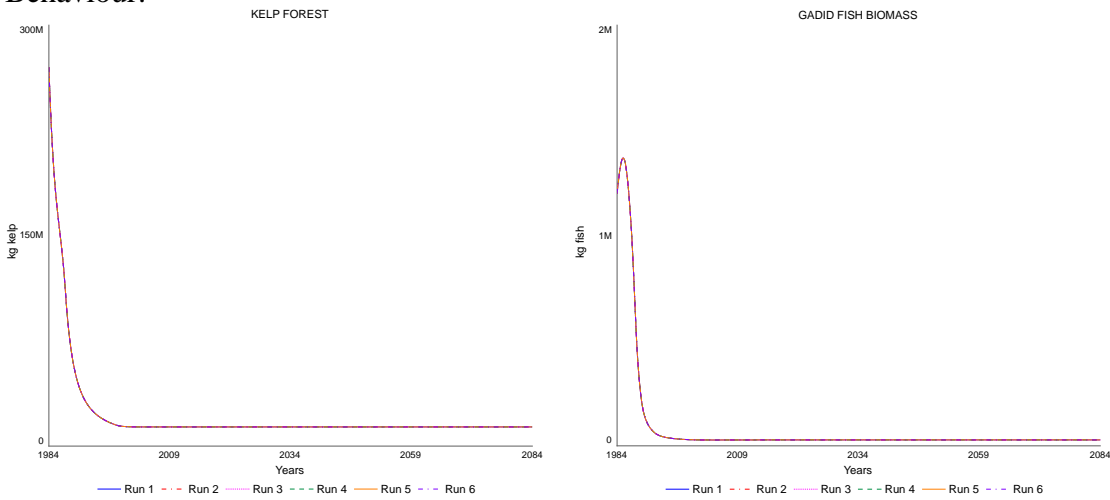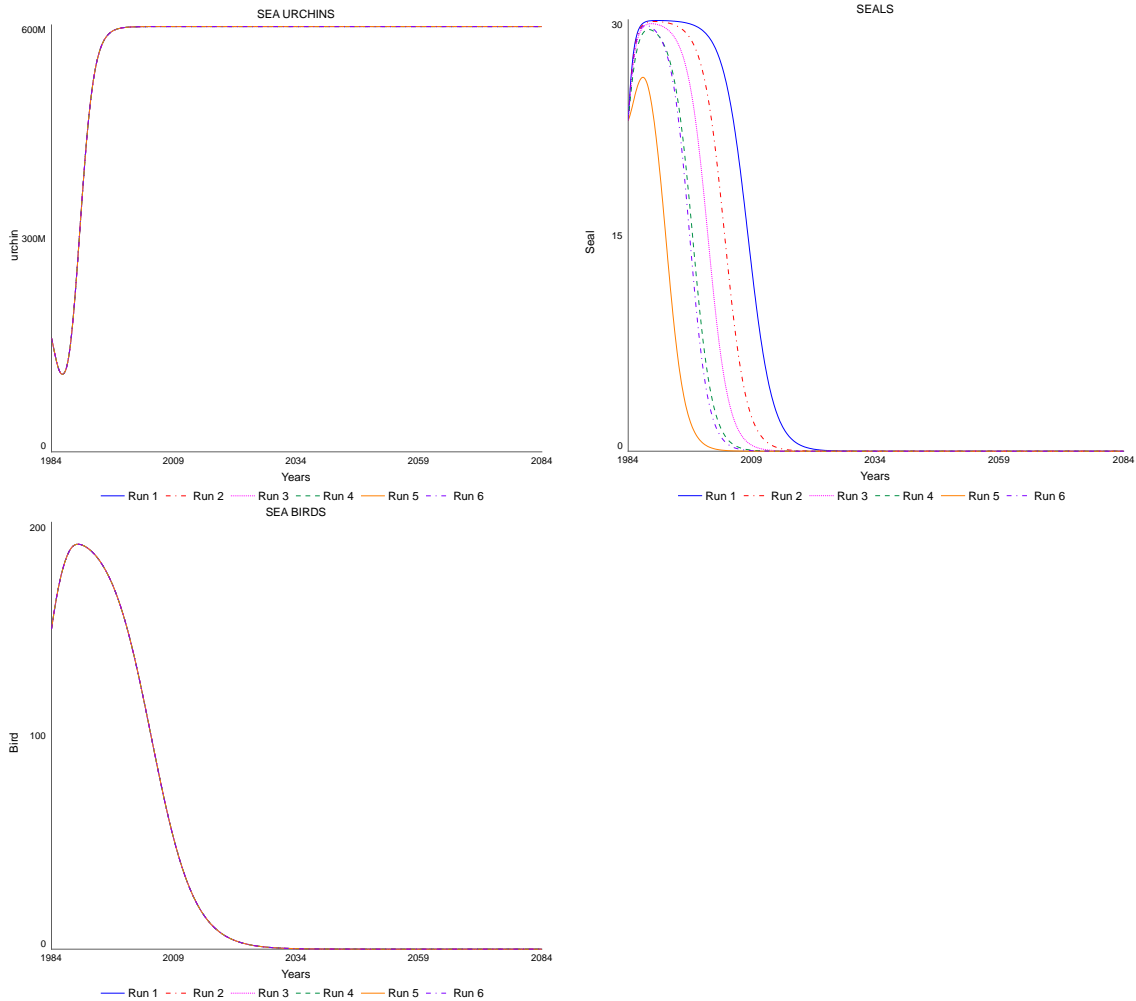
Tested with 16 Initial Urchins due to no effects in the kelp stable state. The parameter is does not change any behaviour in the system expect of numerical changes to the seal stock itself. With more lower values in this parameter the quicker the population will fall, which is expected from a lower catch of fish for seals will decrease their growth rate.

The base run shape is based on common density effects on predation pressure on fish (Morecroft, 2015, p. 22; Swart, 1990, p. 95).

- *Desired kg Fish from kelp forest pr Seal a Year (2-6 kg)*
The base run of desired fish pr seal is 4 kg (Bjørge et al., 2002, pp. 35, 37). The range for testing is set to be 50% up and down from the base run.

Behaviour:

KELP FOREST

GADID FISH BIOMASS

SEA URCHINS

SEALS
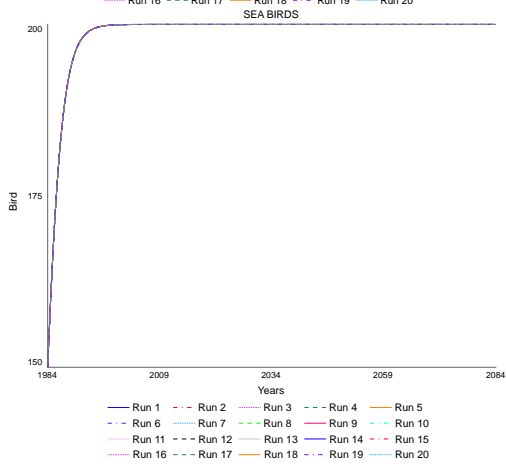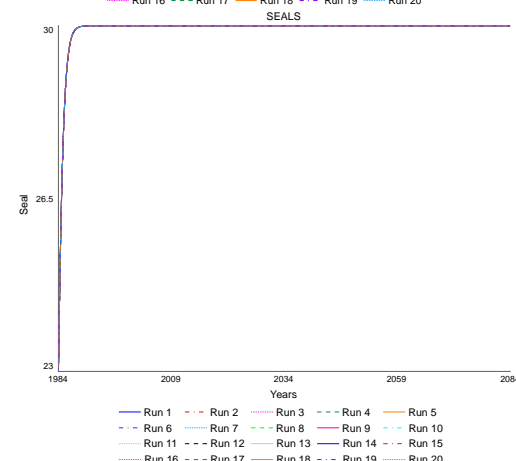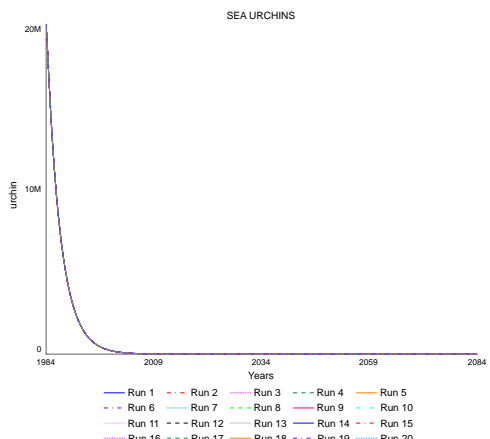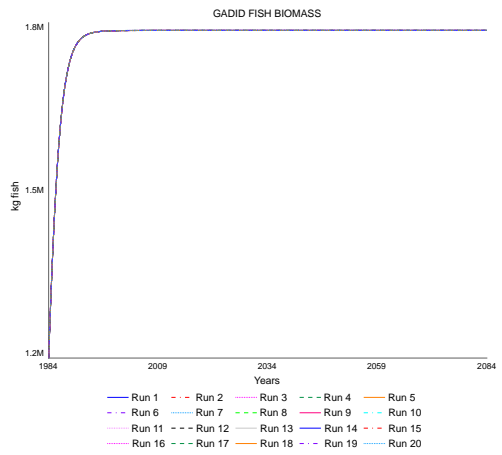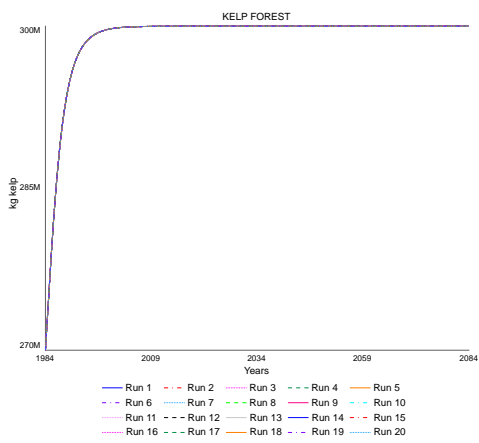
SEA BIRDS

This parameter is not sensitive and confident.

## Apex Predators Sector: Sea Birds

- _Local Bird Net Growth Fraction_

The first of the tested graphical shapes below is the base run.
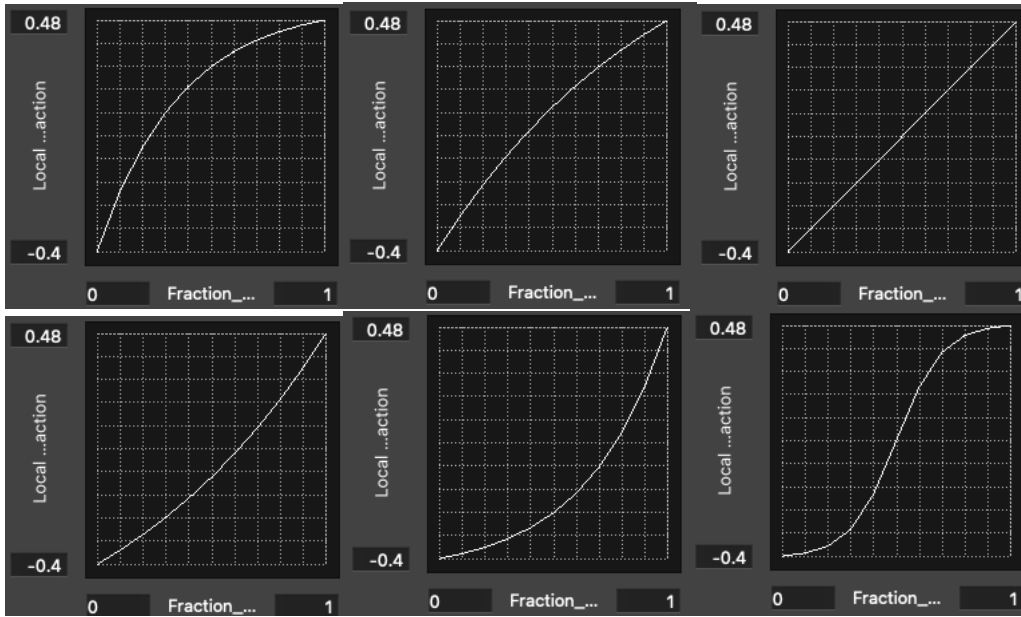
To see the effect in behaviour of changes to the parameter more clearly, the system is initiated with 16 urchins:
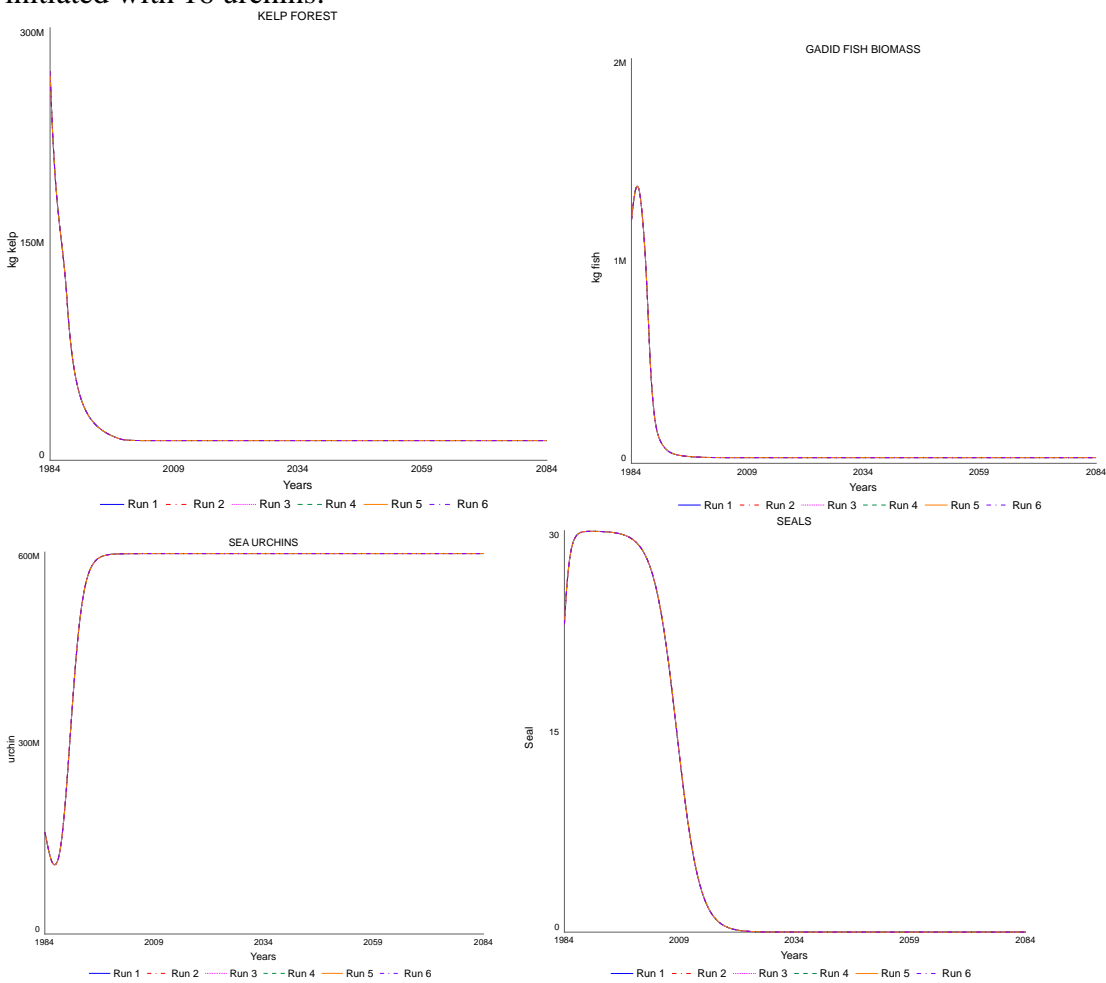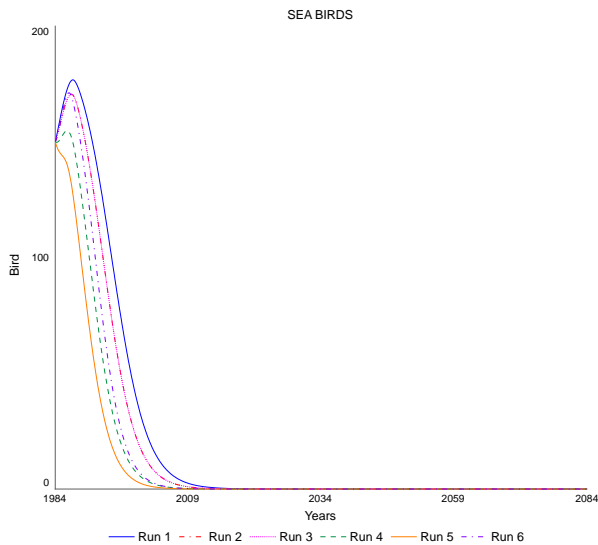
SEA BIRDS

The system is not sensitive to changes in this parameter from the base run. And with 16 urchins, the only difference is seen in the *Sea Birds* stock where an initial and consistent low value disable the population to firstly increase, but rather decreases at once.

- *Effect of Fish Abundance on Bird feeding (Graphical)*

The first of the tested graphical shapes below is the base run. The minimum value oof 0.05, is based on findings of birds that forage in barren grounds (Bustnes et al., 1997, p. 17). The base shape is a common way to represent the density effect on predation pressure on fish (Morecroft, 2015, p. 22; Swart, 1990, p. 95).
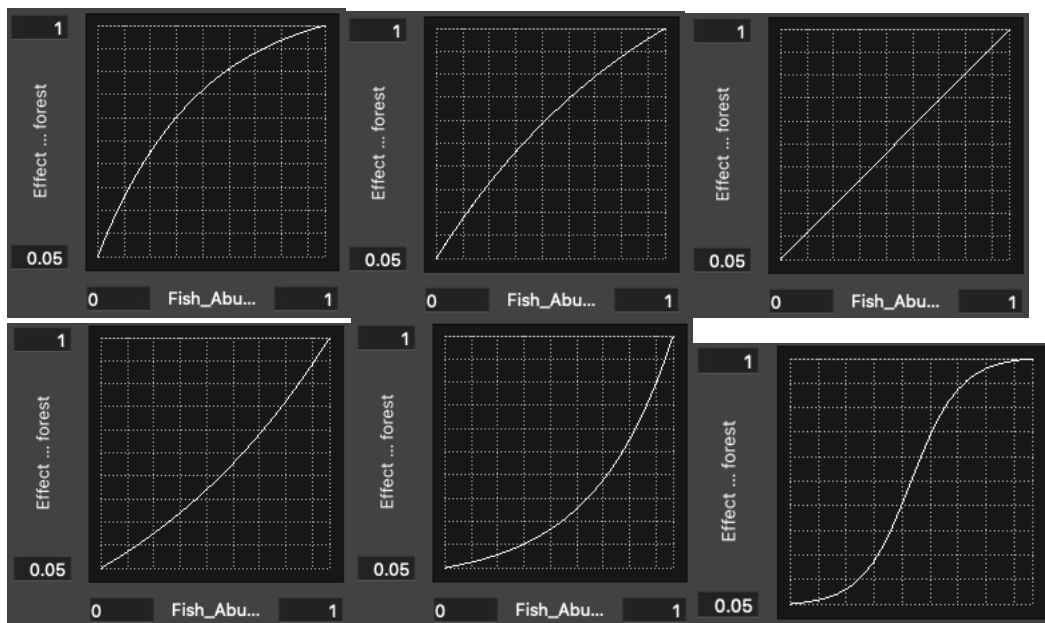
Behaviour:
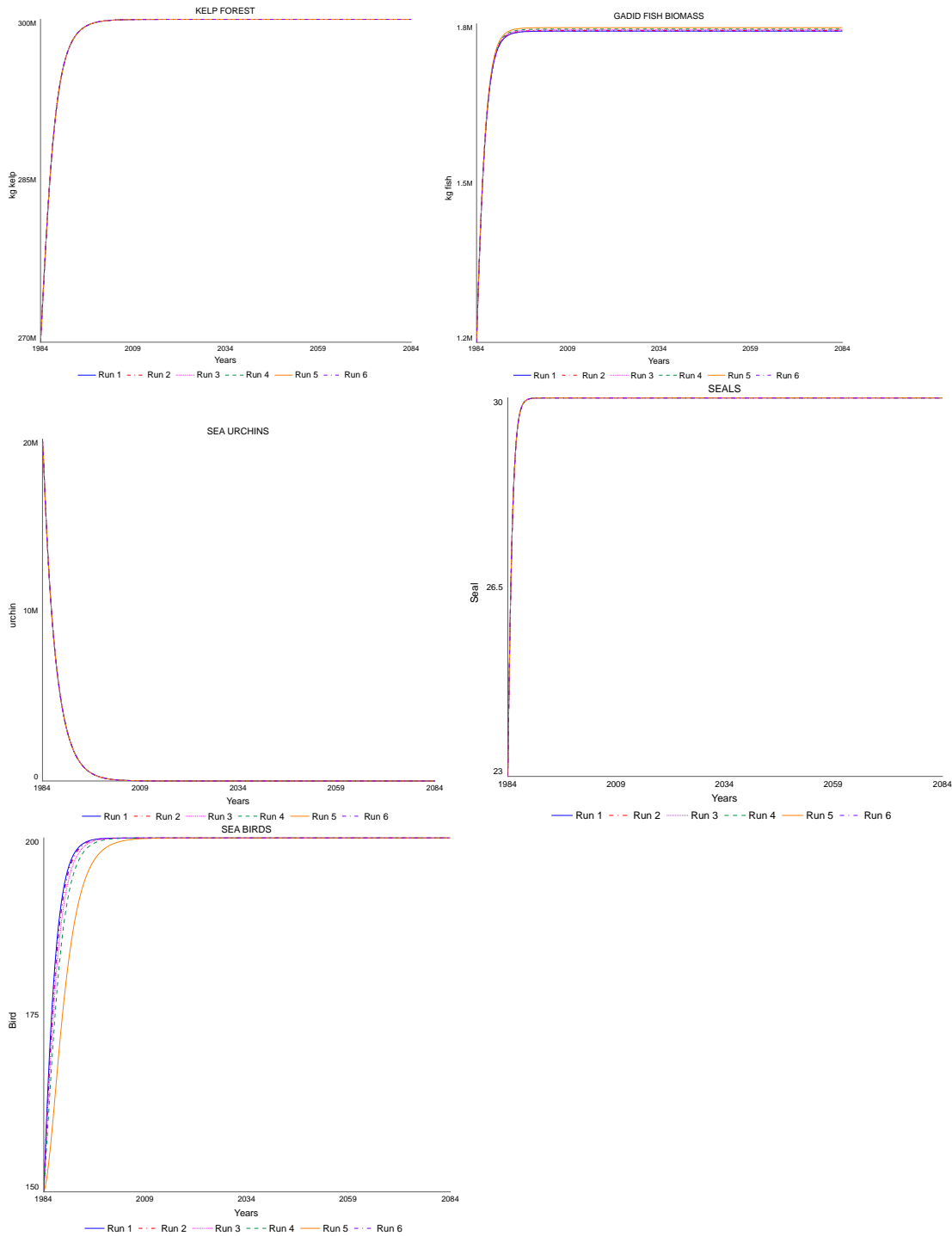
The model is not sensitive to changes in this parameter.

- *Desired Fish from kelp forest pr Bird a year (35-53 kg)*

The base run is 44 kg, and the range is based on observed gadid fish eaten by birds (Bustnes et al., 1997, p. 19; Lorentsen et al., 2004, p. 166; Saraux et al., 2020, p. 266).

Behaviour:

KELP FOREST

GADID FISH BIOMASS

SEA URCHINS

SEALS

SEA BIRDS
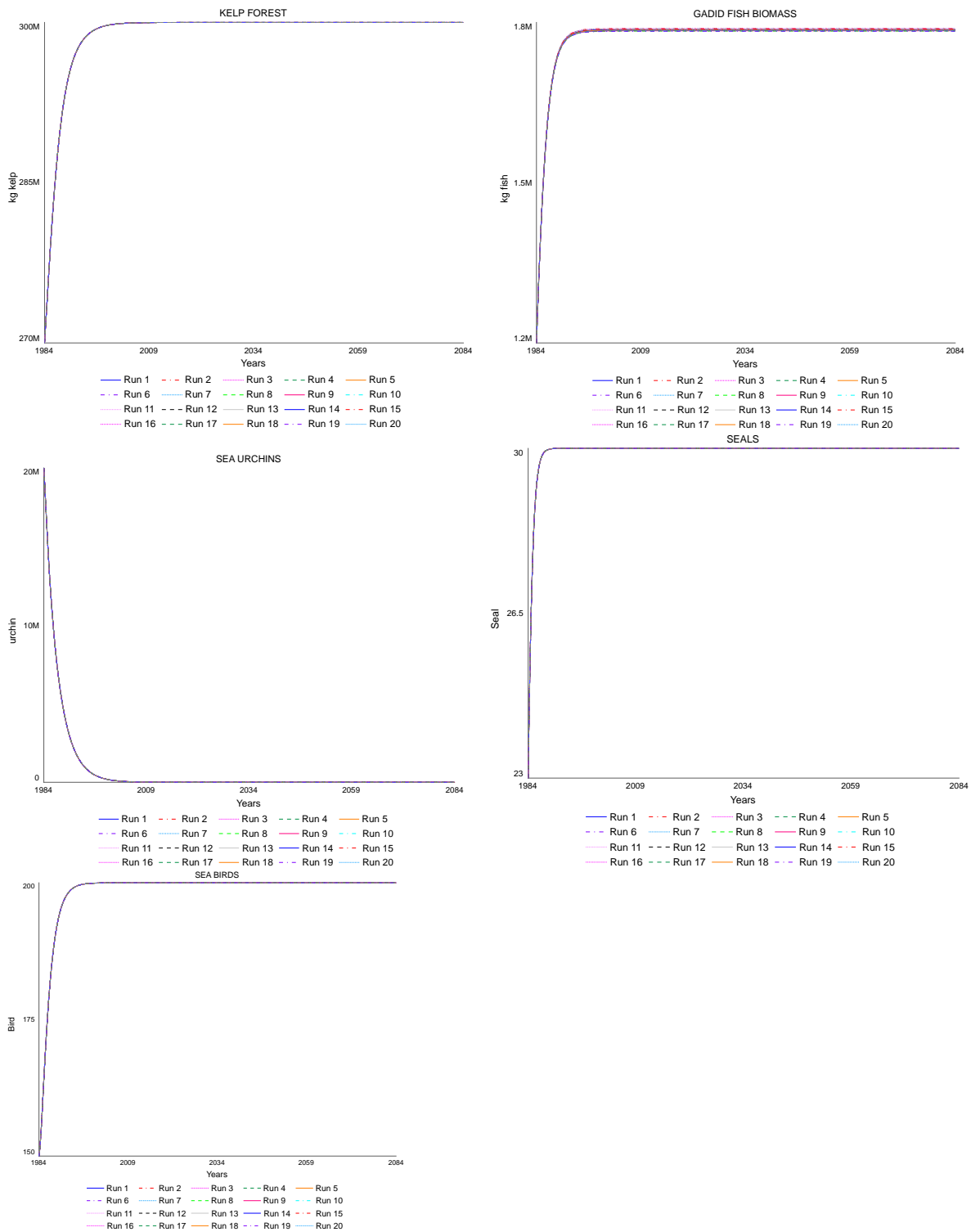
The parameter is not sensitive and confident.

- *Initial SEAL sqm (0.00000115-0.00000345)*

Base run value is 0.0000023 seals pr m^2, based on the CC. The range is 50% increase and decrease of the base run.
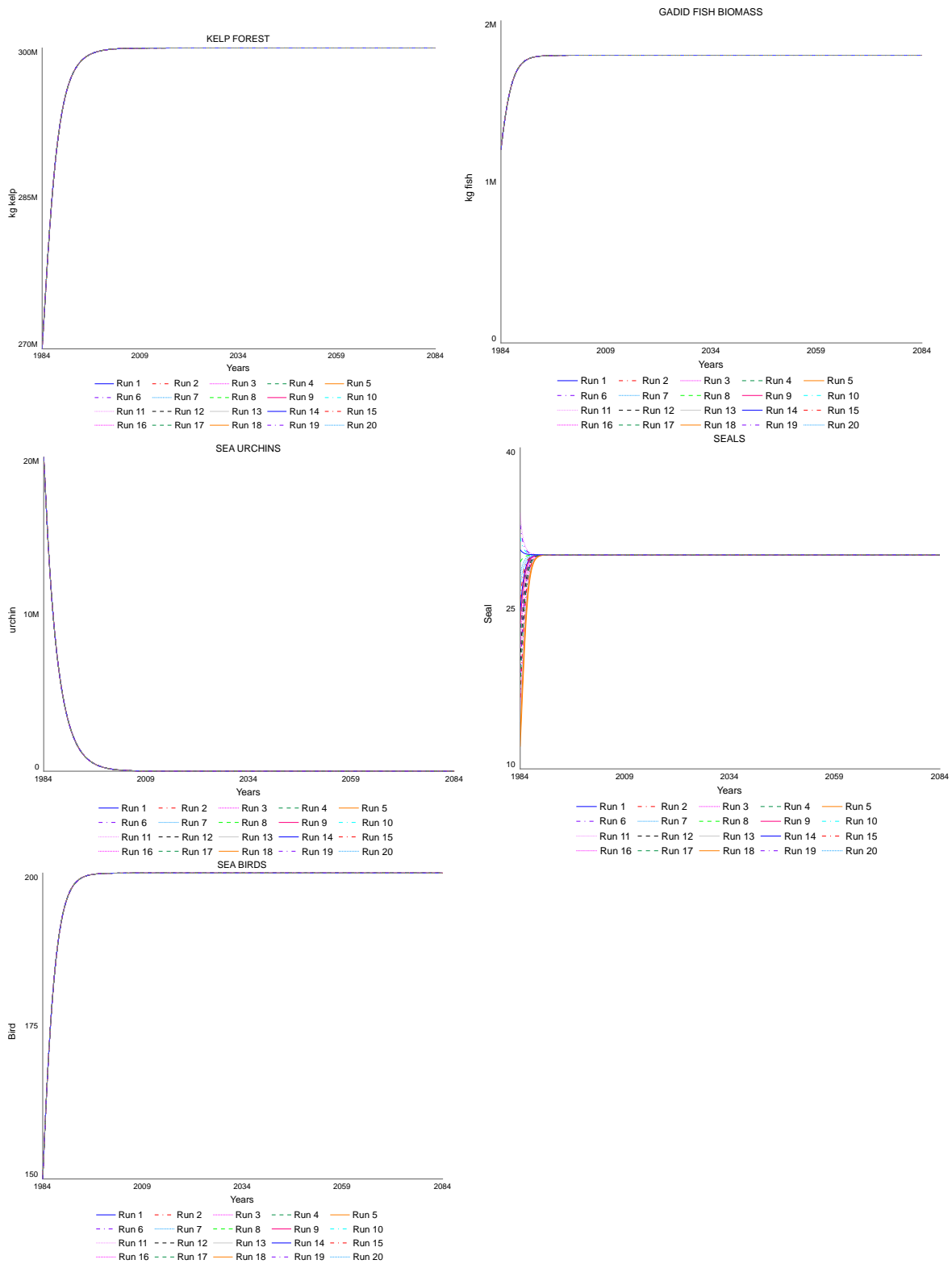
KELP FOREST

GADID FISH BIOMASS

SEA URCHINS

SEALS

SEA BIRDS

This parameter is not sensitive, as expected, because the pressure from seals on the fish stock is minimal.

- *Seal CC pr sqm (0.0000012-0.0000036)*

The base value of seal CC pr m^2 is 0.0000024 (Bjørge et al., 2002, pp. 35, 37). The test range is 50% up and down.
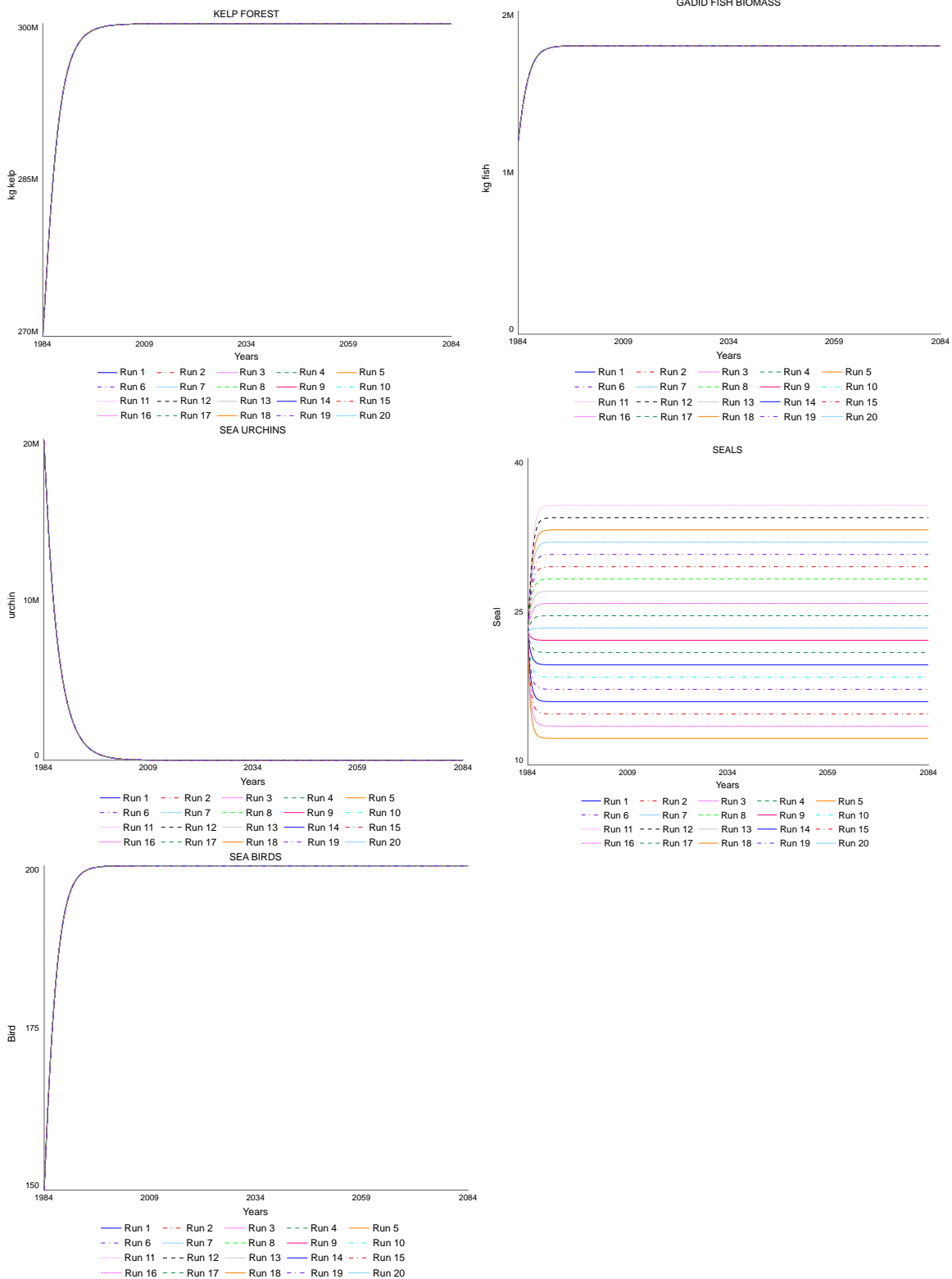
KELP FOREST

GADID FISH BIOMASS

SEA URCHINS

SEALS

SEA BIRDS

This parameter is not sensitive, as expected, because the pressure from seals on the fish stock is minimal.

- *Initial Birds sqm (0.0000075-0.0000225)*

The base value is 0.000015 birds pr m^2 (see Model Validation of this parameter for the estimates). The range is set to 50% up and down from the base value.
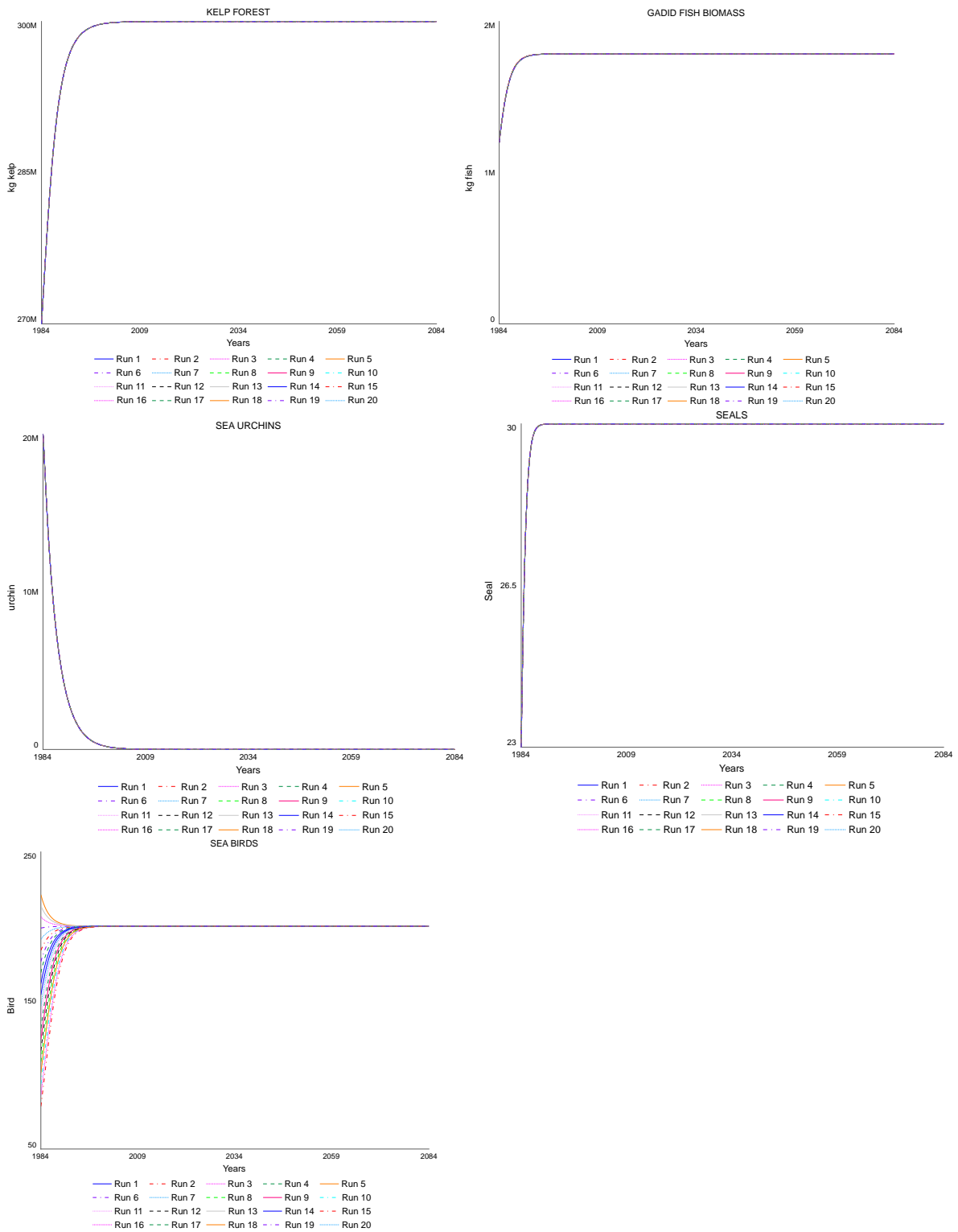
This parameter is not sensitive, as expected, because the pressure from sea birds on the fish stock is minimal.

- *Bird CC pr sqm (0.00001-0.00003)*
The base run is 0.00002, based on the estimations of initial sea birds. The test runs are set within a range of 50% increase and decrease of the base run.
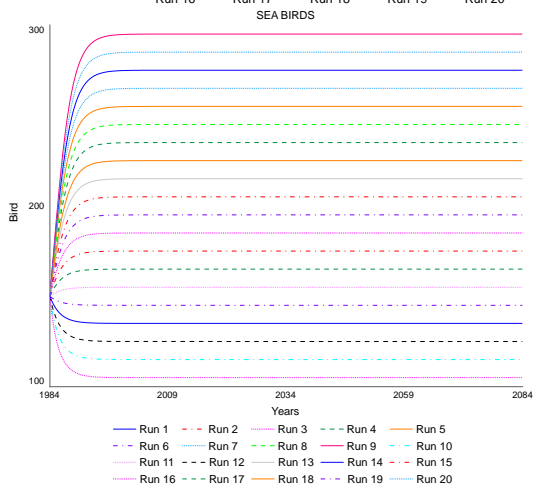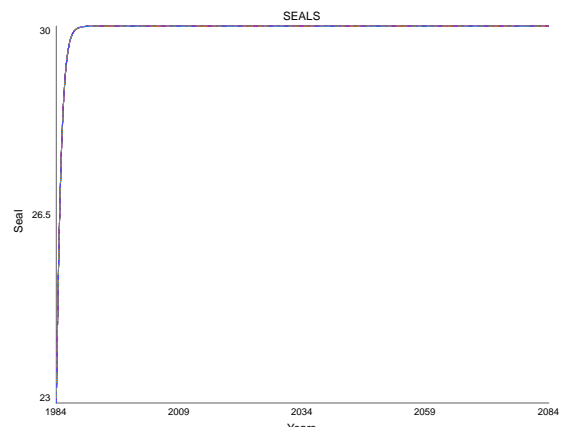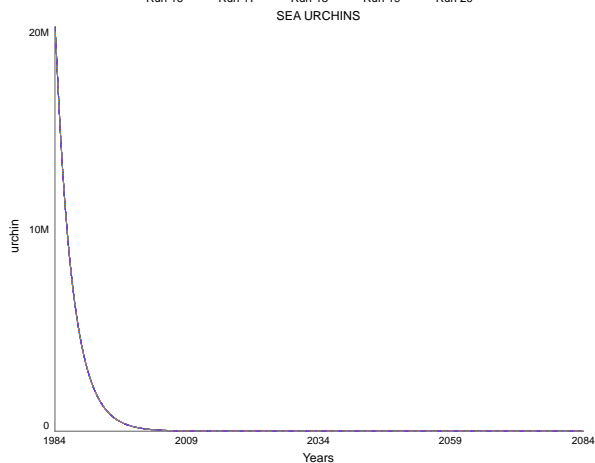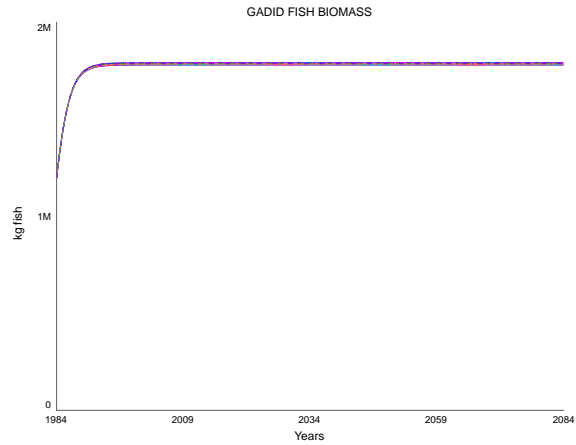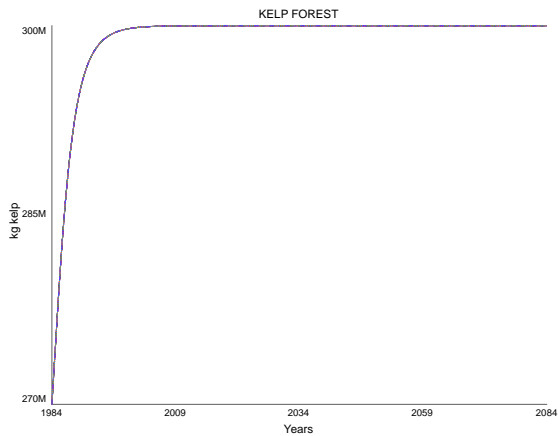
KELP FOREST

GADID FISH BIOMASS

SEA URCHINS

SEALS

SEA BIRDS

This parameter is not sensitive, as expected, because the pressure from sea birds on the fish stock is minimal.

Appendix B – Model Documentation

	Equation	Properties	Units	Documentation	Annotation
Apex_Predator_Sector:					
CC_Utilization_Birds	SEA_BIRDS/Total_CC_Birds		dmnl	The bird stock is divided on the Total CC Birds to find the percentage bird left of the carrying capacity.	
CC_utilization_SEAL	SEALS/Total_CC_SEAL		dmnl	The seal stock is divided on the Total CC Seal to find the percentage seal left of the carrying capacity.	
Desired_Fish_from_kelp_forest_pr_Bird_a_year	44		kg fish/Bird/year	Votier found that seabirds consume 15-20% of their bodyweight (Votier & Sherley, 2017), but Saraux found that seabirds needs to consume 30-80% of their mass daily. With the wide range in consumption, the average intake is 35% of their weight a day. An average of seabird body mass from the Norwegian sea is 460 g (Saraux et al., 2020, p. 266). 460g = 0.46kg, which 35% of is 0.161 a day. In a year that is 58.7 kg. Further, seabirds eat mostly young Gadid fish, making up approx. 60-90% of their diet (Bustnes et al., 1997, p. 19; Lorentsen et al., 2004, p. 166). That is an average of 75% of diet. 58.7 x 0.75 = 44 kg fish pr year.	
Desired_kg_Fish_from_kelp_forest_pr_Seal_a_Year	4		kg fish/Seal/year	The desired amount of fish per seal from the kelp forest. Two seals forage ca. 8 kg (4.7+3.2) of fish from kelp forest each year (Bjørge et al., 2002, pp. 35, 37). Making it 4 kg pr seal.	
Effect_of_Fish_Abundance_on_Bird_feeding_in_kelp_forest	GRAPH(Fish_Abundance) Points: (0.000, 0.0500), (0.0384615384615, 0.1378), (0.0769230769231, 0.2183), (0.115384615385, 0.2922), (0.153846153846, 0.3599), (0.192307692308, 0.4221), (0.230769230769, 0.4792), (0.269230769231, 0.5315),		dmnl	It is found that sea birds favour kelp forest as habitat using up to a 100% of their foraging ground in kelp forests. But sea birds can also use up to 20%, more common 10%, of their foraging area in barren grounds. I will thus assume that their foraging pressure only decreases to 5% when fish abundance is low (Bustnes et al., 1997, p. 17). I use a concave curve as the effect of density or abundance (from 0 to 1) of fish on predation pressure as it is a common way to explain the predation	

	(0.307692307692, 0.5795), (0.346153846154, 0.6236), (0.384615384615, 0.6640), (0.423076923077, 0.7011), (0.461538461538, 0.7351), (0.500, 0.7663), (0.538461538462, 0.7949), (0.576923076923, 0.8212), (0.615384615385, 0.8453), (0.653846153846, 0.8674), (0.692307692308, 0.8877), (0.730769230769, 0.9063), (0.769230769231, 0.9234), (0.807692307692, 0.9391), (0.846153846154, 0.9534), (0.884615384615, 0.9666), (0.923076923077, 0.9787), (0.961538461538, 0.9898), (1.000, 1.0000)			pressure on fish population based on attributes of fish behaviour and composition (Morecroft, 2015, p. 22; Swart, 1990, p. 95).	
Effect_of_Fish_Abundance_on_Seal_feeding_in_kelp_forest	GRAPH(Fish_Abundance) Points: (0.000, 0.0500), (0.050, 0.1627), (0.100, 0.2634), (0.150, 0.3534), (0.200, 0.4339), (0.250, 0.5059), (0.300, 0.5702), (0.350, 0.6278), (0.400, 0.6792), (0.450, 0.7252), (0.500, 0.7663), (0.550, 0.8030), (0.600, 0.8359), (0.650, 0.8653), (0.700, 0.8916), (0.750, 0.9150), (0.800, 0.9360), (0.850, 0.9548), (0.900, 0.9716), (0.950, 0.9866), (1.000, 1.0000)	dmnl	Knowing that fish predate on urchin, there will probably be some fish swimming in the barren areas if there is some kelp forest in proximity. Thus, I assume that foraging by seals in areas with low fish abundance will be at least a bit more than zero. I set it to the same as for birds as that is the only number I got on such a relationship. 0.05. I use a concave curve as the effect of density or abundance (from 0 to 1) on predation pressure as it is a common way to explain the predation pressure on fish population based on attributes of fish behaviour and composition (Morecroft, 2015, p. 22; Swart, 1990, p. 95).	
Fraction_Of_Desired_Fish_for_Seal	(Fish_Predated*(1-Fraction_of_predation_allocator_birds))//Total_Desired_Fish_for_Seal	dmnl	The total predation pressure from birds and seals is then separated with its respective fraction and divided by the desired amount of fish, also seen as the amount of fish needed to uphold a growth rate that will keep the population close to the carrying capacity, giving us a fraction.	

Fraction_of_Desired_Fish_pr_Bird	(Fish_Predated*Fraction_of_predation_allocator_birds)//Total_Desired_Fish_for_Bird		dmnl	The total predation pressure from birds and seals is here separated with its respective fraction and divided by the desired amount of fish, also seen as the amount of fish needed to uphold a growth rate that will keep the population close to the carrying capacity, giving us a fraction.
Fraction_of_predation_allocator_birds	Total_Fish_for_Birds//(Total_Fish_for_Birds+Total_Fish_for_Seals)		dmnl	The weight of fish predated by birds and seals are divided to get the fraction of their respective predation pressure which is combined in the predation outflow of the fish stock, so I can use the value of the outflow from predation on fish to affect the growth rate of each predator by separating the combined rate through this fraction.
Local_Bird_Net_Growth_Fraction	GRAPH(Fraction_of_Desired_Fish_pr_Bird) Points: (0.000, -0.4000), (0.100, -0.1740), (0.200, -0.002291), (0.300, 0.1281), (0.400, 0.2272), (0.500, 0.3024), (0.600, 0.3596), (0.700, 0.4030), (0.800, 0.4359), (0.900, 0.4610), (1.000, 0.4800)		dmnl/year	The fraction predated fish of the desired amount is put into a table function which shows the effect of their total foraging success on the net growth of the bird population. If they get less fish than they desire the growth rate will decrease from its maximum growth rate. If food is scarce the growth rate will go to minus, decreasing the total population. Maximal growth rate is derived from Norway (Bustnes et al., 2013). In Fig.3 at page 238, the highest growth rate was about 1.2 and the lowest -1. And, at page 242, they state that food availability explains up to 40% of the variation in population. Since I am not modelling other factors, the growth rates will be from 1.2x0.4 = 0.48 to -1x0.4 = -0.4. The choice of graphical shape, a curved line being steep towards zero, is based on that seabird mortality does not increase much before the food resources are scarce (Cairns, 1988, pp. 262-263).
Local_Net_Growth_Birds	((SEA_BIRDS*Local_Bird_Net_Growth_Fraction)*(1-CC_Utilization_Birds))		Bird/Years	The in- and outflow of the bird stock. The net growth of birds is the sum of increase and decrease rate in birds per area of kelp. The flow is governed by a normal population dynamics formulation, as used in all growth flows in this model, where growth decreases towards the CC or zero. As for seal, I use a concave slope, based on Weisse, to determine the growth rate based on food levels (Weisse et al., 2002, pp. 1448-1449).
Local_Net_Growth_Seals	(SEALS*Local_Seal_Net_Growth_Fraction)*(1-CC_utilization_SEAL)		Seal/Years	The local growth rate of the of the seal stock. It is local because I only measure the average number of seals that is found to forage in the kelp. With other words, what normally would be deaths in a population equation is here

				labelled as migration. The inflow is governed with the generic population function as the other populations in this model.	
Local_Seal_Net_ Growth_Fraction	GRAPH(Fraction_Of_Desired_Fish_fo r_Seal) Points: (0.000, -0.800), (0.100, -0.2781), (0.200, 0.1279), (0.300, 0.4438), (0.400, 0.6896), (0.500, 0.8808), (0.600, 1.030), (0.700, 1.145), (0.800, 1.235), (0.900, 1.305), (1.000, 1.360)		dmnl/yea r	The fraction predated fish of the desired amount is put into a table function which shows the effect of their total foraging success on the net growth of the seal population. If they get less than they desired the growth rate will decrease from its maximum growth rate. If food is scarce the growth rate will go to minus, decreasing the total population. I use a concave slope based on Weisse, to determine the growth rate based on food levels (Weisse et al., 2002, pp. 1448-1449). The maximum growth fraction is based on found growth rates of fur seals (not in Norway), which is around 9-17 % increase in population a year (Wickens & York, 1997, p. 245). I did not find direct numbers from Norway, but trying to calculate such a number from Bjørge's paper ((Seals in one big haul-out site is 40) x (Pups 150/Seal population 750) – Seal in haul-out site 40/max age 30 = 8 - 1.333333 = 6.66667/Seals in haul-out site 40 = 0.1666675) which resulted in a similar value, 16.7% (Bjørge et al., 2002). Thus, a maximum growth rate of 0.17 (17%) seems fitting. But since seals forage much less in kelp forests than deep basins (8 kg vs 66 kg a year). I must assume that seals will quickly change foraging ground as kelp forests is depleting, thus I need to make a guesstimate of change in local growth. Since they get almost 8 times of their food from outside a kelp forest I will multiply their local growth rate by 8. 0.17x8=1.36. Maximum population disappearance of seals from kelp forest is set to 10% and is also multiplied with 8, equalling 80%.	
SEA_BIRDS(t)	SEA_BIRDS(t - dt) + (Local_Net_Growth_Birds) * dt	INIT SEA_B IRDS = Total_I nitial_B irds	Bird	The stock that represents the number of sea birds in the area modelled at any time.	
SEALS(t)	SEALS(t - dt) + (Local_Net_Growth_Seals) * dt	INIT SEALS = Total_I	Seal	The stock that represents the number of seals in the area modelled kelp forest at any time.	

		nitial_Seals			
Total_Desired_Fish_for_Bird	SEA_BIRDS*Desired_Fish_from_kelp_forest_pr_Bird_a_year		kg fish/year	The total number of birds foraging in the kelp forest are multiplied with the normal weight of fish that one bird eats pr year.	
Total_Desired_Fish_for_Seal	Desired_kg_Fish_from_kelp_forest_pr_Seal_a_Year*SEALS		kg fish/year	The total number of seals in the kelp forest are multiplied with the weight of fish a seal eats in this area a year.	
Total_Fish_for_Birds	Total_Desired_Fish_for_Bird*Effect_of_Fish_Abundance_on_Bird_feeding_in_kelp_forest		kg fish/year	The total weight of gadid fish that sea birds actually will eat after its multiplied with a density effect of fish.	
Total_Fish_for_Seals	Total_Desired_Fish_for_Seal*Effect_of_Fish_Abundance_on_Seal_feeding_in_kelp_forest		kg fish/year	The total weight of gadid fish that the seals will actually eat after its multiplied with a density effect of fish. Gadid fish, particularly saithe and cod dominates the seals diet independent of area and season (Bjørge et al., 2002, p. 29; Nilssen et al., 2019, p. 144). As these fish dominates the kelp forests in Norway, I neglect any other fish in their diet as it will be miniscule.	
Controls_CC:					
Bird_CC_pr_sqm	0.00002		Bird/m^2	The carrying capacity of birds per square meter is set higher than the number estimated for initial birds sqm.	
Fish_CC_pr_sqm	0.24		kg fish/m^2	To find the carrying capacity of gadid fish in kelp forest I took the amount of fish found by Lorentsen (in Initial Fish sqm), 0.116 kg fish pr m^2. Then, since the coastal cod population has decreased drastically the last years, from 350 thousand tonnes to 200 since 1984 (Vondolia et.al, 2020, p. 30), and the annual harvest of coastal cod is 20% of the fish stock, I can assume a higher CC. Based on the above I do a calculative estimation of the CC. First I multiply the recent found amount of fish with the fractional difference between the number of coastal fish now and that of 1984 (350/200=1.75), which gives us 0.116 x 1.75 = 0.203. Lastly, I add the 20% annually harvested fish, 0.203x1.2 (20%), giving the number 0.2436 fish per m^2, which I round to 0.24 kg fish pr m^2 as my approximation of carrying capacity for gadid fish in the kelp forest. It is worth mentioning that Vondolia's measures for CC of coastal cod (0.35 kg fish pr m^2) is way higher than mine because they assume that coastal cod	

				and artic cod has the same carrying capacity (Vondolia et al., 2019, p. 39), even though it is know that the carrying capacity of cod can vary greatly already in different areas and sub-populations in mid Norway. Further, 75% of all coastal cod is found above 67 degrees north, indicating a much higher CC north than in the south, as well as other indices like maturity time, area use, and growth rates (Bjerknes et al., 2006, pp. 11-12; Salvanes et al., 1995, p. 24; Salvanes et al., 2004, pp. 242, 243, 247).	
Kelp_CC_pr_sqm	30		kg kelp/m^2	The carrying capacity (CC) of the kelp forest is found in the Controls CC Sector in the model. The CC is set to 30 kg pr m^2, which assumes good environmental conditions, based on the findings of Rinde and Steen (Rinde, 2007, p. 77; Steen, 2005, p. 1). The relationship between the stock (kelp, epiphytes and fauna) and the CC is a simplification since the carrying capacity of the kelp (Kelp CC) is a measure of maximum weight of kelp in an area, not regarding on-growth and associated fauna. I defend the simplification by that the kelp is set to grow in speed with the full restoration of the area (not just the kelp biomass), and that sea urchins eats down the kelp entirely and cannot leave only epiphytes. Also, the fish is reliant on full restoration and not just kelp biomass.	
Seal_CC_pr_sqm	0.000003		Seal/m^2	The carrying capacity of seal per square meter is derived from Bjørge's findings. Seal pr km^2 kelp forest is 0.8+1.2 = 2 seals, in m^2 that is 0.000002 (Bjørge et al., 2002, pp. 35, 37). Since the area are under fishing pressure I assume a higher CC, 0.0000024.	
Total_CC_Birds	Bird_CC_pr_sqm*Area_Size		Bird	The Bird CC pr spm is multiplied with the chosen area size we want to simulate to get the total carrying capacity of birds in the area.	
Total_CC_fish	Fish_CC_pr_sqm*Area_Size		kg fish	The Fish CC pr spm is multiplied with the chosen area size we want to simulate to get the total carrying capacity of fish in the area.	
Total_CC_Kelp	Kelp_CC_pr_sqm*Area_Size		kg kelp	The Kelp CC is multiplied with the chosen area size we want to simulate to get the total carrying capacity of the area in kg kelp.	
Total_CC_SEAL	Seal_CC_pr_sqm*Area_Size		Seal	The Seal CC pr spm is multiplied with the chosen area size we want to simulate to get the total carrying capacity of seal in the area.	

Total_CC_Urchin	Urchin_CC_pr_sqm*Area_Size		urchin	The Urchin CC is multiplied with the chosen area size we want to simulate to get the total carrying capacity of the area in grown urchins.	
Urchin_CC_pr_sqm	60		urchin/m^2	The carrying capacity of urchins is the maximum number of adult urchins (20 g each) that a barren ground can sustain per square meter. In Norway it is found numbers of 50-60 adult sea urchins per square meter in barren as the upper averages of one area (Fagerli et al., 2013, pp. 120, 125; Leinaas & Christie, 1996, p. 525). So, I have set the CC to 60 adult sea urchins pr m^2.	
Controls_Stock:					
Adjustment_Time	1		year	A parameter of value 1 that is necessary to use in some equations to tell the model that the value of the equation should be counted over 1 year.	
Area_Size	10000000*0 + 1*1		m^2	The area of kelp forest in m^2 that is to be modelled.	
Initial_Birds_sqm	0.000015		Bird/m^2	I found no relevant data on sea bird pr square meter or any other metric, nor the frequency of birds in kelp forest. All we know is that sea birds forage mainly in and around kelp forests (Dalsgaard et al., 2020). I made very approximate estimates of bird pr kelp square meter based on a map in Dalsgaards paper on sea birds and kelp forest. I read the map in Fig.1 on page 136, to find the area covered in kelp and divided that approximate area size on the total number of birds in the present colony. My estimations went: Knowing that one harvest section is 1852 m from north to south (Lorentsen et al., 2010, p. 2055). And the map is approximately 35x50 km = 1750 km. The grids on the map is harvesting sections, and the squares seems to be (1852x(1852/2)), so two grids would be 1852x1852 = 3429904 m^2, making it 3.43 km^2. Of the 1750 km the map covers, and about 225 km is covered by kelp. Then I will guess that 60% of that is pristine kelp forest. 225x0.6= 135 km^2 of pristine kelp forest. 135 divided with number of birds, 2050 = 15.2 birds per km^2. That's 0.000015 per m^2.	
Initial_FISH_sqm	0.12		kg fish/m^2	Bodkin found there to be 0.112 kg fish pr m^2 in a kelp forest in California (Bodkin, 1988, p. 233). In Norway the number is found to be similar. Lorentsen found there to be 25 fish pr 15x5 meter in a kelp forest (Lorentsen et al., 2010, p. 2058). Mounting up to a 0.3333 fish pr m^2, if I assume the same average weight on fish it mounts up to 0.116 kg fish pr m^2.	

				I chose to round the number up to 0.12 kg fish pr m^2, because counting fish physically is found to scare them away (Norderhaug et al., 2005, p. 1284).	
Initial_KELP_sqm	27		kg kelp/m^2	The starting value for each of the stocks in the model are determined by an exogenous variable that can be found in the model sector called "Controls Stock Sector". The variables are termed the "initial" value, which value is per square meter (sqm=m^2). The initial value of kg kelp per m^2 is set to 27 kg pr m^2 as a kelp forest biomass is known to be close to its carrying capacity under good conditions (Rinde, 2007, p. 69). Rinde's time units is months, thus including more detailed behaviour of the system and fluctuations around the equilibrium. My model is much simpler, having only urchins that can keep the forest below CC. And since the urchins in my model can get close to zero, the equilibrium of the kelp forest happens virtually at CC.	
Initial_SEAL_sqm	0.0000023		Seal/m^2	Initial seal per square meter is the amount the stock of seals begins with and is set just below the carrying capacity of seals, 0.0000023.	
Initial_Urchin_sqm	2		urchin/m^2	In pristine kelp forests there are found very few to no urchins. Sivertsen found a mean value of 2 urchin individuals pr m^2 in kelp beds (Sivertsen, 1997, p. 2876), thus the initial value of sea urchins in the sea urchin stock is set to be 2 urchins per square meter (sqm), via this exogenous variable (Initial Urchin sqm).	
"Km^2"	Area_Size/m2_in_km2		Square Kilometers	The area in square meters (m^2) converted to square kilometers (km^2). 1 km^2 = 1.000.000 m^2	
m2_in_km2	1000000		m^2/km^2	Number of square meters in a square kilometer.	
Total_Initial_Birds	Initial_Birds_sqm*Area_Size		Bird	The total number of birds initially is a multiplication of the number per square meter with the total amount of square meter that we chose to simulate.	
Total_Initial_Fish	Initial_FISH_sqm*Area_Size		kg fish	The total number of fish per total area size. The value per square meter is multiplied with the total number of square meters to be modelled.	
Total_Initial_Kelp	Initial_KELP_sqm*Area_Size		kg kelp	The total value of kg kelp per total area size. The value per square meter is multiplied with the total number of square meters to be modelled.	

Total_Initial_Seals	Initial_SEAL_sqm*Area_Size		Seal	The total number of seal initially is a multiplication of the number per square meter with the total amount of square meter that we chose to simulate.	
Total_Initial_Urchins	Initial_Urchin_sqm*Area_Size		urchin	The total number of urchins per total area size. The value per square meter is multiplied with the total number of square meters to be modelled.	
Fish_In_Kelp_Forest_Sector:					
Avg_Weight_pr_Fish	0.35		kg fish/fish	The average weight per fish in the kelp forest. Salvanes found, small gadid fish from 15-50 cm to commonly weigh from 200 to 800 g, which average then becomes 400 g (Salvanes et al., 2004, p. 245). It is also found that fish weight of 3y/o cod averages on 350g (0.35kg) (Waiwood & Majkowski, 1984, p. 68). I will use the lower value of 0.35 kg as there are more younger than older fish in the kelp forest (Salvanes, 1992, p. 14).	
CC_fish_possibility	Total_CC_fish*Habitat_Effect_on_Fish_CC		kg fish	This represents the CC of fish after the habitat effect. Lorentsen found a 90% decrease in small gadid fish in trawled areas. And since current trawling practise leaves large parts of the forest intact around the trawled areas we can assume that the remaining 10% is due to the surrounding kelp forest and that a complete removal of the forest would make the decrease in fish close to 100% (Lorentsen et al., 2010, p. 2054; Vondolia et al., 2019, p. 32).	
CC_utilization_fish	GADID_FISH_BIOMASS//CC_fish_possibility		dmnl	The Fish stock is divided on the Total Fish CC to find the percentage fish left of the carrying capacity.	
Change_in_Harvest	0		dmnl	To experiment with changes to the harvesting pressure on fish this converter lets us add or subtract from the existing pressure, combined with Change in Harvest Time we can chose at what time we want there to be a change in harvest.	
desired_kg_urchin_pr_fish	normal_kg_food_pr_fish*Fraction_of_Urchin_as_Prey		kg urchin/fish/year	The total amount of urchin in kg that each fish would eat.	
Desired_Urchin_for_fish_a_year	((desired_kg_urchin_pr_fish*number_of_fish)//Weight_per_Urchin)		urchin/year	It is well documented that gadid fish, like cod, eats sea urchins and contribute to controlling the urchin density (Norderhaug et al., 2020, p. 166). The number of urchins that one average fish would eat a year is found by multiplying the desired kg urchin pr fish with the total number of fish and	

				then dividing that on the weight per urchin. The equation below shows a double dividing sign (//) which enables a function in the modelling program that prevents the equation to divide by zero, which else would result in an error. ((desired_kg_urchin_pr_fish*number_of_fish)//Weight_per_Urchin)	
Duration_of_Change_in_Harvest	0		year	The duration the change in harvest will persist.	
Fish_Abundance	GADID_FISH_BIOMASS//Total_CC_fish		dmnl	The density measure of fish is based on how many fish there is pr m^2 times the total m^2 divided on the total amount of fish there can maximum be in that area.	
Fish_Harvest	STEP ((Fraction_of_fish_harvest_a_year+(STEP (Change_in_Harvest, Time_of_Change_in_Harvest, Duration_of_Change_in_Harvest)))* GADID_FISH_BIOMASS, Fish_Harvest_Start_time)/Adjustment_Time		kg fish/year	A step function that initiates the fishing pressure at the decided time on the outflow Harvested Fish, from the fish stock. Possibility: STEP ((IF TIME>Time_of_Change_in_Harvest THEN Fraction_of_fish_harvest_a_year + Change_in_Harvest ELSE Fraction_of_fish_harvest_a_year)* GADID_FISH_BIOMASS, Fish_Harvest_Start_time)/Adjustment_Time	
Fish_Harvest_Start_time	1984		year	The start time of fish harvesting. It should be set to the beginning of the simulation as there has not been a stop in fishing of cod since 1984 (where the data line starts from) (Vondolia et al., 2019, p. 30).	
Fish_Predated	(MIN ((Total_Fish_for_Seals+Total_Fish_for_Birds), GADID_FISH_BIOMASS/Adjustment_Time))		kg fish/Years	One of two outflow from the fish stock (Gadid Fish Biomass) that represents the predation pressure from sea birds and seals. If the desired predation from them combined are larger than what is in the fish stock the flow is limited by a MIN-function that subtracts no more than what is in the stock over one time unit (year).	UNIFLOW
Fraction_of_fish_harvest_a_year	0.47		dmnl	From the graph in Vondolia, at page 30, the harvest of costal cod is about 20% of the total biomass each year (Vondolia et al., 2019, p. 30).	
Fraction_of_Urchin_as_Prey	GRAPH(Urchin_CC_utilization) Points: (0.000, 0.0000), (0.100, 0.1253), (0.200, 0.2173), (0.300,		kg urchin/kg food	Sea Urchin is up to 20% of cods prey (Enoksen & Reiss, 2018, p. 251). It is thought that the fraction of urchin in diet will increase when they are abundant (Hagen, 1983, p. 186). And in Salvenes, Table 3, they show cod at	

	0.2849), (0.400, 0.3345), (0.500, 0.3709), (0.600, 0.3976), (0.700, 0.4172), (0.800, 0.4317), (0.900, 0.4422), (1.000, 0.4500)			different ages to feed 5500 mg pr m2 on benthic animals a day, which is about 20-70% of the diet of the age-classes that moves out of the fjords to the kelp forests (Salvanes, 1992, pp. 13, 18). Predators on benthic game is opportunistic and will prey on what is available (Norderhaug et al., 2020, p. 166). So, if the benthic community will be overtaken by urchins, we can assume a higher fraction of the benthic diet to consist of urchins. To not make an overestimation, I set the upper value of urchin in diet of fish to be 45%. I use a concave curve as the effect of density or abundance (from 0 to 1) on predation pressure as it is a common way to explain predation pressure (Morecroft, 2015, p. 22; Swart, 1990, p. 95).	
GADID_FISH_BIOMASS(t)	GADID_FISH_BIOMASS(t - dt) + (Net_Growth_Fish - Harvested_Fish - Fish_Predated) * dt	INIT GADID_FISH_BIOMASS = Total_Initial_Fish	kg fish	The stock in the fish sector represents the total biomass of gadid fish that at any time resides within kelp forest we model. Gadid fish along the Norwegian coast consists mostly of Cod and Saithe. Kelp forests are important habitat for the costal species of this fish family (Lorentsen et al., 2010, p. 2055). The family of gadid fish is the most important controller of urchin populations in Norway, as well as being a commercially important family of fish (Enoksen & Reiss, 2018; Norderhaug et al., 2020; Teagle et al., 2017, p. 93). Most of the values and rates of feeding and growth is based on coastal cod, also done by Salvanes, using the measure of cod to represent other fish that competes with cod (Salvanes, 1992, p. 11).	
Habitat_Effect_on_Fish_CC	GRAPH(Kelp_CC_Utilization) Points: (0.000, 0.0100), (0.100, 0.02251), (0.200, 0.05298), (0.300, 0.1254), (0.400, 0.2749), (0.500, 0.5050), (0.600, 0.7351), (0.700, 0.8846), (0.800, 0.9570), (0.900, 0.9875), (1.000, 1.0000)		dmnl	The level of kelp forest affects the CC of fish. In Norwegian coast there are large areas covered in kelp forests that are important habitat for coastal cod (Bjerknes et al., 2006, p. 6). The amount or level of a kelp forest is known to affect the possible amount of fish in the same forest, and Vondolia assume that carrying capacity of coastal cod depends on kelp forest (Vondolia et al., 2019, p. 32). In kelp areas that were newly harvested the number of small (<15 cm) gadid fish was 92% lower than in un-harvested areas (Lorentsen et al., 2010, p. 2054). Secondary production (small game and invertebrates), which is the nourishment of young cod, decreased with 70 to 98% after trawling. Reestablishment of flora and fauna follows the regrowth of the kelp (Rinde et al., 2006, pp. 7, 9). Gadid fish decreased by 75% from areas with more than 50% kelp coverage to areas with less than 25% kelp coverage. When kelp cover was less than 25% there were very few fish. When more than 50% there was abundant with fish in the kelp forest, indicating an S-shaped behaviour (Lorentsen et al., 2010, p. 2058).	

Harvested_Fish	(MIN (Fish_Harvest, GADID_FISH_BIOMASS/Adjustment _Time))		kg fish/Year s	One of two outflows from the fish stock (Gadid Fish Biomass) that represents the human fishing pressure on costal cod. If the desired harvesting is larger than what is in the fish stock the flow is limited by a MIN-function that subtracts no more than what is in the stock over one time unit (year).	UN IFL OW
Maximum_Growt h_Fraction_Fish	0.8		dmnl/yea r	Vondolia guessed the constant growth rate of costal cod to be 0.5. Based on an upper and lower limit of found growth rate in Artic Cod (0.6 and 0.33, respectively) (Vondolia et al., 2019, p. 39). But Bjerknes states that costal cod has a higher growth rate than artic cod. In addition, Bjerknes says that costal cod reproduction rate increases further south (Bjerknes et al., 2006, p. 11). So, I will use the highest normal growth rate found in artic cod, 0.6, and guess a 0.2 increase = 0.8 to be the maximum growth rate of costal cod.	
Net_Growth_Fish	(GADID_FISH_BIOMASS*Maximum _Growth_Fraction_Fish)*(1- CC_utilization_fish)		kg fish/Year s	The growth rate of the of the fish stock. Governed, as the other growth flows in this model, with the Lotka-Voltera equation, where closing of the stock towards zero or the CC will decrease the growth rate in an up-down U-shaped behaviour, creating an S-shaped behaviour of the fish population.	
normal_kg_food_ pr_fish	0.85		kg food/fish/ year	The average amount of food each fish eats. Fish weight of 3y/o cod averages on 350g (0.35kg). Average food consumption of that weight class is 848 g (0.85 kg) (Waiwood & Majkowski, 1984, p. 68).	
number_of_fish	GADID_FISH_BIOMASS//Avg_Weig ht_pr_Fish		fish	The biomass of gadid fish that is in the stock divided by the average weight of fish found in the kelp forests.	
Other_predators_ Multiplier	GRAPH(Kelp_CC_Utilization) Points: (0.000, 1.000), (0.100, 1.025), (0.200, 1.087), (0.300, 1.233), (0.400, 1.535), (0.500, 2.000), (0.600, 2.465), (0.700, 2.767), (0.800, 2.913), (0.900, 2.975), (1.000, 3.000)		dmnl	The representation of predation pressure from other predators of the sea urchin. There are several other predators than cod of sea urchins, like sea birds, wolffish, flounders, halibut, otters, crab, lobster and bunch of smaller invertebrate predators (Bustnes et al., 1997, p. 16; Hagen, 1983, p. 186; Lorentsen et al., 2022, p. 307). I will assume the same reliance by other predators on kelp forest as that of cod. Thus, an S-Shaped effect of kelp forest on other predators. The upper value of which the predation pressure from gadid fish is multiplied with a guesstimate (x 3), calibrated in the model to fit historical data, and is only based on that there are many other predatory species that prey on urchin and that some of them can feed extensively on urchins, e.g. sea birds (Bustnes et al., 1997, p. 16).	

Time_of_Change_in_Harvest	2015		year	When the change in harvest pressure will happen.	
Total_Desired_Predated_Urchin	Desired_Urchin_for_fish_a_year*Other_predators_Multiplier		urchin/year	The total number of urchins that its predators desires to eat each year.	
Kelp_Forest_Sector:					
Fraction_of_Kelp_Trawled	0.35		dmnl	In an area opened for trawling Sivertsen says that about 25-35% of the kelp is on average harvested (Sivertsen, 1991, p. 29). But locally the harvest can range from 5-75%, numbers from Møre and Romsdal (Steen, 2019, p. 4). And, Rinde, et.al, found the harvest to be between 5-40% (Rinde et al., 2006, p. 5). Since a lot of data in this model comes from mid Norway, like Møre and Romsdal where there has been more trawling than other places (Steen, 2005, p. 52), I will set the yearly trawling pressure to a sober value on the upper side of the scale, 35%. Nevertheless, this parameter represents a decision-rule, which can be freely changed to test different harvesting policies.	
Kelp_CC_Utilization	KELP_FOREST/Total_CC_Kelp		dmnl	The kelp stock is divided on the Total Kelp CC to find the percentage kelp left of the carrying capacity.	
KELP_FOREST(t)	KELP_FOREST(t - dt) + (Net_Growth_Kelp - Kelp_Grazed - Kelp_Trawling) * dt	INIT KELP_FOREST = Total_Initial_Kelp	kg kelp	This stock represents the full forest with kelp plants, epiphytes (on-growths) and the associated fauna. The S-shaped increase of the forest is a result of the predator-prey equation in Net Growth, and it fits with the real systems behaviour. Because, it is found that 4 years after a drastic reduction of sea urchins juvenile kelp were found on 40% of the ocean floor of the former barren area, while most of the growth happened in the last year, indicating a slow but increasing growth in the early stages of the forest (Leinaas & Christie, 1996, p. 531). And, as kelp quickly reaches their maximum hight or canopy layer, the holdfast, stipe, and associated fauna might seems recovered but will still need several years to reach its full size and potential, so it's a decreasing increase in the late stages (Christie et al., 1998, p. 56).	

Kelp_Grazed	(MIN (Total_Kelp_for_Urchin, KELP_FOREST/Adjustment_Time))		kg kelp/year	One of two outflows from Kelp Forest is the grazing from Sea urchins. The sea urchins, S. droebachiensis, is the main herbivore in Norwegian kelp forests, which graze extensively on L.Hyperborea kelp and can graze down entire forests (Norderhaug & Christie, 2009; Scheibling & Anthony, 2001).	UN IFL OW
Kelp_Trawling	IF Kelp_CC_Utilization<Kelp_Trawling_ Limit THEN 0 ELSE Kelp_Trawling_Steps		kg kelp/year	One of the two outflows of the kelp forest is Kelp Trawling. L. Hyperborea accounts for about 90 % of the national (kelp) harvest (Rebours et al., 2014, p. 1946). It is trawled approximately 150,000 tonnes of L. Hyperborea annually in Norway (Lorentsen et al., 2010, p. 2054).	UN IFL OW
Kelp_Trawling_In terval	5		year	The interval of trawling is set to a normal frequency of 5 years, found in e.g. Møre and Romsdal (Steen, 2019, p.2; Norderhaug, 2021, p.7).	
Kelp_Trawling_Li mit	0.3		dmnl	This policy converter acts as a threshold for when kelp harvesting should stop dependent on the amount of kelp left, set to 20%. The highest percentage output form one area is 75% (Steen, 2019, p. 4). There are practical limits due to harvesting capacity, it is prohibited to harvest in areas undergoing or are in areas in risk of down-grazing by sea urchins, and the substrate in one whole harvesting grid may also be a factor for 75% to be the maximum harvest with today's harvesting techniques. I lowered the threshold by 5% as an error margin.	
Kelp_Trawling_St art_Time	1984		year	Earliest available data from kelp trawling is from 1985 (Steen, 2005, p.1).	
Kelp_Trawling_St eps	PULSE (Fraction_of_Kelp_Trawled*KELP_FO REST, Kelp_Trawling_Start_Time, Kelp_Trawling_Interval)		kg kelp/year	The standing stock of kelp is multiplied with the fraction of trawled kelp to get the actual harvest in kg. That amount, frequency of trawling, and time of trawling is controlled by a "step"-function, enabling us to decide the magnitude, start year and interval of kelp harvesting. The Kelp Trawling Interval is set to a normal frequency of 5 years, Møre and Romsdal (Steen, 2019, p. 2). Kelp Trawling Start Time is set to the start of the model simulations, year 1984.	
Maximum_Growt h_Fraction_Kelp	0.8		dmnl/yea r	The growth rate of the kelp forest after harvest is calibrated to a value that fits the findings of Greenhill, saying that a kelp forest's full re-establishment and recolonisation takes a minimum of eight years (Greenhill et al., 2021, p. 2). With a fractional growth rate of 0.8 and a carrying capacity (CC) at 30 kg kelp, the forest reaches 95% of its CC after 8 years, when initializing the kelp stock with 1 kg kelp pr m^2. The calibration is done in isolation from the rest	

				of the model, meaning it is the behaviour we could expect from a regrowing kelp forest in ideal conditions. I initialized the stock with 1 kg kelp in the calibration because there are normally spores or juvenile kelp left after a spot is harvested (Greenhill et al., 2021; Sivertsen, 1991, p. 7).	
Net_Growth_Kelp	KELP_FOREST*Maximum_Growth_Fraction_Kelp*(1-Kelp_CC_Utilization)		kg kelp/year	The inflow to the Kelp Forest Stock, the growth rate, is assumed to rely on the kelp forests carrying capacity with the equation from Lotka-Volterra, as explained initially in this chapter. This equation decreases the growth rate when the kelp forest (stock) goes towards the CC or zero. The maximum growth rate will thus be found when the kelp forest is halfway to its CC, creating a turned U-shape behaviour in the net growth flow (Noy-Meir, 1975, p. 461).	UN IFL OW
Parameters_of_interest:					
Actual_Harvest	Kelp_Trawling/500				
fish_pr_bird	Total_Fish_for_Birds/SEA_BIRDS		kg fish/Bird/ year		
Grazing_pr_urchin	Average_Grazing_per_Urchin*Effect_of_Kelp_Availability_on_Actual_Grazing*Effect_of_forest_composition_on_urchin_grazing		(kg kelp/urchin)/year	The	
Sea_Urchin_Sector:					
Available_Kelp_as_fraction_of_desired_grazing	Kelp_Forest_Available_pr_Urchin/Average_Grazing_per_Urchin		dmnl	The amount of kelp forest available per urchin divided by the normal amount of kelp an urchin eats in a year to find a fraction of normal kelp available per urchin. Based on predator prey model (SOURCE)	
Average_Grazing_per_Urchin	0.56		kg kelp/urchin	One grown (commercial sized) urchin is found to eat between 1 and 2.5 grams laminaria kelp a day, depending on seasonal fluctuations. The average will thus be 2.5+1/2= ca 1.7g pr urchin a day. 1.7g timed with 365, to get in years, is 620.5 g each year. Equalling 0.62 kg (Scheibling & Anthony, 2001, p. 144). These findings were done in a laboratory, lacking natural obstacles (like water movement, climbing physical objects, fighting of predators etc.),	

				which makes it fair to assume a slightly lower value of grazing. A value of 0.56 provides a good behavioural fit with the historical data.	
Effect_of_forest_c omposition_on_ur chin_grazing	GRAPH(Kelp_CC_Utilization) Points: (0.000, 0.005), (0.050, 0.856), (0.100, 0.915), (0.150, 0.956662280702), (0.200, 0.978906088751), (0.250, 0.989959687822), (0.300, 0.995745098039), (0.350, 0.998465105779), (0.400, 0.999453480988), (0.450, 0.999469040248), (0.500, 0.99875336119), (0.550, 0.9971778995), (0.600, 0.994419742796), (0.650, 0.990088235294), (0.700, 0.98375), (0.750, 0.974799535604), (0.800, 0.962086687307), (0.850, 0.943157894737), (0.900, 0.912921052632), (0.950, 0.8615), (1.000, 0.771)		dmnl	To fully explain the relationship of grazing pressure of urchin on the kelp forest we need to take the forest composition into consideration.

Grazing activity is in part a function of available drift kelp and algae (Filbee-Dexter & Scheibling, 2014, p. 15; Harrold & Reed, 1985, p. 1165). When the kelp forest is low, there will be few growing kelp (L.Hyperborea), which is the preferred food of the green sea urchin (S. droebachiensis). Their grazing rate is lower on other food sources like algae and the smaller kelp, Laminaria Saccharina, which are thought to initiate the regrowth of a kelp forest after an urchin die-off (Leinaas & Christie, 1996; Scheibling & Anthony, 2001, p. 143). In the open coast experiment of Leinaas & Christie, when algae, and the faster growing L.Saccharina, started a re-vegetation of a barren ground, kelp was found in 10% of the area after 3 years and in 40% of the area after 4 years, where other algae and L.Saccharina was dominant (covering 70-100% of the ocean floor) within a year after an urchin die-off/removal) (Leinaas & Christie, 1996, p. 531). This gives an indication to that at the very low stages of the forest the urchin grazing will be very low but increase quickly as kelp will outcompete the smaller vegetation fast.

Further, Scheibling and Hamm found that there are enough drifting algae for urchins in pristine kelp beds for urchins to avoid exposing themselves to predators, which they do when grazing directly on the kelp. Thus, grazing on kelp is thought to decrease when kelp is abundant (Christie et al., 2019, p. 15; Filbee-Dexter & Scheibling, 2014, pp. 10, 16; Scheibling & Hamm, 1991, p. 114). Combining that with the findings of Lorentsen, saying that fish in the kelp forests seems abundant when kelp cover was more than 50%, indicating enough prey for fish, which again is a result of a rich flora, which lastly gives a high level of drifting kelp particles (Lorentsen et al., 2010, p. 2058).

The exact values are guesstimates as the relationship is only documented qualitatively but are also calibrated so the behaviour fits historical data. As seen in the picture of the graphical function in Fig.1.1.6, the calibrations favour a sharp decrease of fractional grazing rate from one towards zero when the total kelp forest is very low, as kelp (L.Hyperborea) itself will be very scarce, if any there at all. At 60% of maximum CC there will be an | |

				increasingly decreasing grazing pressure, of a lesser magnitude, to a minimum of 77% of the current grazing pressure. In between these two points the forest composition effect on grazing will be 1 (no effect).	
Effect_of_Kelp_Availability_on_Actual_Grazing	GRAPH(Available_Kelp_as_fraction_of_desired_grazing) Points: (0.000, 0.000), (0.0483870967742, 0.04742), (0.0967741935484, 0.09484), (0.145161290323, 0.1423), (0.193548387097, 0.1897), (0.241935483871, 0.2371), (0.290322580645, 0.2845), (0.338709677419, 0.3319), (0.387096774194, 0.3794), (0.435483870968, 0.4268), (0.483870967742, 0.4742), (0.532258064516, 0.5216), (0.58064516129, 0.569), (0.629032258065, 0.6165), (0.677419354839, 0.6639), (0.725806451613, 0.7113), (0.774193548387, 0.7587), (0.822580645161, 0.8061), (0.870967741935, 0.8535), (0.91935483871, 0.901), (0.967741935484, 0.9484), (1.01612903226, 0.9958), (1.06451612903, 1.043), (1.11290322581, 1.091), (1.16129032258, 1.138), (1.20967741935, 1.185), (1.25806451613, 1.233), (1.3064516129, 1.280), (1.35483870968, 1.328), (1.40322580645, 1.375), (1.45161290323, 1.423), (1.500, 1.470)		dmnl/year	The effect of kelp availability on urchin actual grazing is a graphical function. When the amount of kelp available per urchin is below the found average grazing, the average grazing will decrease. There is no well documented effect of kelp availability on grazing behaviour, but I can use the mentioned findings by Scheibling and Anthony's laboratory experiments (under Average Grazing per Urchin) with generic behaviour used in the Lotka-Volterra model. The lower grazing rate of kelp was based on season and not kelp availability, as well as the upper grazing rate. That tells us that the lower rate can get lower if there is too little kelp to sustain it, but the upper limit will not increase with more kelp. The maximum grazing, they found to be 2.5 g a day = 0.91 kilo a year, the lower was 1 g a day, and the average was found to be 1.7 g a day (Scheibling & Anthony, 2001, p. 144). For this to be in an effect graph (a multiplier) I need to find what 1.7 (the average) is multiplied with to get the maximum, 2.5/1.7 = 1.47. The number that will multiply the average grazing pressure per urchin to get the maximum pressure is thus 1.47. I've set a linear relationship from the max grazing rate to 0 based on possible versions of this relationship derived from predator-prey models by Swart and by Noy-Meir (Swart, 1990, p. 95) & (Noy-Meir, 1975, p. 461). As seen in these articles, several developments of the effect-lines can occur. Since there are little documentation of the exact line in the system in focus, a straight line from 0 to maximum grazing was chosen as it fit better with historical behaviour. As to what level of available kelp per urchin the maximum grazing will occur is hard to say. I have set it to occur approximately when the amount of kelp available per urchin reaches the maximum each urchin can prey, which is 1.5 times average grazing. There are several articles that shows a similar graph but uses actual amounts and not a fraction. But, with some calculation, the values from the paper about prey availability by Lampropus shows us one example of how maximum feeding happens when food (or prey) availability is approximately 1.5 times the normal feeding. At page 610, Fig.1, we see that maximum consumption is 70 prey individuals. We then must assume that the	

				normal or average prey density is half of its maximum, 45 (90/2=45). If we then divide the maximum consumption on the average density we get, 70/45= 1.55 (Lampropoulos et al., 2013). Meaning that the maximum food intake will be when the available food is approximately 1.5 times higher than the average food intake. This graphical effect on grazing alone do not create behaviour that fit with historical behaviour of the system. That is because the grazing pressure is also affected by the composition of the forest, and not just the amount available. The forest composition will be an additional structure variable that is not found in classic Lotka-Volterra model.	
Fraction_Diseased _Urchin	0.999*Mass_Death_Event_Switch		dmnl	The fraction of urchin that will die in a mass mortality event is set to 0.999 as Skadsheim found that urchin mortality events could nearly eliminate local urchin populations (Skadsheim, 1995, p. 200).	
Kelp_Forest_Avai lable_pr_Urchin	KELP_FOREST//SEA_URCHINS		kg kelp/urch in	The biomass of the kelp forest divided on number of urchin showing how much kelp forest is available per urchin. Based on know predator-prey model (SOURCE)	
Mass_Death_Eve nt_Switch	0		dmnl	Policy switch. If the value is 1 there will be a massive urchin die-off, if zero then nothing happens.	
Mass_death_Urch in	PULSE (Fraction_Diseased_Urchin*SEA_URC HINS, "Time_of_Urchin_Die-off", 999)		urchin/Ye ars	Urchin populations is periodically eradicated by disease, which gives the kelp bed a chance to re-establish (Scheibling & Anthony, 2001, p. 139). This is thus one of two outflows of the urchin stock. It is only active when or if the urchin population is affected by a mass mortality event such as a parasite infection or a drastic increase in sea temperature (Fagerli et al., 2013, p. 120; Norderhaug & Christie, 2009, pp. 521-522). The event is enacted by a PULSE function which pushes a value that otherwise would happen over a whole year in only one DT (1/500 year). This makes the program (Stella Architect) visualize the outflow to be four times higher than it should. To avoid too detailed maths, if we divide the visualized outflow with the DT (500) we find the actual amount that is subtracted from the stock, which also fits with the set value in Fraction Diseased Urchin timed with the current stock.	UN IFL OW

| Maximum_Growth_Fraction_Urchin | 0.7 | | dmnl/year | Thompson found that size and health of eggs and gonad size increase with more kelp in diet. He also found that individual growth stops with low food rations but that they re-allocate resources to reproduction effort, counteracting the increased mortality with low kelp consumption (Thompson, 1982, p. 51). Which means bigger and fewer spawn while on a kelp diet, and smaller but more eggs while not. Skadsheim's Fig.4, illustrates this dynamic effect on the population, seeing that when urchin is fewer, they are bigger and when they are more, they are smaller (Skadsheim, 1995, p. 203). That is an indicator to that when the urchin population closes in on its CC, and kelp gets scarce, the total biomass will be fairly stable as the composition of the population changes from big to smaller sized urchins.

To include the dynamics explained above into the model, an average size of urchin comes in handy as a simple way to reflect the grazing pressure. Based on the above I argue that the growth rate of urchin population can be set to a constant as a function of the population size for this model's purpose.

Then the growth constant is calibrated to be approximately 0.7, with the mentioned CC. It is based on historical data saying it can take 1 to 6 years for urchins to complete down grazing of a kelp bed to barren ground (Hagen, 1983, p. 185; Sivertsen, 1997, p. 2880).

Adding a classical grazer-grazed (predator-prey) connection here would not fit as the ability of sea urchin populations to persist on barren grounds is due to great phenotypic plasticity in response to low food availability, with other words, a decrease in kelp availability does not result in decreasing population (Norderhaug & Christie, 2009, p. 515). | |
| Net_Growth_Urchin | IF Mass_death_Urchin>0 THEN 0 ELSE (SEA_URCHINS*Maximum_Growth_Fraction_Urchin)*(1-Urchin_CC_utilization) | | urchin/Years | As in kelp, the equation is derived from the described Predator-Prey model, but with an additional feature:

IF Mass_death_Urchin>0 THEN 0 ELSE (SEA_URCHINS*Maximum_Growth_Fraction_Urchin)*(1-Urchin_CC_utilization)

The IF THEN ELSE function tells the model to stop growth when a massive urchin die-off happens. That is because the inflow (Net Growth Urchins) adds | |

				to the stock of urchins based on the previous year in the same DT as the mass death subtracts from the stock. That results in a smaller decrease than the die-off suggests because there will also be added urchins at the same time interval. This function stops any inflow during the DT a die-off happens, fulfilling the functional effect of the die-off, which is removing the set percentage of the urchin population at a DT, including those born the same time.	
Predated_Urchin	IF Mass_death_Urchin>0 THEN 0 ELSE (MIN(Total_Desired_Predated_Urchin, MAX(0, SEA_URCHINS/Adjustment_Time)))		urchin/Years	One of two outflows from the urchin stock. Urchin is predated by a number of different predators, like all life stages of gadid fish, crabs, seals, otters, birds and smaller invertebrate predators etc., (Fagerli et al., 2014, p. 208; Norderhaug et al., 2020, p. 164; Scheibling & Hamm, 1991, p. 106). As in Net Growth Urchin, the flow is restricted by Mass death Urchin to be zero if an urchin die-off event occurs to prevent the stock going to minus. It is also restrained by a MIN function to prevent the Predated Urchin outflow from exceeding the amount that is in the stock at any time. It will rather extract whatever is in the stock over a 1-year interval.	UN IFL OW
SEA_URCHINS(t)	SEA_URCHINS(t - dt) + (Net_Growth_Urchin - Predated_Urchin - Mass_death_Urchin) * dt	INIT SEA_URCHINS = Total_Initial_Urchins	urchin	The stock that represent the number of urchins, based on an average weight per urchins of 0.02kg (Michelsen et al., 2022, p. 12). The reasoning for use of average weight is found under Maximum Growth Fraction Urchin.	
"Time_of_Urchin _Die-off"	2010		year	The year of which a mass mortality event will occur.	
Total_Kelp_for_Urchin	SEA_URCHINS*Average_Grazing_per_Urchin*Effect_of_Kelp_Availability _on_Actual_Grazing*Effect_of_forest_ composition_on_urchin_grazing		kg kelp/year	The total amount of kelp that urchins will try to eat per year consists of the Average Grazing per Urchin (0.02 kg urchin) multiplied with the number of urchins in the Sea Urchin stock, and further multiplied with how the availability of kelp and the forest composition affects their ability to consume kelp. The equation looks like this: SEA_URCHINS*Average_Grazing_per_Urchin*Effect_of_Kelp_Availability_on_Actual_Grazing*Effect_of_forest_composition_on_urchin_grazing	

					This structure is based on extensions of the Lotka-Volterra model (Noy-Meir, 1975, p. 461).	
Urchin_CC_utilization	SEA_URCHINS/Total_CC_Urchin			dmnl	The Urchin stock is divided on the Total Urchin CC to find the percentage urchin left of the carrying capacity.	
Weight_per_Urchin	0.02			kg urchin/urchin	Adult sea urchin, also called commercial size is about 5 cm in diameter and weighs on average 0.02 kg (20g) (Michelsen et al., 2022, p. 12).	

Total	Count	Including Array Elements
Variables	96	96
Sectors	7	
Stocks	5	5
Flows	11	11
Converters	80	80
Constants	33	33
Equations	58	58
Graphicals	9	9

Run Specs	
Start Time	1984
Stop Time	2084
DT	1/500
Fractional DT	True
Save Interval	0.002
Sim Duration	3
Time Units	Years
Pause Interval	0
Integration Method	RK4
Track flow quantities	True
Keep all variable results	True