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The Value of Adapting to Climate Change for Norwegian Salmonid Aquaculture

A scenario-based analysis

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NORWEGIAN SCHOOL OF ECONOMICS

"Essentially, all models are wrong, but some are useful"

George Box (1976)

Abstract

The Norwegian aquaculture industry accounts for 6.5 percent of total exports from Norway. The United Nations projects that by 2030 the world population will grow to 8.5 billion people. In order to maintain food security, the supply of fish is critical. Ectotherms such as Atlantic Salmon is highly dependent on the temperature of its surroundings. Hence, it is important to estimate what the effects of climate change will have on the Norwegian aquaculture industry.

The aim of this master thesis is to analyze how changes in seasonal temperature may affect the Norwegian salmonid aquaculture industry. The existing bioeconomic theory does not consider that mortality rates for salmon is temperature dependent. The inclusion of temperature dependent mortality rates enables a more realistic estimation of how the projected changes in temperature due to climate change will affect the profitability of the Norwegian aquaculture industry. Mortality rates and price are estimated based on the empirical data obtained and used to adjust the growth model estimated by Lorentzen and Hannesson (2006) analyzing data from a controlled experiment executed by feed producers for the aquaculture industry. By analyzing different scenarios for changes to the seasonal seawater temperatures in Norway, I will estimate the value of adapting the decision variables to the changes.

My findings suggest that within the range of projected changes the Norwegian aquaculture industry will benefit from changes in seasonal temperature even without it adapting to the changes. This is regardless of how temperatures are affected. For increases in average temperature between 0.5 and 4 degrees Celsius the beneficial effects ranges from 6.27 to 28.46 percent increase in the present value of all future profits. For changes to the amplitude of temperature the beneficial effect ranges from 1.34 to 8.63 percent, and for changes to both amplitude and average the effect ranges from 7.44 to 23.36 percent.

By adapting to the changes, the beneficial effects of the projected changes is even higher. The best adaptation to the scenario based changes to temperature is dependent on how the temperature changes. The best response to increases in average temperature is to shorten the rotation time, which yields additional values ranging from 1.17 percent to 11.90 percent of the current value of the aquaculture industry for adapting to the projected changes. The best response to increase in amplitude is to start the rotation earlier, whilst the best response to increase in both amplitude and average is to shorten rotation and to start the rotation later.

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List of Abbreviations

the **UN**	the **U**nited **N**ations
IPCC	**I**ntergovernal **P**anel on **C**limate **C**hange
IMR	**I**nstitute of **M**arine **R**easearch
NASA	**N**ational **A**eronautics and **S**pace **A**dministration
NOAA	**N**ational **O**ceanic and **A**tmospheric **A**dministration
NPV	**N**et **P**resent **V**alue
NASDAQ	**N**ational **A**ssociation of **S**ecurities **D**ealers **A**utomated **Q**uotations
MSY	**M**aximum **S**ustainable **Y**ield

List of Symbols

Economics	
r	Discount factor
p	Price per kilogram salmon
M	Mortalityrate for salmon
$w(t)$	Weight of representative fish at time t
N	Number of fish in pen
R	Recruitment, number of released juvenile fish
$B(t)$	Biomass in the pen at time t
$V(t)$	Nominal value of one rotation
τ	Taxrate[1]
Growth function	
α	ecologic parameter for weight
β	ecologic parameter for weight
γ	temperature dependent parameter for weight
$\prod_1^t$	Product of all $\gamma^{\frac{1}{12}}$ from time 1 to time t
Temperature	
π	mathematical constant
ϕ	amplitude for temperature
ω	average temperature
ψ	adjustment factor temperature
T	Period for cosine function
S	Temperature in seawater

[1] Only used in Appendix

1. Introduction

1.1 Motivation

The world's estimated population will reach 8.5 billion people in 2030 according to projections from the UN (2015). The increase in population is mostly driven by developing countries. Todays estimated global population is about 7.6 billion people (*World population clock live* 2018). In order to meet projected demand for food, future supply of fish is especially important (Béné et al., 2015). The projected climate change by IPCC (2001) may put pressure on food suppliers, especially suppliers of sea food. Salmon contains a higher amount of essential amino acids compared to livestock, and slightly lower compared to poultry (*Essential Amino Acid Content in Red Meat* 2018). Salmon has a higher food conversion rate compared to traditional agriculture livestock (Asche and Bjorndal, 2011). In addition, fish is a major export article for Norway accounting for 6.5 percent of total exports (*Utenrikshandel med varer* 2018). Norway has deep fjords with steady currents and compared to the world low, yet steady, seawater temperatures. As a result of the biological factors for salmon, Norway has a comparative advantage with regards to farming salmon. Therefore, it is in the Norwegian government's economic interest to estimate how the projected climate change may affect production in Norwegian aquaculture.

Worldwide, fisheries are over-exploited, fully-exploited or nearly fully exploited (Brander, 2007; Worm et al., 2009), with few possibilities for growth in countries with well regulated fisheries. In unregulated or poorly regulated fisheries, there is a possibility for long run growth in production. In order to obtain production growth in the sub-optimal managed fisheries however, there need to be less harvesting in the short run. There has been shown a correlation between wealth and the amount of regulation in a nation. Hence, there is reason to question whether poorly managed fisheries are economically capable to suffer lower revenues in the short run. In addition, size-dependent price for fish (Zimmermann and Heino, 2013) has led fishing activities to decrease the yield. The decrease in yield as a result of size-dependent price for fish, occurs even in fisheries that traditionally have been considered well managed (Garcia et al., 2012). In order to maintain food security in the future, a larger portion of the protein rich foodstuff may need to come from sea food. Figure 1.1 shows a stacked form of the total value in billion NOK of unprocessed or frozen fish from aquaculture and fisheries for the period 1980-2015. The values from aquaculture are shown in green (top), whilst the values from fisheries are shown in purple (bottom). In 2015 the value from aquaculture where almost 3 times larger than the value from traditional fisheries (Steinset, 2017). Economically well managed fisheries have the largest sustainable output in terms of value. It is possible with larger outputs in terms of volume (weight) for fisheries well managed in accordance with an MSY-model. However, the MSY-solution is a sub-optimal solution in terms of economic management. Aquaculture has more control of the input factors compared to fisheries, which leads to a higher potential for growth in output for aquaculture compared to fisheries. Hence, production from aquaculture will be important for maintaining the world's future food security.

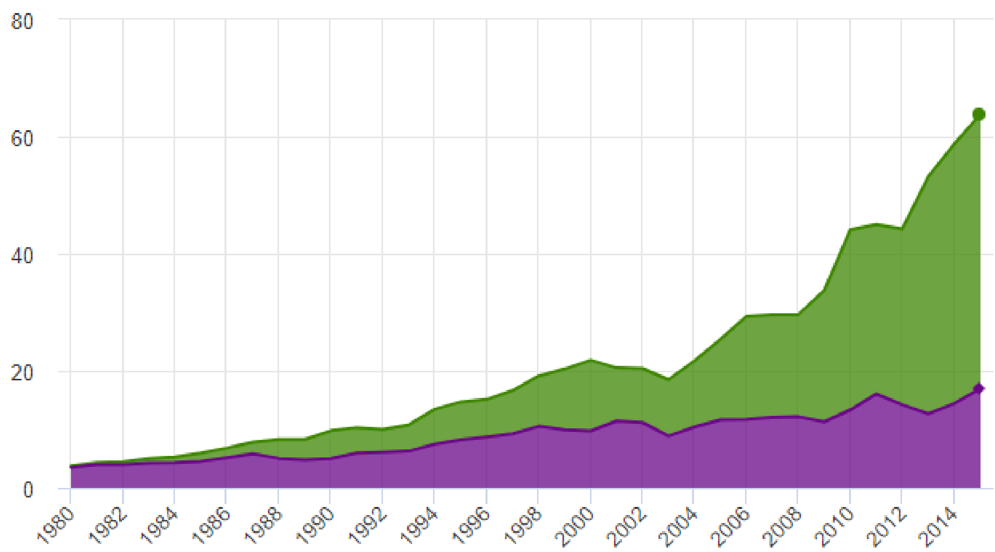


FIGURE 1.1: The total value (*in bn NOK*) of unprocessed or frozen fish from Norwegian aquaculture and fisheries for the period 1980-2015 (Steinset, 2017).

In the analysis I will focus on how increasing seawater temperature may directly affect the value of Norwegian salmonid aquaculture. In Chapter 7 I will briefly discuss how increasing seawater temperature may indirectly affect the value of Norwegian salmonid aquaculture.

1.2 Research question

I will in this thesis answer the following research question:
"For the representative Norwegian fish farm, what is the estimated value of adapting its decision factors in response to different scenarios for changes in seawater temperature?"

In order to answer the research question, I will introduce an extension to the bioeconomic theory analyzing how temperature and weight affects mortality rates. This extension will facilitate how changes to seasonal temperature affects the time dependent total biomass of the fish farm. Additionally; by adjusting the price factor in the model, the resulting analysis will better be able to reflect the actual market. Based on the estimations for the present value of future profits I will analyze how by adapting the rotation time and the time of release, fish farmers may increase the estimated value of a change in temperature.

The analysis will be based on empirical estimations of a growth function and mortality rates dependent on temperature, as well as average prices from the NASDAQ Salmon Price indexes. The analysis will include scenario for changes in seasonal temperature. The estimations for the growth function is from an external source (LORENTZEN, 2008) based on controlled experiments, whilst the estimations for the mortality rates are based on a data set from Norwegian aquaculture in the period from 2009 to 2017.

1.3 Structure of the thesis

In Chapter 2 consist of a brief background of the biological factors for Atlantic Salmon, climate change and its direct and indirect effects on Norwegian aquaculture, and the current regulations in Norwegian aquaculture. The bioeconomic theoretical framework is introduced in Chapter 3, the literature review. In Chapter 4 i will describe how I have used the mathematical model on which the analysis based. I will as well describe the data set form which the regression used to model methodology for the regression and building of the model. Chapter 5 builds the model for optimizing the value of the aquaculture. The results of the analysis is presented in Chapter 6. In Chapter 7 will include a discussion about the limitations of the model, and how the result may change by including other factors. Lastly, in Chapter 8 I will conclude based on the results.

2. Background

In this chapter I will provide some background information regarding: biological factors for Atlantic salmon, climate change and its impact on aquaculture, and the current regulation of the Norwegian aquaculture industry.

2.1 Biological factors for Atlantic salmon (*Salmo salar*)

2.1.1 Effects from the surroundings

Atlantic salmon is an ectotherm organism (Boeuf and Le Bail, 1999), and as such is dependent on its surroundings for regulation of body temperature. Growth for the individual salmon is highly dependent on temperature since the biochemical reactions driving growth are dependent on temperature. The number of hours of daylight and daylight intensity (Oppedal et al., 1997) are important factors for growth and determining the sexual maturation of salmon. By using artificial light, farmers may increase growth and delay sexual maturation (Endal et al., 2000). When the salmon becomes sexually mature, its flesh deteriorates and becomes unmarketable for human consumption (Asche and Bjorndal, 2011; Thyholdt, 2014). When becoming sexually mature the salmon will stop eating, and their current fat supply sustains them. Energy can neither be destroyed nor created, it can only be transferred from one form to another. Hence, sexually mature salmon will have negative growth for a while. Atlantic salmon is an anadromous fish, meaning that it can survive in different magnitudes of salinity. The optimal level of salinity with respect to growth however, is between 20-30 parts per thousands (Lorentzen and Hannesson, 2006). seawater acidity affects chemical reactions and biological toxicity (Marion et al., 2011). The pH scale is a logarithmic scale base 10, measuring acidity in aqueous solutions. The optimal range of pH-values for salmon is between 6 and 8, slightly acidic and slightly basic respectively[1].

[1] A pH-level of 7 is considered to be neutral. pH is based on the concentration of H_3O^+-ions (acidic) or OH^--ions (basic) in the solution.

2.1.2 Natural survival strategy of the species

In Biology, one way of modelling reproduction strategies for organisms is in terms of the r-K continuum (Pianka, 1970). Where r refers to the maximal intrinsic rate of natural increase, and K refers to carrying capacity. In the models, the objective for the organisms is to maximize the probability of successfully having offspring reaching reproducing age. The organisms can control how many offspring the have, and how much care are afforded each individual offspring. The constraining factors is how much total care an organism is able to give its offspring, and energy used for reproduction. Hence, the two endpoints of the model is the r-endpoint and the K-endpoint. The r-endpoint the strategy where organisms maximizes the number of offspring, and have little to no care for the offspring. The K-endpoint is the strategy where organisms have few offspring, and have a lot of care for each offspring. The r-strategist typically have shorter lives and are reproductive at an earlier age, compared to K-strategists (*K and r Reproductive Strategies* 2010). Due to shorter periods between generations; under natural selection, the r-strategist may be better able to quickly adapt to changing conditions in the environment. However, in order to achieve a quicker adaptation an r-strategist has higher mortality rates in the short run.

The species of Salmon can be classified as an r-strategist[2] (*K and r Reproductive Strategies* 2010). In other words, salmon produces a high number of progeny, but with minimal care for the individual offspring. In aquaculture natural selection has been substituted for selective breeding. Hence, the short run increase in mortality rate as a result of changing environments will not naturally lead to better adaptation in aquaculture as it will in nature. An adaptation to changing environments in aquaculture must be a result of choices in the selective breeding process. When performing selective breeding it is more difficult to achieve wanted traits when the amount of wanted traits a larger (Asche and Bjorndal, 2011). In other words, in order to adapt to changes in the environment breeders may have to select for traits better suited for changing environments in stead of selecting for else wise more profitable traits.

[2] No organisms is fully an r-strategist or a K-strategist. Rather, organisms are somewhere on the continuum

2.1.3 Feed additive

The flesh of wild salmon has a natural pink color due to a diet consisting of (among other things) crustaceans. The aforementioned color is due to crustacean eating algae containing the organic pigments, mainly the pigment astaxanthin. Farmed fish do not get astaxanthin through their diet. Consumers have a significantly higher willingness to pay for salmon with a natural coloration to the flesh compared to salmon with paler flesh (Alfnes et al., 2006). In Europe, natural astaxanthin is classified as a food dye (Ambati et al., 2014). About 15 percent of the total feed costs in conventional salmon aquaculture is from added synthetic astaxanthin (Guttormsen, 2002). Hence, a large part of the value from aquaculture stems from adding a substance in the diet of the farmed fish. A substance produced by international pharmaceutical companies (Alfnes et al., 2006). In other words, the Norwegian aquaculture industry is highly dependent on international trade.

2.1.4 Sea lice

Sea lice is a big problem in salmon aquaculture. Sea lice attaches to the gills of the fish, sucking blood. How much damage occurs from this depends on how many sea lice attaches to an individual salmon, and the age and weight of the salmon. The degree of the damage ranges from weakened growth and immune system, to mortal damage(Liu and Bjelland, 2014). Traditionally farmers treated the salmons with chemicals. Due to sea lice developing a resistance, other delousing methods has been tried out by fish farmers. One of the currently most popular methods are using wrasse (*Spør en forsker: Hvorfor er leppefisken så populær?*).

2.2 Climate change

Climate is defined by Cambridge Dictionary as "*the general weather conditions usually found in a particular place*" (2018). Changes in climate may include, but are not limited to; changes in temperatures, changes in humidity, changes in winds, changes in currents, changes in salinity, and changes in acidity. Global climate change is a process affected by the natural variations in earth's axial tilt, the sun's natural variations in activity, changing amount of greenhouse gasses in the atmosphere, changing amount of albedo-acting gasses, and more. Since the recording of global temperature measurements started in the 19th, 17 out of the 18 warmest years have occurred after the year 2001 (*Long-Term Warming Trend Continued in 2017: NASA,* *NOAA* 2018). One of IPCC (Change, 2001) predictions is that seawater temperature will rise as an effect of the ongoing climate change.

2.2.1 Main points from IPCC's report (2001)

Climate change in IPCC usage is not limited to change attributed directly to human activity, but includes natural variability in addition (Change, 2001). The main points from the Assessment Report were as follows

i: Regional climate changes

There is high confidence that regional climate changes, temperature increases in particular, affect many natural systems. The observational evidence comes from all continents and most oceans. There are enlargement and increased number of glaciers, decreasing ground stability in permafrost regions, and warming of lakes and rivers in many regions affecting water quality. There are increases in algal, plankton and fish abundance in high-latitude oceans. Oceans have become more acidic since the uptake of carbon derived from human activities since 1750. In terms of pH-levels, there has been an average decrease of 0.1 units in the worlds oceans.

ii: Knowledge about future impacts

Water supplies stored in glaciers and snow cover are projected to decline over the 21^{st} century. This would cause water stress in regions where currently one-sixth of the world population lives. Terrestrial ecosystems are projected to have a peak in net carbon uptake around mid century. Followed by a weakened or reversal in carbon uptake, which would further amplify climate change. Increases in global average temperature exceeding 1.5-2.5 degrees will lead to increased risk of extinction of approximately 20-30 percent of all animal and plant species. There will be regional variation for the impacts of climate change. Aggregated and discounted, the net impact will be negative and increasing over time as average temperatures increases. Large-scale climate events, such as the melting of terrestrial ice on Greenland, have a large potential to impact global climate negatively.

iii: Responding to climate change

There is a necessity for adaptation to unavoidable warming due to past emissions. If atmospheric greenhouse gas concentrations remains at the same levels as for 2000, the unavoidable warming is projected to be around 0.6 degrees by 2100. More extensive adaptation than what is currently occurring needs to be done in order to reduce vulnerability to future climate change. There are limits to adaptability, but there are currently not clear what these limits are. Nor are the costs of more extensive adaptation clearly estimated. Some adaptation will be positive in the short run, but will be negligible in the long run if the current trend in climate change holds. One way to reduce vulnerability to climate change is to adopt sustainable development. However, climate change could hinder nations from achieving sustainable development pathways.

2.2.2 Direct effect of climate change on aquaculture in Norway

An increase of sea temperature will lead to lower levels of oxygen and higher level of CO_2 in the sea (Brander, 2007). Oxygen is necessary for salmonid respiration, whilst CO_2 dissolved in water becomes carbonic acid (H_2CO_3) which lowers the pH-level in the water. Water in liquid form will expand as a result of higher temperature. At the macro level this expansion leads to higher sea levels. Locations currently suited for aquaculture may be negatively affected due to erosion (Change, 2001) etc.

A higher probability for extreme weather events increases the risk for property damage and escapement in aquaculture. This could mean a loss of the valuable stock, but also extra costs as a result of required efforts to salvage the loss from the weather events. Due to the scope of this thesis, the risk factor will not be a part of the analysis. It should however be an important factor for the profit maximizing fish farmer, optimizing expected profits. Amacher, Ollikainen, and Koskela (2009, p:267), argues that natural hazards decreases rents and the value of a stand in forestry. Given that fish farming can be modelled as an optimal rotation problem, natural hazard decreases rents and the value of the stock in aquaculture. For the northernmost aquaculture facilities the melting of the polar ice may decrease salinity in the water below the range in which salmonid species thrives. An sub-optimal salinity will affect growth of salmon, reducing the value of the stock.

2.2.3 Indirect effect of climate change on aquaculture in Norway

Fisheries and marine ecosystems are dependent on factors such as temperature, pH, and flows of currents. A change in the ecological factors may affect the expected yield from fisheries negatively, directly and indirectly via the ecosystem (Brander, 2007). Higher sea temperature may increase the jellyfish[3] population, which may damage the aquaculture industry by causing gill disorders and by fouling net pens (Purcell, Baxter, and Fuentes, 2013). Due to decline in winter ice in the polar regions polar bears will be able to hunt less seals (*How do Polar Bears Hunt Seals?* 2018). Hence, humans may face increased competition from seals for the fish stocks in the northernmost parts of Norway. This could result in more expensive input factors for the aquaculture, and it may lead to less competition from traditional fisheries. The fish stocks will probably not be over-exploited, or decimated, since the Norwegian government has implemented Individual Vessel Quotas (IVQs) as a fisheries management system (Standal and Aarset, 2008). But with a lesser yield, the supply of fish meal and fish oil will be more expensive. If fish meal is an essential input in aquaculture production, and only partial substitutable by other protein sources, then the feeding costs in aquaculture will become more expensive (Asche and Bjorndal, 2011). Fish meal has both higher protein content, and a different nutritional structure compared to other protein meals.

Climate change may lead to fish stock shifts from one nation to another (Diekert and Nieminen, 2017). This may shift a nation's incentive from conservation of the stock, to depletion of the stock. A shift in incentives may indirectly strain in international relations if there are no binding agreements between the nation from which the fish stock shifts and the nation the fish stock shifts from. If there are changes to international trade due to climate changes, both the export of fish and the import of input factors may be affected. If the access to the Asian markets are restricted, salmon from Norwegian needs to be sold in the European market. This would drive prices for salmon down. Norwegian aquaculture industry would probably have difficulties remaining profitable if the access to the European markets were limited. Roche Vitamins, based in Switzerland, is the largest producer of astaxanthin to the aquaculture industry (Alfnes et al., 2006). Hence, one of the most important input factors for fish farming in Norway are dependent on international trade.

2.3 Regulation of the Aquaculture Industry

Since aquaculture can be considered to be the controlled form of fishing, I will start this section regarding regulation with the regulation of inland fisheries in the time before aquaculture emerged as an industry. I will then briefly describe how regulation of aquaculture has evolved over time. Lastly I will describe the current

[3]Especially the Lion's mane jellyfish (*Cyanea capillata*) represents a risk for the aquaculture industry.

act regulation of aquaculture. The regulations discussed in Section 2.3 dictates the operations of aquaculture, regulation regarding trade will not be discussed.

2.3.1 Pre-aquaculture

Laws regulating inland fishing has existed in Norway since the 13th century, granting riparian rights for fishing in rivers (Chutko, 2011). This entails that landowners ajoined to rivers had rights to fish as long as they did not impede the flow of the river. Since salmon has their spawning ground up river in the lakes where they spawned themselves, it was far more efficient fishing salmon at the river compared to fishing at sea. Conflicts regarding allocation of resources, lead to new laws regulating fishing of salmon were adopted in the middle of the 19 th century. Increasing use of fishing nets at the estuaries blocking the path up rivers for salmon, were especially disconcerting for landowners up river. During the 1850s wealthy Brits began regularly using Norwegian rivers for sport fishing as a recreational activity. This lead to a very profitable practice of renting out fishing rights for landowners up river, and a strong economic incentive for stricter regulation for fishing down river.

2.3.2 Current regulation

The first regulation of the Norwegian aquaculture industry was implemented in 1973 (Asche and Bjorndal, 2011). The current act regulating (Fiskeridepartementet, 2008) was first implemented in 2008, by The Norwegian Ministry of Trade, Industry and Fisheries ("*Nærings- og fiskeridepartamentet*"). It was last amended 19.04.2018. It is a general act regulating aquaculture industry, with special regulations for: fish for consumption, brood fish, crustaceans and molluscs, and cleaner wrasse. The act regulates locations in seawater containing fish meant for consumption or breeding needs to be fallowed for a minimum of 2 months after each production cycle (§4-40). Other examples are the maximum allowable total biomass for each production unit (§4-47), and maximum number of fish for each production unit (§4-47a).

3. Literature review

3.1 Optimal harvest in aquaculture

The theory of optimal management of renewable resources is based on theory developed for forestry management. For a forestry the decision variable is time of harvest. Hence, we often call it the optimal rotation decision. Foresters and economists argued whether the two school of thoughts for optimal solution was the maximum sustainable yield solution or the optimal solution for a single rotation (Amacher, Ollikainen, and Koskela, 2009).

In 1849 Martin Fautsmann argued that the optimal time for harvest in a forestry with infinite rotations is when the marginal value of delaying the harvest of the current stand is equal the sum of marginal costs of delaying the harvest. The sum of the marginal costs of delaying harvest is the marginal cost of delaying the current stand plus the marginal cost of delaying the future stands. This is commonly referred to the Faustmann's formula, though it was Max Pressler (*1850*) and Bertil Ohlin (*1923*) [1] who showed it mathematically. Kirilenko and Sejo (2007) estimated that the effects from climate changes on the profitability of forestry will vary depending on regional climate changes, some will be positively affected, others will be negatively affected. IPCC (2001) predicts that boreal forestry may benefit from an increase in average temperature, whilst tropical forestry will likely be less profitable.

The control of production process is substantially higher in profitable aquaculture compared to fisheries (Asche, 2008), which leads to different decision factors for fisheries and aquaculture. Asche argues that aquaculture is stock cultivation, which is comparable to forestry and agriculture, and less so fisheries. Hence, the optimal management of a aquaculture solves the optimal rotation time in accordance with the Faustmann formula. The optimal rotation time according to the Faustmann formula is when the growth rate of the biomass is equal to the sum of the real

[1] Ohlin worked it out independently of Pressler

rate of return and the opportunity cost of the facility (Lorentzen and Hannesson, 2006).

A simplified version (Guttormsen, 2008) of the process of salmon aquaculture can be described in with the following steps; (i) the farmer releases a certain amount of recruits into the pen (ii) the fish is fed for a certain amount of time (iii) the farmer decides when to harvest the fish. By vertical integration, the fish farmer may also control the process of producing smolt (upstream) and slaughtering (downstream). However, for simplification models are often made without the vertical integration factor. This factor can later be added to obtain adjusted models.

3.1.1 Growth function for Atlantic Salmon in Norway

The growth function describes how an individual salmon's growth evolves depending on the function's variables. Lorentzen and Hannesson estimates (2006) that the growth function for Atlantic salmon in Norway should take the form of a logistic growth function based on laboratory studies. Thyholdt (2014) argues the same based on regional empirical data from aquaculture plants from the South, Middle and North of Norway. Both Lorentzen and Hannesson, and Thyholdt rejected the Von Bertalanffy's growth function, and rejected the exponential growth function for describing the growth of Atlantic salmon. Growth depends on amount of daylight in combination with temperature, modern aquaculture facilities uses artificial light sources to stimulate growth (Asche and Bjorndal, 2011). Assuming the cost of providing light is negligible, i.e. optimal light is assumed provided at no cost, number of hours of daylight will not be included in the model.

Further analysis will be based on Lorentzen and Hannesson's (2006) model of logistic growth for Atlantic salmon in the Norwegian salmon aquaculture. Due to similarities between the decision factors in fish farming and forestry, the most common way to model optimal time of harvest is by using the Faustmann formula.

3.2 Mortality as a function of temperature and weight

Lorentzen and Hannesson (2008), Thyholdt (2014) and Guttormsen (2008) treats mortality as constant in their models. This is a somewhat reasonable simplification. However, they recognize that in reality mortality rate is not constant with regards to temperature. In fact, temperatures exceeding 20 degrees may inflict total loss of the biomass due to mortality (Lorentzen and Hannesson, 2006). In the IMR's report (2018) they argue that mortality for salmon in Norwegian aquaculture is dependent on both the individual's weight and the sea temperature. Since Salmon is both an ectotherm and an r-strategist, it makes sense from a biological perspective to model mortality rate as dependent on temperature and weight. By law (§2-16), Norwegian aquaculture facilities are required to remove dead salmon from the pens daily and treat the waste. The removal requires labor which leads to extra costs due to mortality. However, the incurred costs from mortality in the aquaculture will be treated as negligible in the further analysis, in part since I will not account for other cost elements in the analysis. Hence; in the model, the loss incurred from mortality will be strictly a result of the loss in potential sales.

4. Methodology

In this chapter how the model were built from bioeconomic theory will be briefly explained, the sources for the empirical data will be disclosed, and a explanation of how results of the analysis were calculated. In Section 4.2 I will declare the source of the data set for the regression analysis, and briefly explain what operations were made on the data set in order to not include flawed observations

4.1 Building the model

In Chapter 5 I will describe which assumptions have been made in order to model growth of salmon, number of salmons in the fish farm depending on time, when and how harvesting can be conducted, as well as starting a new rotation.

4.1.1 Growth function

The growth function used in the analysis were derived by Lorentzen (2008) by refining the model he and Hannesson (2006) estimated from regression analysis of raw data from controlled experiments by producers of feed for the aquaculture industry. The controlled experiments measured growth for juvenile salmons at different, constant temperature regiments. The different regiments were integer degrees in the range from 1 to 18 degrees Celsius. Hence, for temperatures outside of the given range the growth function may not be applicable. However, I will assume that the growth function is valid for all projected temperatures.

The continuous model for number of fish in the fish farm will be presented in Section 5.1, and I will show how it can be adjusted to a discrete model. The reason for adjusting the model into a discrete version is that one of the assumptions in Chapter 5 is that fish farmers can only harvest at the beginning of any one month. The logistic growth function (LORENTZEN, 2008) will then be presented and I will explain the parameters and variables more closely. I will briefly comment on the assumed starting weight and maximum weight of an individual salmon. In Section 5.2 I will introduce rotations in the model and explain how a rational fish farmer will act in order to optimize the value of the aquaculture based on decision variables.

4.1.2 Prices

Prices in the model will be based on prices retrieved from the NASDAQ Salmon Index (2018). The index includes weekly data from the period 2013-2018. Weekly average kg prices depend on the weight class of the salmon sold. NASDAQ have classified the weight classes as 1 kg ranges from 1-9 kg, e.g. one weight class is 4-5 kg. Salmon lighter than 1 kg is not included, and salmon heavier than 9 kg are grouped together.

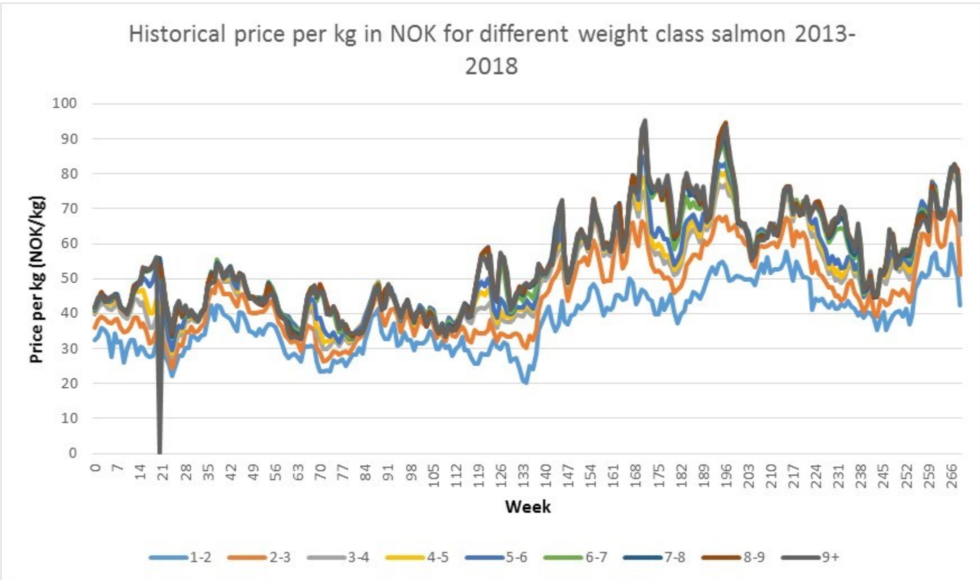


FIGURE 4.1: Weekly average sales prices per kg in NOK for salmon from 2013 to 2018, source: NASDAQ Salmon Index (2018)

Figure 4.1 shows how the weekly average kg prices in NOK for salmon have developed over time for the different weight classes. The y-axis shows the kg price in NOK. The x-axis shows number of weeks after the starting point in 2013. The kg price for the weight classes 1-2 kg and 2-3 is consistently less than the heavier weight classes. For the weight class 1-2 kg, the kg price is most weeks less by a clear margin. Not included in Figure 4.1 is the grouping of the weight classes 3-4 kg, 4-5 kg and 5-6 kg into the group weight class 3-6 kg which NASDAQ includes in their index. We see from the sales distribution of the group weight class 3-6 kg in Figure 4.2, that the group class 3-6 kg consistently makes up between 60 and 85 percent of total sales in the period. For this reason and the fact that prices are lower for the weight classes 1-2 kg and 2-3 kg, I make a distinction between kg prices for salmon in the weight classes: less than 1 kg, 1-2 kg, 2-3 kg and more than 3 kg. The kg prices used in the analysis are the average kg prices of the whole period for said groupings. It is assumed that salmon less than 1 kg can not be sold, hence have a kg price of 0 NOK. Prices for the different weight classes used in the model will be presented in Table 5.2 from Section 5.4. Because there is assumed no cost for attaining new salmon at the start of the rotation, there would be possibilities for arbitration is prices exceed 0 in the start of the rotation. In reality there could be possible to sell fish less than 1 kg to other fish farmers, but with no chance of arbitration.

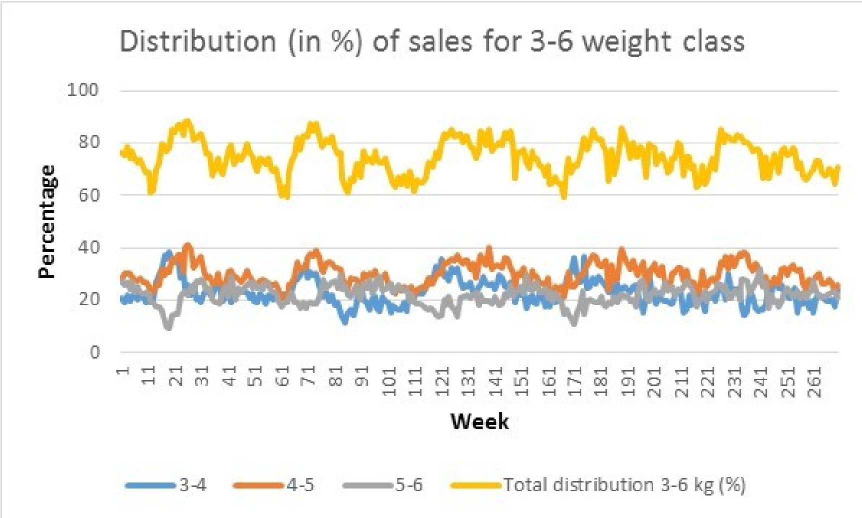


FIGURE 4.2: Sales distribution for weight classes $3-4$ kg, $4-5$ kg, $5-6$ kg and total distribution for $3-6$ kg from 2013 to 2018, source: NASDAQ Salmon Index(2018)

4.2 Regression, mortality rate

The regression in Section 6.1 will be based on anonymized data given by Lars Helge Stien from IMR upon request. The original data were used in IMR's "*Risk report for Norwegian aquaculture*" (2018) to analyze how temperature affects mortality rates in Norwegian salmon aquaculture.

Using four heatmap-graphs, figure 4.3 shows the self-reported mortality rates from Norwegian aquaculture facilities in the period 2009-2016 (Grefsrud et al., 2018). The x-axis shows average temperature of the seawater in degrees Celsius the previous month, and the y-axis shows the average weight of the fish the previous month. The report date of the mortality rates was the first day of the month. Figure 4.3 seem to show a possible effect on mortality rate seawater temperature. In Section 6.1 I will estimate a function for monthly mortality rate for fish in Norwegian aquaculture.

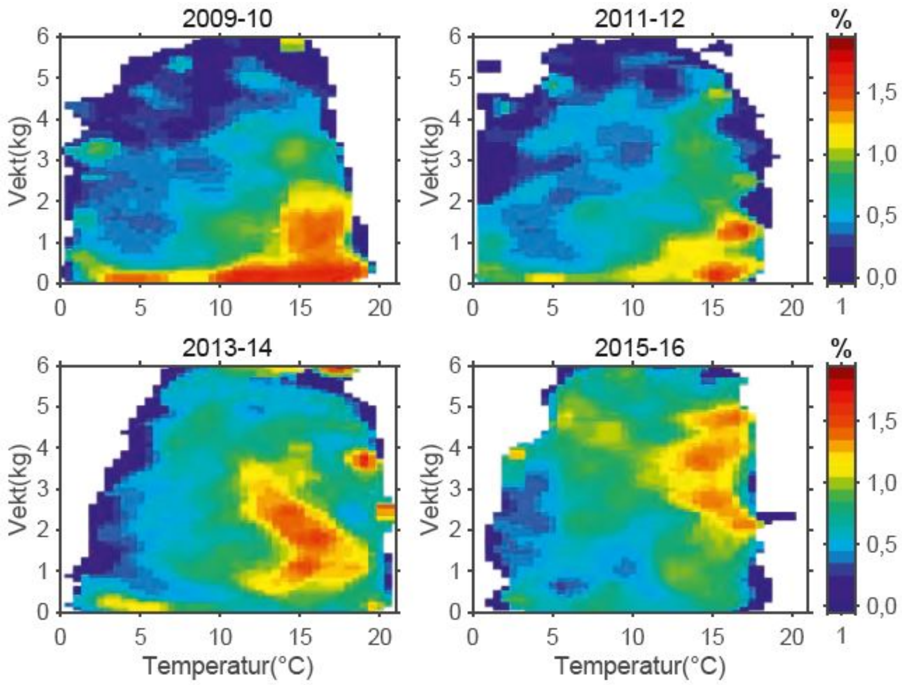


FIGURE 4.3: The relationship between mortality rate in Norwegian salmon aquaculture, and sea temperature and the average weight of fish, source: *IMR* (2018)

Points with negative weight, and weight equal to 0 kg were dropped from the analysis. They were dropped because neither negative nor no weight is a possibility. Observations with monthly mortality rates of 10 percent, or higher, were considered to be outliers caused by other factors than temperature. The assumption is that these high mortality rates were caused by non-included factors such as outbreaks of algae or sea lice etc. A total of 724 observations out of 50 998 observations were dropped from the analysis.

4.3 NPV calculations

In Section 6.2 I will present scenarios for changes to the temperature function (5.27), and show how the affect the seasonal temperatures. I will then present the results for NPV and how fish farmers can possibly add value by changing their decision variables. The results will be presented for each scenario individually and summarized at the end. In order to calculate the results for the NPVs for the different scenarios I used Microsoft Excel. The figures showing the results for the NPVs under different scenarios were made in Excel.

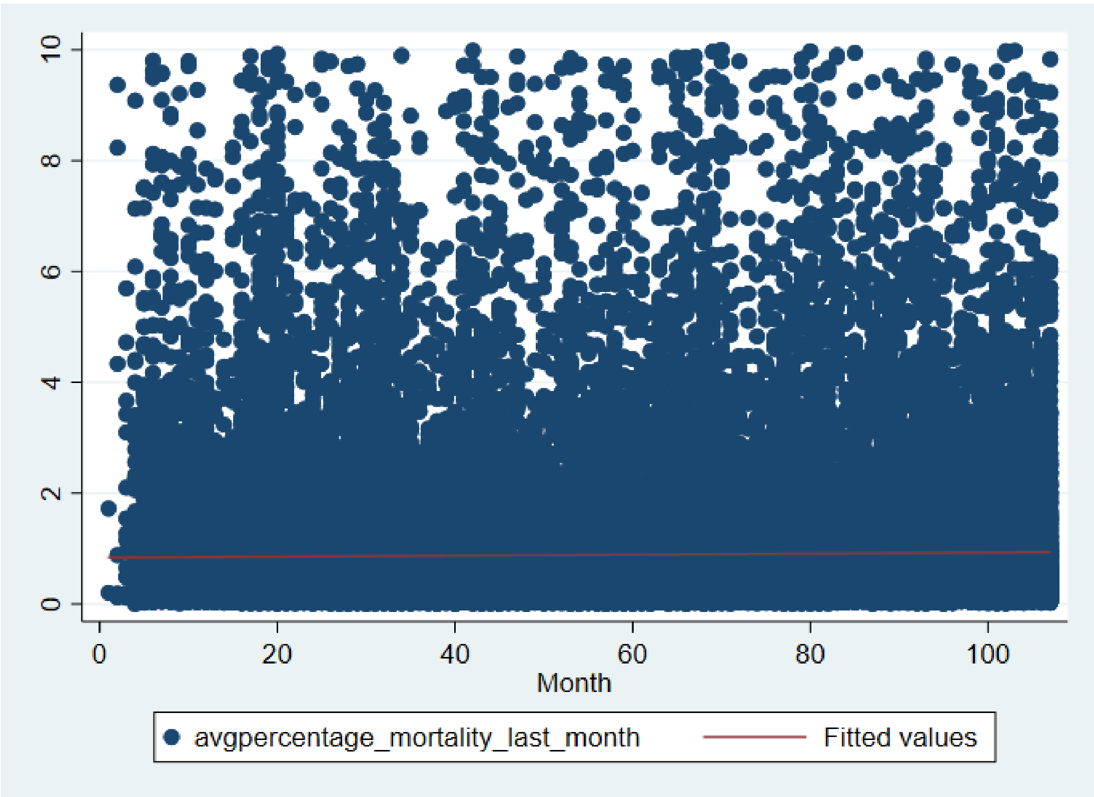


FIGURE 4.4: Scatter plot of mortality rates in Norwegian Salmon aquaculture (IMR) over time with the corresponding linear regression.

5. Model

In this chapter I will in Section 5.1 describe the assumptions that were made in order to build the model for NPV in Section 5.2. The function used to project the seasonal temperatures is introduced in Section 5.3. Finally, I will present the parameter values used in the model in Section 5.4.

5.1 Model assumptions, and building the model

An assumption needed is that the fish farmers maximizes the present value of the future cash flows from the aquaculture. In order to simplify the model, we assume no feeding costs, and no harvesting costs. This simplification It is fairly easy to adjust the model by adding the cost elements. Harvest will be assumed to be a binary choice, i.e. either the fish farm harvests all salmon in the period, or no salmon in the period. Another assumption is that the numbers of year classes in a fish farm at any given time is restricted to one year class. This is in accordance with Norwegian regulations on aquaculture plants (*Regulations on the operation of aquaculture plants (NOR)*2008). Hence, we assume one simultaneous rotation, and harvesting decisions to be binary.

Recruitment is in the model assumed determined either by technological or legal restrictions, and recruitment is assumed constant throughout the analysis. Assuming a constant mortality rate M, we have that the number of fish in the pen at time t can be expressed in a continuous expression as

$$N(t) = N_0 e^{-\int_0^t M(u)du}$$

Where $N(t)$ is the number of fish at the farm at time t. The recruitment is the number for fish for at the start of the rotation, it is common practice to denote the recruitment as R in optimal rotation problems (Asche and Bjorndal, 2011). $M(u)$ is the mortality function. The mortality function may be multivariate hence, the notation of u. Several prior studies assume that mortality rate is constant, i.e. $M(u) = M$

(LORENTZEN, 2008; Guttormsen, 2008; Thyholdt, 2014). This leads to the former expression to be rewritten as

$$N(t) = Re^{-Mt} \tag{5.1}$$

When using a discrete expression for describing mortality rate, we have that in the first period after the release the number of fish is equal to the number of fish that survived the previous period. This is equivalent to saying the number of fish from the previous period times the share of fish that survived the previous period. The share of fish that survived the previous period is equal to 1 minus the share of fish that did not survive the previous period.

$$N_1 = N_0 \cdot (1 - m_0) = R(1 - m_0)$$
$$N_2 = N1 \cdot (1 - m_1) = R(1 - m_0)(1 - m_1)$$
$$\vdots$$

$$N_t = R(1 - m_0)(1 - m_1) \cdots (1 - m_{t-1}) = R \cdot \prod_{k=0}^{k=t-1} (1 - m_k) \tag{5.2}$$

Here $\prod$ is the product of all terms from $k = 0$ til $k = t - 1$. When assuming constant monthly mortality rate we have that the number of fish can be described as the following discrete function

$$N_t = N_0(1 - m)^t \tag{5.3}$$

Where m is the fixed discrete monthly mortality rate.

The growth function for Norwegian salmon in aquaculture used in this thesis is based a logistic growth function estimated by Lorentzen and Hannesson (2006). They estimated the growth function based on raw data from controlled experiments organized by producers of feed for the aquaculture industry. In the controlled experiment, daily percentage increases in weight for juvenile salmon were measured given different, constant temperature regimes.

The logistic growth function estimated at different temperatures is expressed as

$$w(t) = \frac{1}{\alpha + \beta \cdot \gamma^t} \tag{5.4}$$

In equation (5.4) α and β are biological parameters independent of temperature, whilst γ_t is a temperature dependent parameter. The temperature dependent parameter γ can be calculated the following way

$$\gamma = e^{-z \cdot S + D_1 \cdot x_1 + D_2 \cdot x_2} \tag{5.5}$$

Where S is the temperature of seawater in the pen, and z is the estimated parameter. D_1 and D_2 are dummy variables dependent on temperature of seawater. The dummy variables are for 17 degrees and 18 degrees respectively, with x_1 and x_2 as the associated estimated parameter values.

$$\mathrm{D}_1 = \begin{cases} 1, & \text{if} \quad S \geq 17 \\ 0, & \text{if} \quad S < 17 \end{cases} \quad , \quad \mathrm{D}_2 = \begin{cases} 1, & \text{if} \quad S \geq 18 \\ 0, & \text{if} \quad S < 18 \end{cases}$$

From equation (5.4) we have that weight depend on t, and that γ is raised to the power of t. From equation (5.5) we have that γ is dependent on seawater temperature, S. Combining equation (5.4) and equation (5.5), we have that weight depends on both time and seawater temperature

$$w(t, S) = \frac{1}{\alpha + \beta \cdot (e^{-zS + D_1 x_1 + D_2 x_2})^t} \tag{5.6}$$

Using the facts that

$$e^A > 0, \quad \forall\, A$$

$$e^{-A} < 1, \quad \forall\, A > 0$$

We can from equation (5.5) infer that γ is greater than 0 and less than 1.

$$z \cdot S + D_1 x_1 + D_2 x_2 > 0 \implies 0 < \gamma < 1 \tag{5.7}$$

The discrete version [1] of the logistic growth model substitutes the continuous variable γ^t by the discrete variable $\prod^t$,

$$w_t = \frac{1}{\alpha + \beta \cdot \prod^t} \tag{5.8}$$

where $\prod^t$ is the product of the discrete $\gamma_{\Delta t}$'s from period 1 until period t and 1.

$$\prod^t = \gamma_1^{\frac{1}{12}} \cdot \gamma_2^{\frac{1}{12}} \cdots \gamma_t^{\frac{1}{12}} \tag{5.9}$$

[1] For derivation of the discrete version see Lorentzen (2006)

Since $\prod$ at period 0 is equal to 1, the weight at period 0 is given as

$$w_0 = \frac{1}{\alpha + \beta} \tag{5.10}$$

Hence, from equation (5.10) we see that the biological parameters α and β determines the weight of the start of the rotation.

By taking the limit when t tends to infinity of equation (5.4) we can find what the theoretical maximum weight of an individual salmon according to the model

$$\lim_{t\to\infty} w_t = \lim_{t\to\infty} \frac{1}{\alpha + \beta \cdot \prod^t} \tag{5.11}$$

The parameters α and β are biological parameters not dependent on time. From equation (5.7) we have that $\prod$ is greater than 0 and less than 1. Hence, we can simplify equation (5.11) as follows

$$\lim_{t\to\infty} \frac{1}{\alpha + \beta \cdot \prod^t} = \frac{1}{\alpha + \beta \cdot \lim_{t\to\infty} \prod^t} \tag{5.12}$$

$$\implies \frac{1}{\alpha + \beta \cdot 0} = \frac{1}{\alpha} \tag{5.13}$$

Hence, from equation (5.13) we see that the biological parameter α determines an asymptotic weight. This simply means that there is a maximum weight for an individual fish. The fish farmers' objective is to maximize the discounted value of all future cash flow from the fish farm. Hence, (5.13) and (5.10) serves more as indications that equation (5.6) is a realistic growth function, rather than give an intuition regarding optimal rotation time.

5.2 Multiple rotations, with no costs

Fish farmers with optimal rotation time maximizes NPV of all future rotations. When modelling the NPV we assume that the farmers will with regular time intervals receive the value of harvesting. The received value needs to be discounted according to the discounting factor and time. For continuous models the discounting needs to be continuous, whilst discrete models can use continuous and discrete discounting. Hence, when not accounting for costs the NPV of the aquaculture can been viewed as an infinite geometric series of the values of infinite amounts of harvests that farmers receive with regular intervals. We could model the NPV as a finite geometric series, but since the difference is relatively small[2] we will use infinite series. This is because the purpose of the model is to offer insight of the value of adapting, not reflect an actual valuation of adapting. An assumption in the model is that the setting time of the stock is the same for all periods. There are no restrictions for when fish farmer can start a new rotation, other than the demand for non-simultaneously year-classes.

The value of each harvest is dependent on the price for salmon and the biomass of the stock. Further, the biomass of the stock is dependent on how much each individual fish weigh, and how many fish still lives this far into the rotation.

$$V_t = p_i \cdot B_t = p_i \cdot w_t \cdot N_t \tag{5.14}$$

Where V_t is the value of a rotation. B_t is the total biomass of the rotation at time t, p_i is the kilogram price of salmon depending on which weight class the salmon is at during time t, w_t is the weight of an individual salmon at time t, and N_t is the number of fish in the pen at time t.

The net present value of the aquaculture is the discounted values of all future incomes. This can be described as a geometric series, described as

$$NPV = V_t \cdot e^{-rt} + V_t \cdot e^{-2rt} + V_t \cdot e^{-3rt} + \dots \tag{5.15}$$

Multiplying both sides by e^{rt}

$$NPVe^{rt} = V_t + V_t e^{-rt} + V_t e^{-2rt} + \dots \tag{5.16}$$

Subtracting the first expression (5.15) from the second expression (5.16) yields

$$(e^{rt} - 1)NPV = V_t \tag{5.17}$$

Dividing by $(e^{rt} - 1)$ we get

$$NPV = \frac{V_t}{e^{rt} - 1} \tag{5.18}$$

By substituting V_t with the expression in (5.14) we have that

$$NPV = \frac{p_i \cdot w_t \cdot N_t}{e^{rt} - 1} \tag{5.19}$$

[2]See (A.2) for calculations for how many rotations are needed for the difference to be negligible

Hence, the rational fish farmer will choose rotation time t such that it that maximizes equation (5.19). In a continuous model the time variable is continuous, and optimal time of harvest can be calculated. For a discrete model the time variable is discrete, and optimal time of harvest must be chosen among a set of possible times of harvest. In this thesis, the model used will have the set of possible times of harvest is the beginning of each month, $t^* \in [0, 1, \dots, 40]$. Where $t = 40$ is used as a sufficiently large upper limit.

Equation (5.19) can be rewritten using equation (5.8) to substitute for w_t. Which yields

$$NPV = \frac{p_i N_t}{(\alpha + \beta \cdot \prod^t)(e^{rt} - 1)} \tag{5.20}$$

Where NPV can be described as a multivariate function, with time and temperature as variables. From a combination of equations (5.5) and (5.9) we can see that variable affecting the growth of salmon in (5.20) is dependent on temperature. In Section 6.1 I will show that the monthly mortality rate is dependent on temperature, which means that N_t in (5.20) is dependent on temperature.

5.2.1 Faustmann's formula

In order to link equation (5.20) to the theoretical foundation derived by Faustmann and Ohlin, we need to go back to the continuous model with constant mortality rate. In order to find the optimal rotation time we need to derive the discounted value of all future profits by time

$$\max_t \left(\pi(t) = V(t)e^{-rt} + V(t)e^{-r2t} + \dots \right) \tag{5.21}$$

Where π is the sum of all the discounted future profits, NPV earlier in the model. By using the sum of the geometric series from equation (5.18) and subsituting $V(t)$ for $pw(t)N(t)$ we get

$$\max_t \left(\pi(t) = \frac{pw(t)N(t)}{e^{rt} -} = \frac{pw(t)Re^{-Mt}}{e^{rt} -} \right) \tag{5.22}$$

By setting the derivative equal to 0, we get

$$\frac{(pw'(t)Re^{-Mt} - pw(t)MRe^{-Mt})(e^{rt} - 1) - re^{rt}pw(t)Re^{-Mt}}{(e^{rt} - 1)^2} = 0 \tag{5.23}$$

Since a fraction can only be equal to 0 if the numerator is equal to 0[3], we have that

$$pw'(t)Re^{-Mt}(e^{rt}-1) - pw(t)MRe^{-Mt}(e^{rt}-1) - re^{rt}pw(t)Re^{-Mt} = 0 \tag{5.24}$$

Dividing (5.24) by $pRw(t)e^{-Mt}(e^{rt}-1)$ we get

$$\frac{w'(t)}{w(t)} - M - r\left(\frac{e^{rt}}{e^{rt}-1}\right) = 0 \tag{5.25}$$

Rearranging the terms yields and adding and subtracting by 1 in the numerator

$$\frac{w'(t)}{w(t)} = M + r\left(\frac{e^{rt}-1+1}{e^{rt}-1}\right)$$

$$\implies \frac{w'(t)}{w(t)} = M + r\left(\frac{e^{rt}-1}{e^{rt}-1} + \frac{1}{e^{rt}-1}\right)$$

$$\implies \frac{w'(t)}{w(t)} = M + r + \frac{r}{e^{rt}-1} \tag{5.26}$$

Where $w'(t)/w(t)$ is the relative growth rate of the fish, $M + r$ is the opportunity cost of not selling the fish, and $r/(e^{rt}-1)$ is the alternative cost of keeping the fish in cages not substituting for younger faster growing fish. The left hands side of equation (5.26) is the marignal value of delaying harvest, whilst the right hand side of the equation is the marginal cost of delaying harvest.

5.3 Temperature as a cosine function

When sunlight hits Earth, the sunlight can either be absorbed or reflected. If sunlight is absorbed, it increases the energy of the system into which the sunlight is absorbed. This can lead to higher temperature in the absorbing system. Due to the earth's axial tilt, the amount of sunlight Norway receives per day can be described as a cosine function, with the period of one year. The average temperature in Norway is high compared to other places with the same latitude. The reason for higher average temperature in Norway is the Gulf Stream. Hence, temperature in Norway can be approximated to a cosine function with respect to time.

$$S(t) = \phi \cdot \cos\left(\frac{2\pi(t-\psi)}{T}\right) + \omega \tag{5.27}$$

[3]Nothing can be equal to infinity! If the denominator could be equal to infinity, the nominator would not have to be equal to 0 and this reasoning would be flawed

Where S is the expected seawater temperature at time t. The amplitude ϕ is the range between the coldest and warmest expected seawater temperature. T is the period of the function and π is a mathematical constant. Time t is the variable of the function. The adjustment factor ψ shifts the function horizontally and is estimated according to when the start of the rotation is relatively to the warmest month. The yearly average seawater temperature is denoted as ω.

Lorentzen (2008) described seawater temperature as a sine function. But since $\sin(v) = \cos\left(\frac{\pi}{2} - v\right)$ the main difference is how the adjustment factor is calculated. A cosine function without adjustment starts at the maximum value, whilst a sine function starts at the middle value without adjustment. Hence, for $\psi > 0$ the adjustment factor for a cosine function is the number of time units to the right the maximum is relative to the starting time. For sine functions the adjustment factor is less intuitive. For this, reason I chose to use a cosine function rather than a sine function.

Different locations in Norway will have different parameter values. Daily, even hourly, temperature fluctuations are expected. Hence, equation (5.27) is supposed to describe expected temperature. In the further analysis the temperature function is describing expected temperature for the aquaculture facility in Lista (LORENTZEN, 2008).

Some of the energy the environment absorbs from sunlight will be emitted as infrared radiation due to black body radiation [4]. Green house gasses in the atmosphere is able to reflect infrared radiation back towards Earth. Hence, we will assume that in periods with more sunlight, more infrared radiation may be reflected back to earth compared to periods with less sunlight. In other words, we assume that the projected climate change is more likely to increase the amplitude parameter, rather than decrease the amplitude parameter. Hence, in the following scenarios only increasing, or constant, amplitude scenarios will be included. IPCC (2001) argues for an increase in average sea temperature in the North Atlantic in their report. Hence, only positive shifts, or no shift, in average temperature will be included in the scenarios.

We will assume that the changes in the average and the amplitude for the temperature function are instantaneously. However, gradual changes in averages and amplitudes are more realistic.

[4] Stefan-Boltzmann law for black body radiation derived in 1879

5.4 Parameters

The parameters values for the growth function in Table 5.1 are based on Lorenzten (2008). Lorentzen and Hannesson (2006) estimated the parameters through regression analysis of raw data from laboratory tests conducted by feed producers for the aquaculture industry.

α	β	z	x_1	x_2
0.11	5.32	0.388	0.73399	1.7005

TABLE 5.1: Parameter values for growth function of Atlantic salmon. (LORENTZEN, 2008)

Prices that are used for the different weight classes in Table 5.2 are the average prices for the period $2013-2018$ (NASDAQ, 2018). The share of fish that are harvested in the weight classes between $3-6$ kg is steadily around 60 to 85 percentage of the total amount of fish sold[5].

Weight class	**Less than 1 kg**	**1-2 kg**	**2-3 kg**	**3+ kg**
Price in NOK	0	38.29	45.34	51.66

TABLE 5.2: Price in NOK per kg salmon for different weight classes of salmon (*source: NASDAQ (2018)*)

The expected seawater temperature function is based on the temperature function for the aquaculture facility located in Lista, Norway (LORENTZEN, 2008). The function implies that expected temperature ranges from 3.66 degrees Celsius to 13.14 degrees Celsius.

	Amplitude	**Average**	**Adjusting factor**	**Period**
Symbol	ϕ	ω	ψ	T
Value	4.74	8.40	1	12

TABLE 5.3: Values used in the temperature functions for the aquaculture located in Lista, Norway (LORENTZEN, 2008)

[5]See Figure (4.2)

6. Results

In the following chapter I will present the results of the regression analysis in Section 6.1. I will discuss why I have used one the regressions, whilst the others are not as relevant. In Section 6.2 I will explain what the scenarios entails in form of changes, and I will present the result for how the changes affect NPV and the potential value of adapting to the changes.

6.1 Regressions, mortality rate

In order to see whether there might be a time trend in the data, we have a regression with mortality rate as the dependent variable and month as the independent variable. As shown in Table 6.1 there seem to be a clear correlation between month and mortality rate. Hence, in the regression used to model mortality rate, month should be added as a control variable. The observations span multiple rotations. To include month as a variable would mean that we expect the time trend to be valid across rotations. This may be accurate if the surroundings for the pens, or the pens themselves, used for fish farming leads to increasing mortality rates with multiple rotations. In Norway there are clear regulations concerning cleaning between rotations in fish farming. As a result, month will be regarded as a control variable for the regression. But month will not be included as a variable in the model.

$$\hat{m} = \hat{\beta}_1 Month + \hat{\beta}_0 \tag{6.1}$$

The linear regressions of mortality rate with regards to average temperature and weight are statistically significant, see Table 6.2. Though for the different periods the coefficient for the weight component is both positive (for month< 36 and month> 72) and negative (for $36 <$month≤ 72), see Table 6.3. This combined with Figure 4.3, which shows mortality rates for different combinations of temperatures and weights, I argue that we should introduce non-linear variables.

	Mortality rate
Month	0.000962^{***}
	(4.54)
Constant	0.836^{***}
	(60.33)
N	50 275

t statistics in parentheses
$^{*}p < 0.05, ^{**}p < 0.001, ^{***}p < 0.001$

TABLE 6.1: Regression of mortality rate in Norwegian salmon aquaculture facilities (2009-20017) with month as an independent variable

	Mortality rate
Weight	0.0000337^{***}
	(11.50)
Average temperature	0.0390^{***}
	(22.83)
Month	0.000250
	(1.17)
Constant	0.454^{***}
	(22.04)
N	50 275

t statistics in paranthesis
$^{*}p < 0.05, ^{**}p > 0.01, ^{***}p < 0.001$

TABLE 6.2: Regression for whole period with mortality rate as dependent variable, weight average temperature, and month as independent variables.

	Mortality rate for month≤ 36	Mortality rate for $36 <$month≤ 72	Mortality rate for month > 72
Weight	-0.000108^{***}	0.0000393^{***}	0.000128^{***}
	(-17.38)	(9.15)	(25.72)
Avg temp	0.0371^{***}	0.0393^{***}	0.0409^{***}
	(11.15)	(15.53)	(13.65)
Constant	0.812^{***}	0.356^{***}	0.297^{***}
	(23.79)	(13.35)	(9.19)
N	13 595	18 603	18 077

t statistics in paranthesis
$^{*}p < 0.05, ^{**}p > 0.01, ^{***}p < 0.001$

TABLE 6.3: Regressions with mortality rate as the dependent variable. The independent variables are weight and average temperature. The regressions are for different periods.

From a biological analysis we have that there is an optimal range for mortality rate with regards to temperature (Lorentzen and Hannesson, 2006). This is true for most (all) living beings, but especially true for ectotherms. Hence, the regression should include a second order term for temperature as well as the first order term. We can deduce that heavier salmon is older compared to lighter salmon. Since harvest is before sexual maturation, age should equate to lower mortality rates. Though the decreasing effect on mortality rate due to age should itself be diminishing. Hence, some form of logarithmic transformation of the weight variable should be included in the regression. Lastly, I will argue that there should be an interaction term of weight and temperature. This is based on assumption that heavier (sturdier) fish handles more extreme temperature better than lighter fish do. As mentioned earlier, month should be added as a control variable.

	Mortality rate
Average temperature	-0.101^{***}
	(-11.74)
(Average temperature)^2	0.00566^{***}
	(12.88)
ln(Weight)	-0.201^{***}
	(-23.75)
Weight·Temp	0.0000137^{***}
	(27.22)
Month	0.000921^{***}
	(4.33)
Constant	2.391^{***}
	(32.33)
N	50 275

t statistics in parenthesis
$^{*}p < 0.05, ^{**}p < 0.01, ^{***}p < 0.001$

TABLE 6.4: Linear regression with non-linear variables for mortality rate in Norwegian salmon aquaculture $(2009 - 2018)$

Estimated monthly mortality rate can be expressed as equation (6.2). In this equation the variable month has not been included, as we assume that the observed time trend for increasing mortality will not hold. Assuming the opposite would conclude that no fish would be able to survive a single month in Norwegian aquaculture. The estimated monthly mortality rate is given in percentages.

$$\hat{m}_{month} = -0.101 \cdot S + 0.00566 \cdot S^2 - 0.201 \ln(w) + 1.37 \cdot 10^{-5} \cdot (w \cdot S) + 2.390 \quad (6.2)$$

By partial derivation we can assess both; how a degree change in temperature, and a gram increase in weight, would affect monthly mortality rate ceteris paribus.

Partial derivation with regards to temperature yields

$$\frac{\partial \hat{m}_{month}}{\partial S} = \frac{\partial}{\partial S}\left(0.101 \cdot S + 0.00566 \cdot S^2 - 0.201 \ln(w) + 1.37 \cdot 10^{-5} \cdot (w \cdot S) + 2.390\right)$$

$$\implies \frac{\partial \hat{m}_{month}}{\partial S} = -0.101 + 0.01132S + 1.37 \cdot 10^{-5} w \tag{6.3}$$

Partial derivation with regards to weight yields

$$\frac{\partial \hat{m}_{month}}{\partial w} = \frac{\partial}{\partial w}\left(0.101 \cdot S + 0.00566 \cdot S^2 - 0.201 \ln(w) + 1.37 \cdot 10^{-5} \cdot (w \cdot S) + 2.390\right)$$

$$\implies \frac{\partial \hat{m}_{month}}{\partial w} = -\frac{0.201}{w} + 1.37 \cdot 10^{-5} S \tag{6.4}$$

From equation (6.3) and equation (6.4) we see that the heavier the fish, the effect of increasing the temperature one degree on monthly mortality rate. By setting equation (6.3) equal to 0 we can find the estimated optimum for mortality with regards to temperature

$$-0.101 + 0.01132S + 1.37 \cdot 10^{-5} w = 0$$

$$S = \frac{0.101 - 1.37 \cdot 10^{-5} w}{0.01132} = 8,916 - 0.0012w \tag{6.5}$$

Hence, from equation (6.5) we see that the optimal seawater temperature with regards to mortality rates are 8.92 degrees for a weightless fish and decreasing 1.2 degrees for every kg increase.

6.2 Scenarios for changes in temperature of sea water in Norway

The postulated changes used in the analysis are shown in Table (6.5). The changes will be the basis for the scenario-based analysis in Scenario I, Scenario II, Scenario III. In Scenario I the postulated changes affect average temperature. In Scenario II the postulated changes affects the amplitude of the temperature, in other words the difference between the coldest and the warmest months. In Scenario III the postulated changes affect both average temperature and the amplitude of temperature.

Change	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0

TABLE 6.5: Changes in used in the scenario-based analysis in Scenario I, Scenario II, and Scenario III

When there are no changes in the temperature function (5.27), the optimal rotation time is 16 months. Since the recruitment were not based on actual data, the nominal value of the NPVs is not as relevant as the relative values of NPVs. Hence, all NPV are stated as a fractional value of the current NPV with optimal rotation time. In mathematical terms

$$NPV_{relative} = \frac{NPV_t^j - NPV_{t^*}^i}{NPV_{t^*}^i} \tag{6.6}$$

Where j can be any scenario, whilst i is the current situation i.e. without changes. And t is any possible rotation time, t^* is the optimal rotation time under the current situation with no change in temperature. $NPV_{relative}$ is the fractional value of current optimal NPV.

In all scenarios the additional value fish farmers may achieve by adapting to the postulated changes were estimated. Fish farmers may adapt by changing the month of harvest and by changing in which month to start the rotation. The additional value of adapting to the postulated changes were measured in terms of percentage of the NPV gained by the postulated change, and not changing time of harvest or month of starting the rotations. In figures 6.3, 6.6, and 6.9; the term "Fixed" refers to not changing time of harvest or starting time of new rotations, the term "Setting fixed" refers to choosing the optimal time of harvest not changing the starting time of new rotations, and the term "Not fixed" refers to changing both time of harvest and starting time of new rotations.

6.2.1 Scenario I: Increases in average temperature

In Scenario I the changes from Table (6.5) will affect the average temperatures. Which means that equation (5.27) can be rewritten as

$$S = \phi \cdot \cos\left(\frac{2\pi(t-\psi)}{T}\right) + (\omega + \omega_{\Delta}) \tag{6.7}$$

Where ω_Δ is the change in average temperature due to climate change.

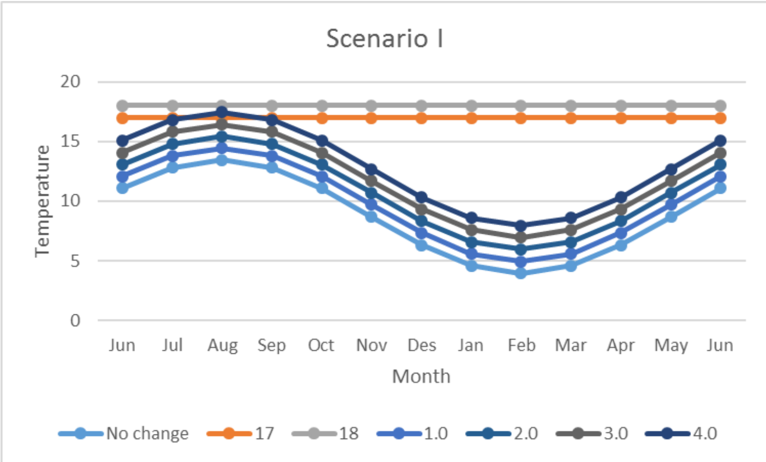


FIGURE 6.1: Seawater temperature for different changes to average temperature

Figure 6.1 shows the seasonal temperatures from June one year to June the following year for different changes to average temperature. As well it shows lines for the degrees 17 and 18, which are the decisive temperatures for when the dummy variables affecting growth function (5.8). Note that in order to get a better overview, only integer changes were assessed in Figure 6.1. We can see that a 4 degree increase in the average temperature, will lead to an affected growth during the months of July, August, and September due to a too high temperature. For Scenario I, we see that every point of projected temperature are shifted upwards the same degree as the increase in average temperature.

From Figure 6.2 we see that the NPV of the fish farm is consistently higher for higher temperatures. E.g. an increase in average temperature of 2 degrees Celsius leads to a strictly larger NPV compared to the NPV for an increase of 1 degree Celsius for any give rotation time. Weight for the individual fish is according to equation (5.8) asymptotic with regards to time. Hence, the NPVs of all the postulated changes in average temperature will with time converge towards no value. Furthermore if the fish farm has a fixed rotation time, it is increasingly better off with increasing average temperatures. The fish farm may, however increase its NPV by changing its rotation time depending on actual change in average temperature.

Figure 6.3 shows that in the event of increases in average temperature equal to 0.5 degree or 1 degree there is no additional value of changing the rotation time from the current optimal rotation time. For temperature increases equal to or larger than 1.5 there are with regards to increase in temperature increasing values from adapting the rotation time to a new optimal rotation time. There are no extra benefit

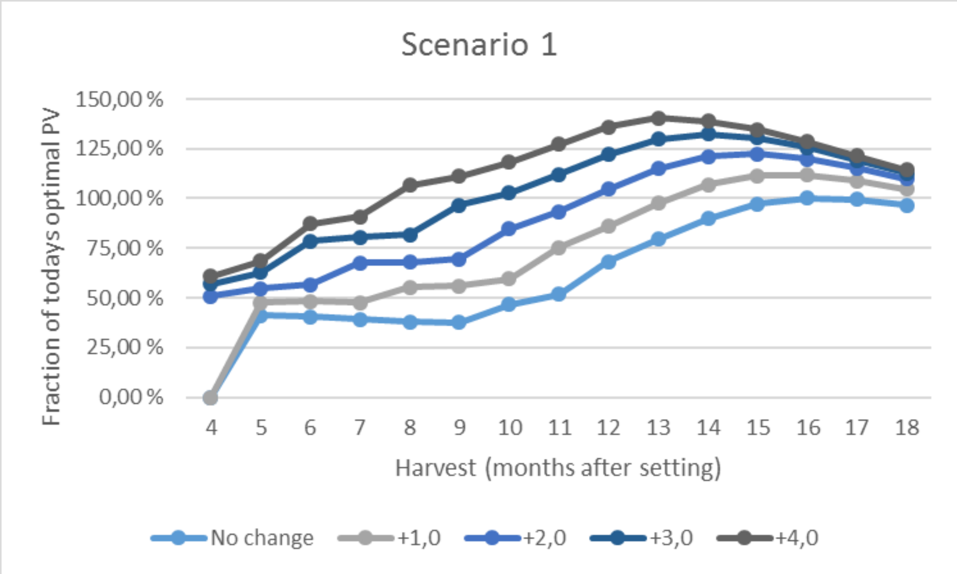
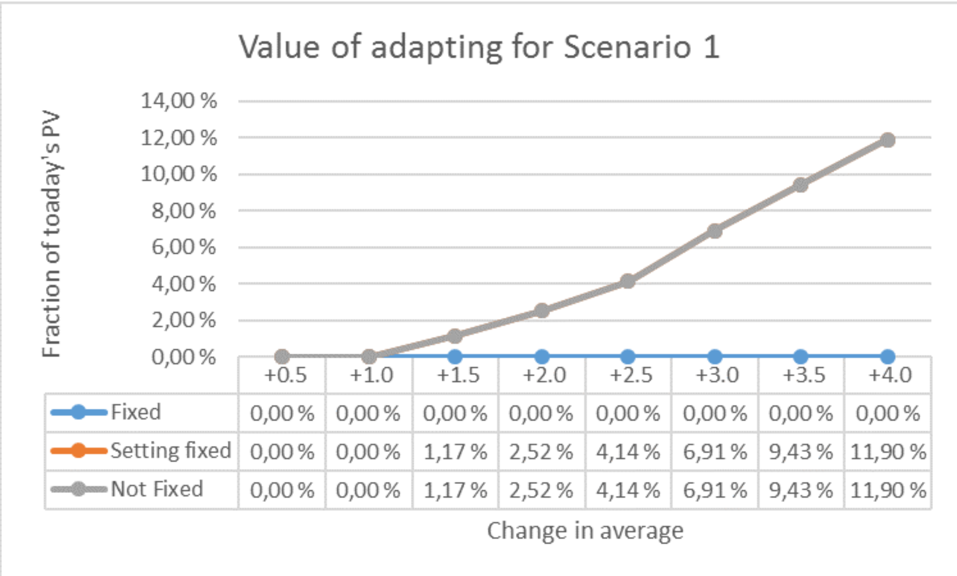


FIGURE 6.2: Effects of changes in average temperature (degrees Celsius) on the NPV of the infinite rotations. The effects are compared to current NPV for optimal harvest choice



	+0.5	+1.0	+1.5	+2.0	+2.5	+3.0	+3.5	+4.0
Fixed	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %
Setting fixed	0,00 %	0,00 %	1,17 %	2,52 %	4,14 %	6,91 %	9,43 %	11,90 %
Not Fixed	0,00 %	0,00 %	1,17 %	2,52 %	4,14 %	6,91 %	9,43 %	11,90 %

FIGURE 6.3: The additional value of changing harvest time and changing setting time for the aquaculture to different changes in average temperature.

of choosing a different starting month once the fish farmers have adapted to the new optimal time of harvest, which holds for all postulated changes.

6.2.2 Scenario II: Increases in temperatures amplitude

In Scenario II the postulated changes from Table 6.5 will affect the amplitude of the seasonal temperature. Which means that equation (5.27) can be rewritten as

$$S = (\phi + \phi_{\Delta}) \cdot \cos\left(\frac{2\pi(t-\psi)}{T}\right) + \omega \tag{6.8}$$

Where ϕ_{Δ} is the change in the amplitude of temperature due to climate change.

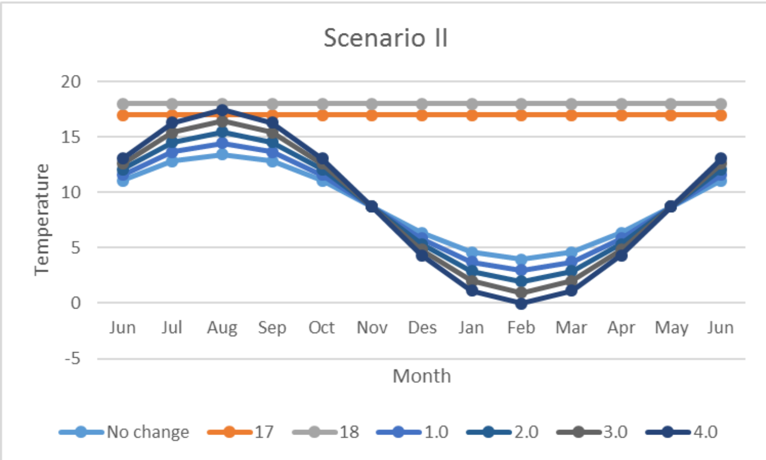


FIGURE 6.4: Seawater temperature for different changes to the amplitude of temperature

Figure 6.4 shows the seasonal temperatures from June one year to June the following year for different changes to the amplitude of temperature. In addition, the temperatures 17 and 18 degrees are highlighted in the form of straight lines. These temperatures are the decisive temperatures for the dummy variables. Note that only integer changes were assessed int Figure 6.4, whilst in the analysis expected temperatures for all changes were used to project monthly mortality rates and growth paths. For a increase in amplitude by 4, the month of August is expected to be warm enough that growth are affected by the dummy variable. We can also note that in the months November and May the projected temperatures are the same, regardless of the change in amplitude. This is due to the cosine component of equation (6.8) being equal to 0, meaning that $S = \omega$. The maximum and minimum values for temperatures are vertical shifts from the current projected temperature equal to the shift in amplitude.

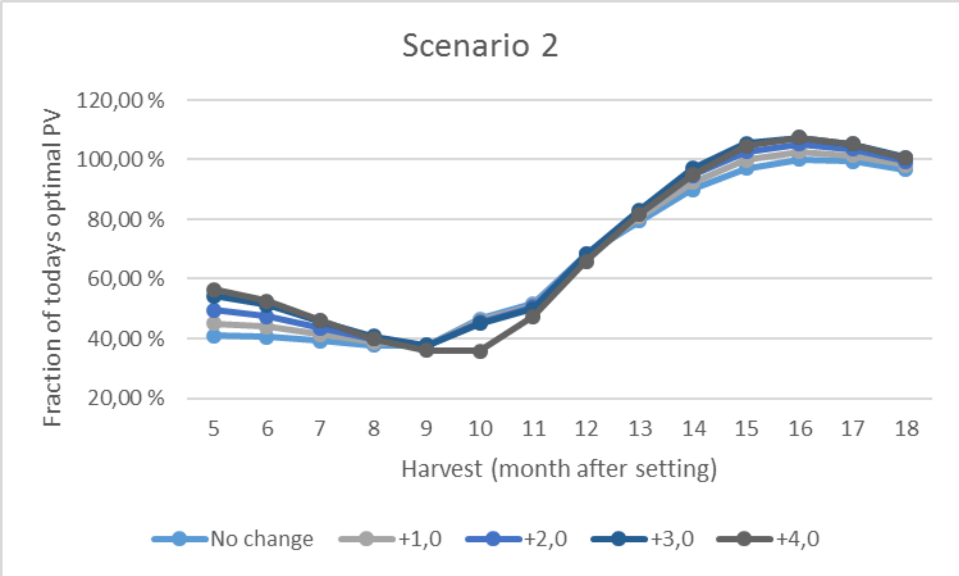
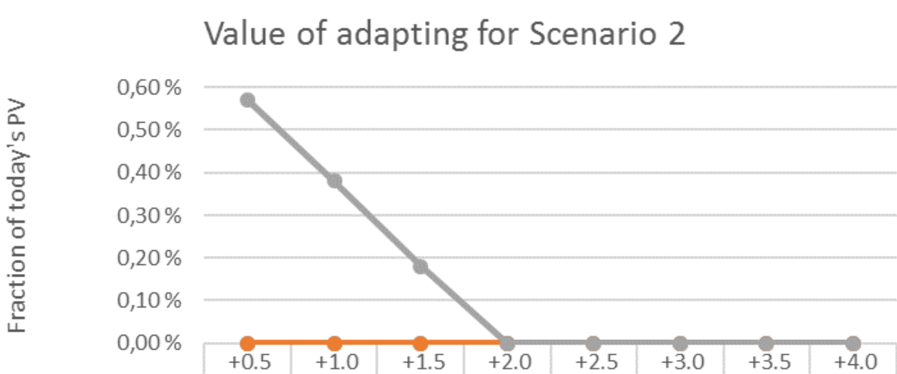


FIGURE 6.5: Effect on the present value of infinite rotations measured compared to today's present value for optimal harvest choice by changes in amplitude of temperature

From Figure 6.5 we see that there are small differences between the NPVs for different changes in amplitude, almost regardless of the different time of harvest. One interesting thing to note is that for the larger postulated increases in amplitude, there are a positive effect on NPV for shorter (5-7 months) rotations as well as for the longer periods (longer than 14 months). Whilst for a harvest time of 10 months the NPV of the largest postulated change in amplitude is the lowest. The current situation with no change in amplitude has a lower NPV (or as low as the lowest) compared to all the different changes in amplitude for all times of harvesting, other than 10 months.

From figure 6.6 we see that for all possible changes in amplitude, there are no benefits of adapting the time of harvest, whilst for changes in amplitude from 0.5 to 1.5 there are benefits of changing the starting time of the rotations. However, these benefits are all less than 0.6 percent of the new NPV due to change in amplitude. The value of adapting was by starting the rotation in May in stead of in June.



	+0.5	+1.0	+1.5	+2.0	+2.5	+3.0	+3.5	+4.0
Fixed	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %
Setting fixed	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %
Not Fixed	0,57 %	0,38 %	0,18 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %

FIGURE 6.6: The value of changing harvest time and setting time for the aquaculture to different changes in amplitude for the temperature function.

6.2.3 Scenario III: Increases in average temperature and temperature's amplitude

In Scenario III the postulated changes from Table 6.5 affects average temperature and the amplitude of seasonal temperature. Which means that equation (5.27) can be rewritten as

$$S = (\phi + \phi_\Delta) \cdot \cos\left(\frac{2\pi(t-\psi)}{T}\right) + (\omega + \omega_\Delta) \tag{6.9}$$

Where ϕ_Δ is the change in the amplitude of temperature due to climate change, and ω_Δ is the change in average temperature.

Figure 6.7 shows the seasonal temperatures from June one year to June the following year for different changes in average temperature and of the amplitude of temperature. In addition the decisive temperatures with regards to the dummy variables, 17 and 18 degrees are included in the figure. We see that in the month of February temperatures coincide for all projected changes. Whilst for August, the warmest month, projected temperature shifts upwards with the sum of the increase in amplitude and the increase in average. If the average and amplitude changes by 2 or more, the negative effect on growth from the high temperature occurs in the month of August. The negative effect is double for the changes of 2.5 or more, i.e. both dummy variables is equal to 1. Not included in the model is that if the changes are 3.5 there will be average seawater temperature above 20 degrees in August. If

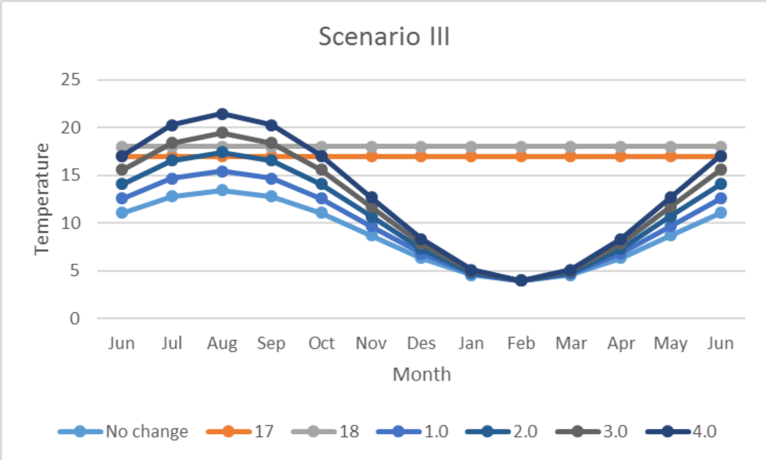


FIGURE 6.7: Seawater temperature for different changes to average temperature and amplitude of temperature

the change is 4 the expected average temperature in the months of July, August, and September will exceed 20 degrees. This may lead to a physical breakdown for the salmon, which mean a collapse of the stock. The possibility of a collapse of the stock is however not included in the calculations of NPVs.

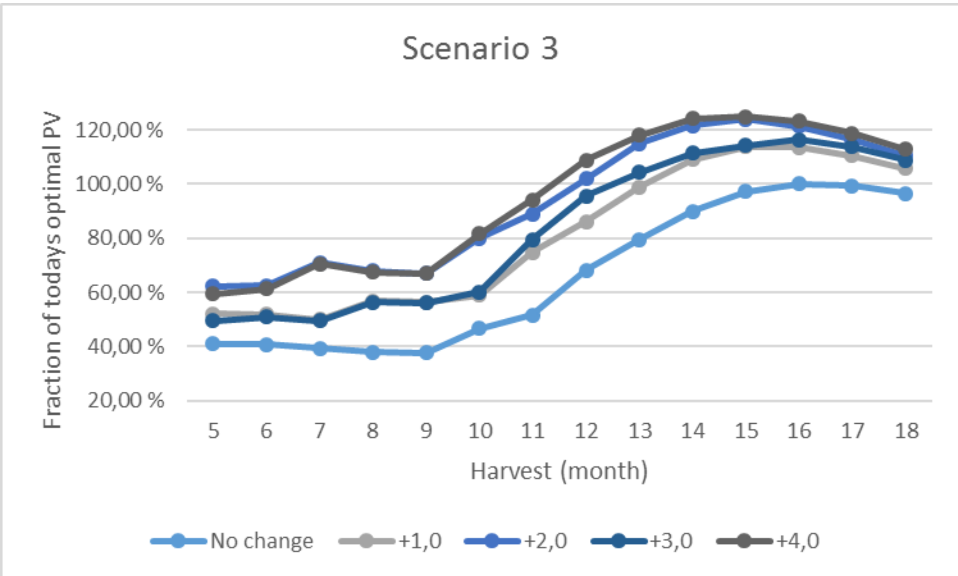
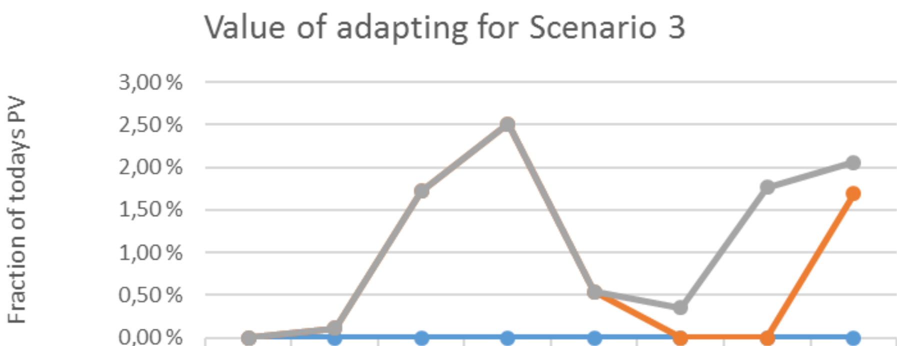


FIGURE 6.8: Effect of Scenario III on NPV for fish farmers with infinite rotations. Effect measured compared to NPV for present optimal value

From Figure 6.8 we see that there NPV will be positively affected by changes to average temperature and amplitude. Within the range of changes from Table 6.5 there is a strictly positive effect with increasing changes. We can as well see that the positive effect is comparatively larger by changing for the current situation to an increase of 1, than a change from 1 to 2.

From Figure 6.9 we can see that there are relatively small values by adapting to the changes. If the changes in amplitude and average is 2.5 or less the added value is from changing the rotation time, there are no additional value of changing the staring time of the rotation. For changes of 3 or 3.5 there is no value from changing the rotation time, the only added value comes from changing the starting time of the rotation. For a change of 4 for the average and amplitude there is both a positive effect from changing the rotation time as well as changing the starting time of rotation.



	+0.5	+1.0	+1.5	+2.0	+2.5	+3.0	+3.5	+4.0
Fixed	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %
Setting fixed	0,00 %	0,11 %	1,72 %	2,51 %	0,54 %	0,00 %	0,00 %	1,69 %
Not Fixed	0,00 %	0,11 %	1,72 %	2,51 %	0,54 %	0,35 %	1,77 %	2,06 %

FIGURE 6.9: The values of changing harvest time and setting time for the fish farmer in Scenario III.

6.2.4 Summarizing the results, Scenarios

The analysis from the sections 6.2.1, 6.2.2, and 6.2.3 projects a strictly beneficial effect of climate for the Norwegian aquaculture. The analysis varied concerning how much the value added from adapting to climate change. There was a positive effect from adapting. However, the effect were not strictly positive for Scenario II. I.e. there were some changes to amplitude that were no value of adapting the rotation time or the staring time of the rotation.

For Scenario I the beneficial value of a change in average temperature ranges from 6.27 percent to 28.46 percent of the optimal NPV for the current situation. The beneficial value increased with regards to change in average temperature. I.e. a change in average of 4 degree yields the highest beneficial value. The value of adapting was due to decreasing the rotation time.

For Scenario II the beneficial value of a change in the amplitude of temperature ranges from 1.34 percent to 8.63 percent. The beneficial value of a change in the amplitude of temperature increased with regards to change in amplitude up to a change of 3.5. A change of 4.0 would yield the third highest beneficial value. The value of adapting was due to starting a month earlier, i.e. starting the rotations in May.

For Scenario III the beneficial value of a change in both the average temperature and the amplitude of the temperature ranges from 7.44 percent to 23.26 percent. The least change yielded the lowest value, whilst the largest change yielded the highest value. However, there was not a strict increase of value with regards to change within the range of change. E.g. a change of 2.0 yields a higher value than a change of 2.5. The value of adapting was from decreasing the rotation time, and for changes equal to or larger than 3 starting a month later, i.e. starting the rotations in July.

Hence, the best way to adapt is highly dependent on what kind of changes that will occur. As a result, the aquaculture industry needs to stay informed on the latest projections for climate change in order to optimize the net present value of its future cash flows.

7. Discussion

7.1 Non-included variables and parameters

There are multiple variables and parameters that has not been included in the model. Examples of non-included variables are taxes, cost of feeding, pH-levels, salinity, harvest costs, sea level, and flow of current.

In (A.1) non-distortionary taxes (like Capital gain taxes) are shown to be a scalable factor that does not affect the optimal solution. Hence, non-distortionary taxes is not necessary to include in the model. Distortionary taxes such as Payroll tax, Property taxes, Sales taxes, etc. has not been included, due to the scope of the thesis.

It is difficult to estimate the effect from the projected climate change on salinity, flow of current, cost of feeding, and pH-levels. Salinity, flow of current, and pH-levels are important factors for the growth and mortality rates for salmons, and as such should be a part of the complete analysis for the regulating government.

7.2 Limitations of the model

The model does not account for changes in salinity or pH-level due to climate change, and how they could affect they value of the aquaculture. Lorentzen (2006) and Thyholdt (2014) argues in their papers that the projected temperature increase will lead to higher NPV for aquaculture located in the north of Norway. However, it is likely that due to the geographical location the north of Norway will have a larger change in salinity compared to southern regions as a result of melting polar-ice. How the pH-levels will change is difficult to project in any part of the country, due to both change in volume and change in the amount of CO_2 in the atmosphere. A temperature rise would lead to sea water expanding its volume. Hence, more CO_2 in the atmosphere could lead to lower, higher or unchanged pH-levels. Looking at the decline in coral reefs (Brander, 2007) and the fact that coral reefs are more vulnerable to lower pH-levels, may lead one to infer that the pH-levels in sea water are in fact decreasing. The decrease in pH-levels may however be temporary. A large change in pH-levels will negatively affect the value of Norwegian aquaculture, both a large decrease and a large increase. Fish farms may have counter-measures, e.g. using chalk to neutralize acidic water. However, any counter-measure could prove to be costly.

The logistic growth function is based on raw data from different, constant temperature regimes. Hence the growth function may not account for how fluctuations in temperature affects growth.

In the analysis the effect on NPV for Norwegian fish farmers were the only measurement for value. For regulators and governments this is an incomplete information set. The externalities from aquaculture will likely be affected climate changes. The externalities from fish farming could affect tourism dependent industry, fishing industry etc. In accordance to traditional economic theory the fish is treated as a commodity, and the life of the fish is regarded as having no value of its own. As a side note, the assumption that the life of salmon does not have any inherit value, could be disputed on ethical grounds.

The model assumes that the feeding of salmon and pen sizes are non-restrictive. In a realistic optimization problem feeding and pen sizes should be treated as (possibly binding) constraints.

7.2.1 Prices

The assumption that prices can have discrete jumps depending on to which weight class they belong may not be a valid assumption. In which case a continuous function for price per kg with regards to weight should have been used as an alternative. In his article Guttormsen (2008) argues that the relative kilogram prices are seasonally dependent, including this may further improve my analysis. Because of Norwegian aquaculture's market share one may argue that there is a theoretical possibility for price control through market power. Historically this has not proved to be successful, and Norway has even been fined by the EU for illegally dumping prices (Asche and Bjorndal, 2011).

7.2.2 Mortality rate

The growth function used in the analysis were based on laboratory experiments, which yielded good estimations for how different temperatures affected growth. The function for monthly mortality rate was based on reported mortality rates in Norwegian aquaculture. Fish farmers would likely actively try to minimize mortality when higher temperatures incur. Efforts to minimize mortality could be successful but would likely be costly. Hence, the model could estimate too large profitability for higher temperatures. In this case the costs of climate change would be underestimated, and the value of adapting to changes would be larger than previously estimated.

Furthermore, since the controlled experiments were conducted for the range from 1 degree to 18 degrees, the growth function is not necessarily valid for temperatures outside of this range. Temperatures outside of this range includes some of the changes from Scenario III. The observations from the data set used in the regression analysis were the monthly mortality rates exceeded 10 percent may have been due to a physiological breakdown in salmons due to too high temperatures.

In order to comply with laws and regulations, the data for mortality rates in Norwegian aquaculture had to be anonymized before I received the data. There could be systematically different mortality rates based on locations, companies, and other factors. In order to estimate a more correct function for mortality rates the regression would need to control for the location-based effects. By controlling for e.g. locations the constant factor for the estimated monthly mortality rate may have been too big, whilst the estimated parameter values for temperature and weight dependent factors may have been too small. The effects of climate change on the value of Norwegian aquaculture may be underestimated as a result.

The data set for mortality rates showed the average temperature for the previous month. There are no data for how much temperature fluctuated within each month. As ectotherms salmons do not have well regulated body temperatures, and the daily (hourly) temperature are more significant for mortality than averages. Hence, the regression may have underestimated the effect of higher temperatures with regards to mortality rates.

7.3 Assumption that infinite rotations is possible

When comparing the NPV for a finite amount of rotation and the NPV for an infinite amount of rotations, we see from equation (A.1) that the number of finite rotations needed to approximate the infinite rotations case is almost negligible. As stated in the Literature review the purpose of the model is to provide insight into how changes in temperature may affect value, the precise effects were less emphasized. Thus, in order to have a more concise model infinite rotations were used.

7.4 Indirect effects of temperature change

Higher sea water temperatures is one of multiple results from the energy increase due to the increase of greenhouse gasses in the atmosphere. Other results of the energy increase is changes to weather patterns. One of the weather patterns that may change is precipitation. The amount of precipitation in certain geographical locations may change drastically. This could lead to lower production for the producers of feed to the salmon industry, resulting in larger costs for the fish farms. Since wind and currents behave according to fluid dynamics, it is difficult to estimate how they may be affected by changes in temperature. Precipitation is a result of often complex wind and current systems. Hence, even if the expected costs remain the same the risk of change in costs can be treated as increasing. A higher risk in costs would lead to shorter rotation times for the profit maximizing agent. Shorter rotation times leads to lower a decrease in the value of aquaculture, compared to the optimal solution with no increase in risk of costs.

A more energetic climate system will lead to more frequent, more powerful, or both more frequent and more powerful storms compared to the current situation. Pens are currently made to endure a lot of energy in forms of powerful waves. But they will over time degrade and there is a need to change or repair pens in order to counteract escapements. Escapements can be doubly costly since the fish farmers may lose revenue and may need to reimburse other industry. More frequent storms will mean that the wear and tear on the pens will be larger. Leading to higher costs. More powerful storms increase the risk of destruction of the pens, leading to possible escapements. Fish farmers may protect the pens by moving them. But the assumption is that any location is chosen as a part of an optimization. I.e. the act of moving the pens can be costly as it is labor demanding and may lead to sub-optimal growth for the salmon.

Since many countries may be affected by the projected climate changes to a higher degree than Norway, international politics may dictate that international trade decreases. This in order to lessen the amount of greenhouse gasses emitted. Large parts of the current production is exported, and by limiting the geographic market the demand may be severely decreased. Lower demand leads to lower prices, which leads to lower profits. Hence, the indirect effects of climate change may have a bigger impact on the value of Norwegian aquaculture compared to the direct effects.

8. Conclusion

I have in this thesis aimed at estimating for the representative Norwegian fish farm the value of adapting to changes in the seasonal temperatures projected as a result of climate change. I adjusted the bioeconomic theory by including variable mortality rates and kilogram price dependent on weight, which enabled me to have a more realistic modeling of the total biomass and in an aquaculture and its value. By using scenarios for changes in temperature, combined with

The analysis shows that changes to temperature within the range of the scenarios are all estimated to be beneficial to the value of Norwegian aquaculture. The value of the benefits from the scenario-based changes are dependent on what aspect of the temperature the changes affect. The highest values was if the changes only affected average temperatures, whilst the lowest values were when only the amplitude were changed. The value of adapting to changes were as well the highest for when only the average changed, and the lowest when the amplitude changed. For the scenario with increasing average temperature the best adaptation were to decrease the rotation time. The best adaptation to an increase in amplitude were to start the rotation earlier. For the scenario with increases in both average temperature and amplitude of temperature the best adaptations were to decrease the rotation time and start the rotation later.

Furthermore, the beneficial value of the projected changes is less certain when both the amplitude of temperature and the average temperature changes. In combination with the fact that the best adaptation is dependent on which of the scenarios occurs, Norwegian aquaculture needs to be informed about the most recent climate projections in order to maximize the net present value of its profits.

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A. Appendix A (Equations)

A.1 Assumption of infinite rotations

The present value of an finite rotation

$$\sum_{n=1}^{n} V(t) \cdot e^{-nrt} = \sum_{n=0}^{n} V(t) e^{-rnt} - V(t) = \frac{V(t)(1-e^{-r(n+1)t})}{1-e^{-rt}} - V(t)$$

$$= V(t)\left(\frac{1-e^{-(n+1)rt} - 1 + e^{-rt}}{1-e^{-rt}}\right) = V(t)\left(\frac{1-e^{nrt}}{e^{rt}-1}\right)$$

Hence, the finite rotation as a percentage of the infinite rotation is, assuming that $t_n = t_\infty$

$$\frac{V(t)\left(\frac{1-e^{-nrt}}{e^{rt}-1}\right)}{V(t)\left(\frac{1}{e^{rt}-1}\right)} = 1 - e^{nrt}$$

For it to be greater or equal to a certain percentage x we have

$$1 - e^{-nrt} \geq x$$

$$1 - x \geq e^{-nrt}$$

$$\ln(1-x) \geq -nrt$$

$$nrt \geq \ln(1-x)^{-1}$$

$$n \geq \frac{-\ln(1-x)}{rt^*} \tag{A.1}$$

For $r = 0.05$, $t = 1.33$ and $x = 99\%$ we need at least n rotation

$$n \geq \frac{-\ln 0.01}{0.05 \cdot 1.33} \approx 69$$

A.2 Taxes

When including non-distortionary taxes (tax rate τ) as a parameter

$$\max_t \sum_{n=1}^{\infty}(1-\tau)V(t)e^{-nrt} = \max_t[(1-\tau) \cdot \frac{V(t^)}{1-e^{-rt}}]$$

$$\implies (1-\tau)\cdot\frac{V'(t)(1-e^{-rt})-V(t)(-re^{-rt})}{(1-e^{-rt})^2}=0$$

$$\implies V'(t)(1-e^{-rt})+V(t)re^{-rt}=0$$

Multiplying entire equation by e^{rt}

$$V'(t)(e^{rt}-1)+V(t)r=0$$

$$V'(t)(e^{rt}-1)=-V(t)r$$

Dividing both sides of the equation by $V(t)(e^{rt}-1)$

$$\frac{V'(t)}{V(t)}=\frac{-r}{e^{rt}-1}$$

Expanding the fraction on the RHS by (-1) we get

$$\frac{V'(t^*)}{V(t^*)}=\frac{r}{1-e^{rt^*}} \tag{A.2}$$