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The Economic Effects of the Production Area Regulation

An Empirical Study of the Norwegian Aquaculture Industry

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NORWEGIAN SCHOOL OF ECONOMICS

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This thesis is written as our final part of the Master of Science in Economics and Business Administration at the Norwegian School of Economics, and our majors in Business Analysis and Performance Management. Analyzing the Norwegian aquaculture industry has been interesting and challenging. The industry has been given much attention over the years and some are highlighting it to be the next major industry adventure in the post-fossil fuel age, making it even more rewarding to gain insight into the industry.

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Abstract

The Norwegian aquaculture industry has grown and developed substantially since its mere beginning in the 1970s (Nærings- og fiskeridepartementet, 2015; PwC, 2016b; Statistisk sentralbyrå, 2018c). Governmental regulation of the industry has developed accordingly, with shifting intentions from ensuring local ownership and jobs, to the newfound focus on sustainability (Asche & Bjørndal, 2011; Nærings- og fiskeridepartementet, 2015; Schwach et al., 2015).

The aim of this thesis is to estimate the economic effects of the recently implemented Production Area Regulation on commercial fish farming companies. Existing bioeconomic theory does not take into account the capacity constraints faced by the industry participants, and we suggest such an extension to the theoretical models. The inclusion of capacity constraints enables the calculation of changes in rotation length and the corresponding willingness-to-pay for changes in capacity, which in turn can be used to evaluate the effects of the regulation. A growth model and a price model are estimated based on the empirical data obtained, which in turn are utilized in the calculation of the overall economic effects of the regulation.

Our findings suggest that the introduction of capacity constraints leads to shorter rotation lengths than what is optimal for Norwegian fish farmers. The average willingness-to-pay for 2 % increased capacity is 99.10 NOK/kg. Overall, the regulation will lead to an increase in profits per production license of NOK 410 485. The variation between the production areas are large, with changes in profits ranging from -6.2 million to almost 2.3 million per production license. Assumptions about interest rate, mortality rate, number of fish, costs, prices and growth largely influences the economic effects of the regulation.

Contents

Tables

Figures

1. Introduction

Norway is the largest producer of farmed salmonids in the world, and the World Bank highlights the production of salmonids as one of the most cost-efficient production methods of animal protein, and an important source of seafood to an emerging global population (2013). Norway thus has an excellent opportunity to supply the world population with an important source of food, both now and in the future. Simultaneously, the aquaculture industry is facing major challenges regarding sustainability which must be dealt with in order to increase production (Nærings- og fiskeridepartementet, 2015). These sustainability challenges resulted in the implementation of a new regulation of the industry in Norway in October 2017.

1.1 Motivation and Purpose

The Norwegian aquaculture industry has gone through major developments since its commercial beginning in the early 1970s. Substantial changes has been made in both market structure, production methods and technology; resulting in a total production of almost 1.2 million ton in 2016 (Nærings- og fiskeridepartementet, 2015; PwC, 2016b; Statistisk sentralbyrå, 2018c). It is projected that the Norwegian production of salmonids will reach 5 million ton in 2050 with the current growth in production efficiency and demand, which thus constitutes a fourfold increase from today’s production level (Olafsen, Winther, Olsen, & Skjermo, 2012).

As the industry has developed, so has the industry regulation. The first regulation of the industry was implemented in 1973, and since then the objective of governmental regulation has varied from ensuring local ownership and jobs in the 1980s and 1990s, to controlling the production with the use of feed quota schemes in the 2000s, up until today where sustainable operations have become the main focus as a result of increasing environmental challenges (Asche & Bjørndal, 2011; Nærings- og fiskeridepartementet, 2015; Schwach et al., 2015). The newfound sustainability focus led to the implementation of the Production Area Regulation in October 2017, which aims at ensuring the advancement of the aquaculture industry within the parameters set for sustainable development (Produksjonsområdeforskriften, 2017). In this regulation, the production capacity is regulated jointly for 13 appointed geographical areas. The changes in capacity is regulated based on chosen environmental indicators, which, for now, is the infestation pressure of salmon lice on wild stocks of salmon. Areas with a high infestation pressure will be imposed a capacity decrease, while areas with a low infestation pressure will be granted a capacity increase.

The regulation has been criticized by industry participants, law makers and stakeholders for being complicated and for creating heterogenetic economic impacts, which makes it challenging for fish farming companies to estimate their respective economic consequence and to adjust their behavior accordingly (Sjømat Norge, Norsk Industri, & NSL, 2017).

Limited studies of the economic impact of the Production Area Regulation on company level have been conducted by policy makers, and no empirical study has been conducted to analyze the degree of heterogeneity in the economic effects. In addition, no theoretical extension of bioeconomic theory describes the impact of changes in capacity on optimal production of salmonids.

1.2 Research Question

We will in this thesis answer the following research question:

What are the economic effects of the Production Area Regulation on commercial fish farming companies?

Several objectives will be fulfilled in order to answer the research question. We will first introduce an extension to the bioeconomic theory to analyze how capacity constraints affect optimal rotation length of generations of fish. This theoretical extension will allow us to analyze how optimal rotation length is affected by changes in capacity according to the Production Area Regulation. The changes in optimal rotation length will be used to estimate the corresponding changes in present value of future profits per production license and the fish farmers' willingness-to-pay for increased capacity. Based on these estimations, we will provide a discussion of the heterogeneity in the economic effects between the different regulative areas.

The analysis will be based on empirical estimations of a growth function for each production area, as well as estimations of price, mortality rate and the number of fish per generation of salmonids. The growth function will be estimated using monthly production data from 945 fish farming companies in the period of 2005 to 2016, which allow us to estimate the average weight of an individual fish as a function of time after the fish has been released into the sea.

1.3 Structure

The structure of the thesis is as following: Chapter 2 provides an introduction to the Norwegian aquaculture industry including an overview of the historical economic development, as well as production method and growth conditions of salmon farming. In Chapter 3, we introduce an overview of the historical regulative development, as well the content and purpose of the Production Area Regulation. Chapter 4 is devoted to the introduction of the bioeconomic theoretical framework, while Chapter 5 gives an introduction to the data set used in the empirical analysis. Chapter 6 introduces the empirical framework of the analysis, and the respective regression results will be evaluated in Chapter 7. Finally, we conduct an economic analysis and provide a discussion of the economic effects of the Production Area Regulation in Chapter 8, before we conclude in Chapter 9.

2. The Norwegian Aquaculture Industry

This chapter provides an introduction to the Norwegian aquaculture industry, with an overview of the historical economic development in Section 2.1 and 2.2. A description of the production method of salmonids is provided in Section 2.3, while biological growth conditions are described in Section 2.4. By the end of the chapter, the reader will have been provided with a basic understanding of the biology of fish farming, as well as current challenges in the industry. This knowledge constitutes a good basis for understanding the current regulative regime of the industry, as well as the content of the empirical growth model introduced in Chapter 6.

2.1 About the Aquaculture Industry

Aquaculture refers to cultivation of organisms in sea or fresh water and includes breeding, rearing and harvesting of fish, shellfish and plants (Store norske leksikon, 2018). Fish farming has grown to be a sustainable and important source of protein to an emerging global population, as fisheries approach their maximum take of natural deposits of seafood. The World Bank projects that aquaculture will supply 60 % of all fish destined for human consumption by 2030, which thus will constitute the prime source of seafood in the world (2013).

Early records show that aquaculture originated in eastern Asia about 4 000 years ago, when fishermen deduced the practice of aquaculture from storage of surplus wild catch in small enclosures (Ling & Mumaw, 1977). Salmon aquaculture was not economically efficient until the 1970s, when technological improvements and increased demand lead to a rapid expansion of the industry (Flåten & Skonhoft, 2014; Heen, Monahan, & Utter, 1993). The global production of salmonids increased from 65 thousand ton in 1970 to 3.3 million ton in 2015 (The Food and Agriculture Organization of the United States, 2018), and the World Bank projects a global production of 5 million ton in 2030 (2013).

Norway has traditionally been a large seafood nation due to its long coastline with rich marine resources. Large investments in research and development within aquaculture production technology, as well as ideal temperature conditions has made Norway the largest producer of farmed salmon in the world, with a total production of close to 1.2 million ton in 2016. The production in 2016 was valued at approximately 64 billion NOK and was created by an industry employment of 7700 people (Statistisk sentralbyrå, 2018a, 2018c).

There are several major challenges for the Norwegian aquaculture industry to overcome in the years ahead. Lice and diseases affect the overall fish welfare, which must be sustained as the industry grows. In addition, wild salmon are threatened by lice infections from aquaculture facilities and escaped farmed salmon may lead to genetic dilution of wild salmon cultures (Teknologirådet, 2012). Also, pollution from fish excrement, surplus feed and medicaments constitutes environmental challenges.

Furthermore, technological enhancements of offshore and land-based fish farming facilities may disrupt the comparative advantage of the Norwegian coastline. As mentioned, it is projected that the Norwegian production of salmonids will reach 5 million ton in 2050 if current environmental and disease challenges are solved, together with successful innovations in feed and production technology (Olafsen et al., 2012). A predictable regulative regime is essential to realize this economic potential, and the implementation of the Production Area Regulation aims at meeting this objective. The Production Area Regulation will be introduced more in detail in Chapter 3.

2.2 Economic Development

2.2.1 Production and Productivity

The Norwegian aquaculture industry has experienced a huge expansion in salmon production since its commercialization during the 1970s. One can see from Figure 1 that the value of Norwegian aquaculture production has increased exponentially since the 1980s, and that aquaculture constitutes the majority of the Norwegian seafood production from 2000.

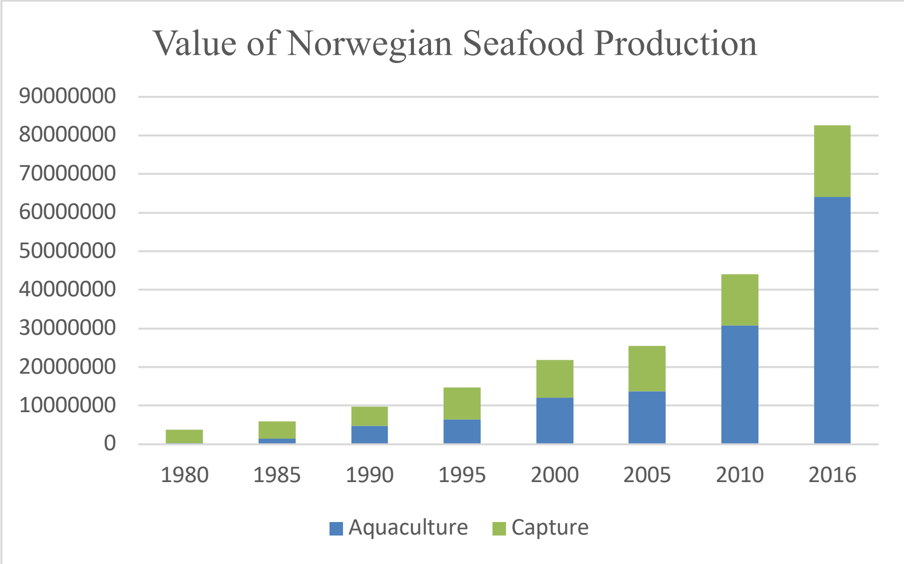

Figure 1 Value of Norwegian Seafood Production (Statistisk sentralbyrå, 2018b, 2018c)

Figure 2 illustrates the Norwegian total production of salmonids, the number of licenses from 1995 and the average production per license. During the same period, the number of fish farming locations has been reduced from its peak of 1806 locations in 2000 to 986 locations in 2017 (Andreassen & Robertsen, 2014; Fiskeridirektoratet, 2018b). Even though the number of fish farming locations has decreased, the total production has increased due to the increase in locations' size and utilization, which is represented by increased production per license. Increased productivity, defined as the production in kilograms per man-labor-year, is another explanatory factor of increased industry production (Fiskeridirektoratet, 2017a).

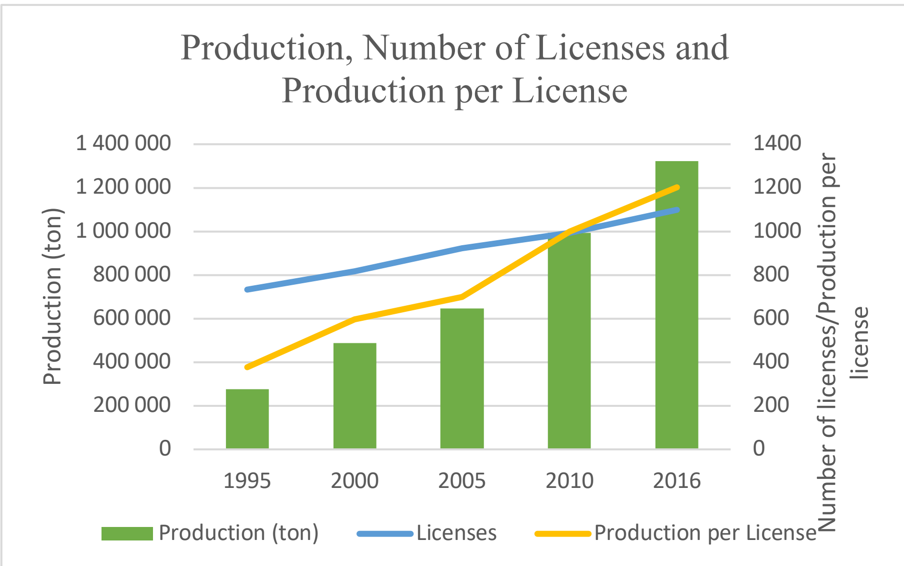

Figure 2 Production, Number of Licenses and Production per License (Fiskeridirektoratet, 2018e; Statistisk sentralbyrå, 2018c)

2.2.2 Price

The development in sales price over time is illustrated in Figure 3. The year of 2016 was a historically good year for Norwegian salmon farmers, with an average price of 51.02 NOK/kg. This represented an increase in price of 47.31 % from 2015 to 2016 (Fiskeridirektoratet, 2017a).

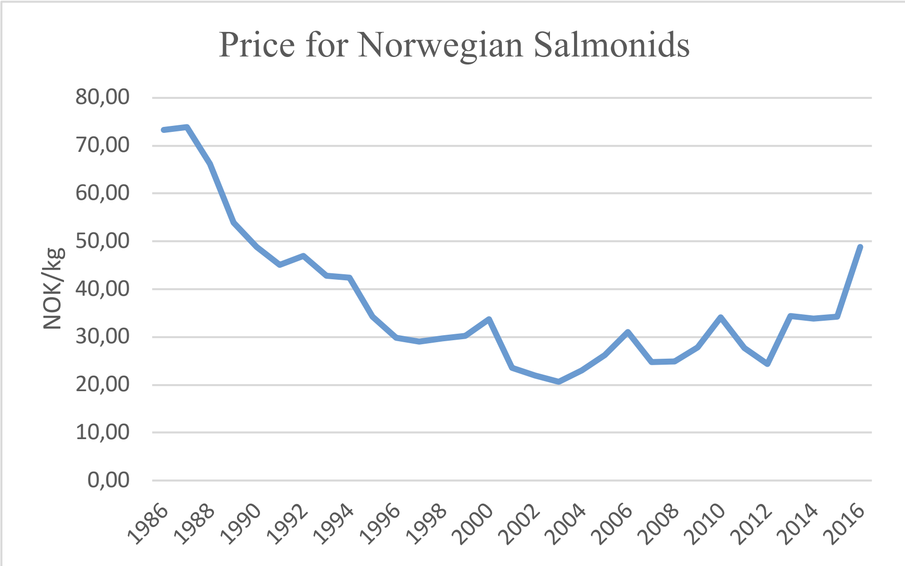

Figure 3 Price for Norwegian salmonids, numbers adjusted to 2015 level (Fiskeridirektoratet, 2009, 2017b; Statistisk sentralbyrå, 2018d)

The price of salmon is dependent on a variety of factors related to supply and demand, amongst them the weight of the fish, as illustrated in Figure 4. The fish are grouped into weight classes when determining price, where the category 1-2 are fish that are 1 to 2 kilos, 2-3 are fish that are 2 to 3 kilos and so forth. The prices are head on gutted prices adjusted for inflation using 2015 as reference year. The fact that large fish normally are more expensive per kilo than small fish becomes evident in the graph, as well as the fact that the price differences vary according to time of the year.

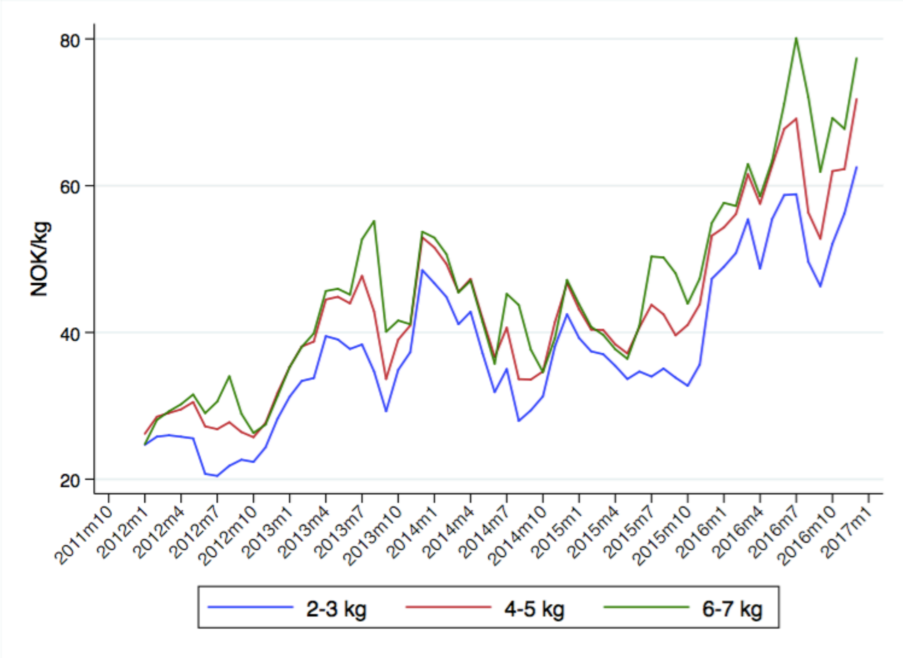

Figure 4 Price development for selected weight classes from January 2012 until December 2016, numbers adjusted to 2015 level (Fishpool; Statistisk sentralbyrå, 2018d)

2.2.3 Cost

The exceptional development in salmon prices resulted in record levels for profits, earning per kilo and operating margins in 2016. The challenges faced by the industry has at the same time led to higher operating costs and lower productivity. Production cost per kilo was in 2016 30.60 NOK on average, an increase from the lowest recorded level in 2005 at 17.76 NOK. It is important to emphasize that the dispersion between companies is quite large, with best-performers having production costs at around 15 NOK/kg.

The main cost drivers for a fish farm are smolt costs, feed costs, wages, and other operating costs (Fiskeridirektoratet, 2017b). From 2015 to 2016, all these cost items increased, with the largest increase in other operating costs per kilo, as illustrated in Figure 5. The increase in other operating costs results largely from increased costs related to fish health, environmental issues and maintenance. The increase in feed costs has also been substantial in recent years, a result of a weak Norwegian krone and the transition to new ingredients in feed (Fiskeridirektoratet, 2017b).

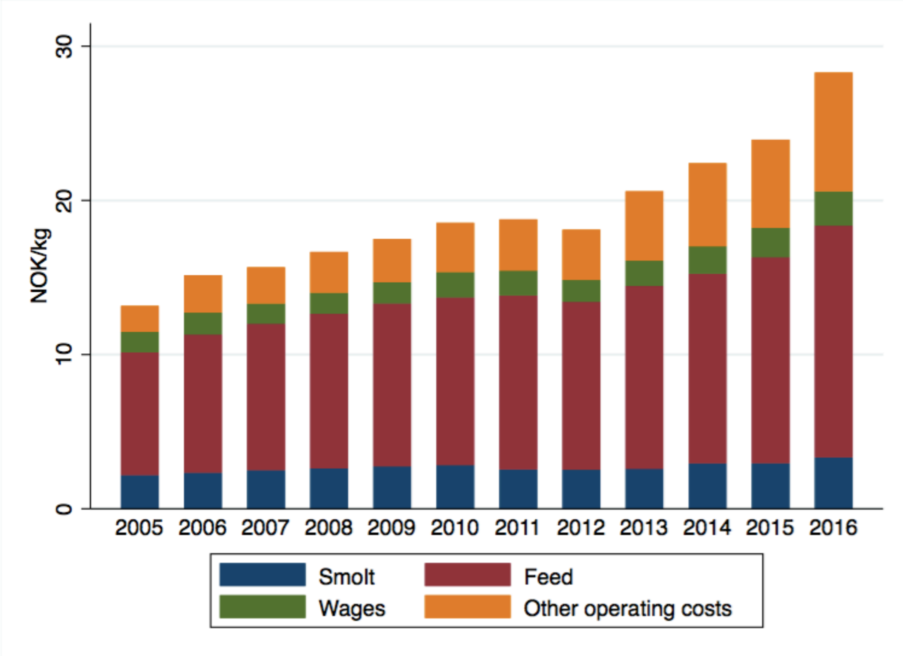

Figure 5 Development in major operating cost items from 2005 to 2016. Prices not adjusted for inflation (Fiskeridirektoratet, 2018d)

2.3 Production Method and Value Chain

Salmon farming is an intensive and closed production process determined by a high degree of human control during all stages of the fish' life cycle and with no dependence on the wild population of the species. *Salmo salar, Chinook* and *Coho* are the farmed species of salmon, together with salmon trout. *Salmo salar,* which is also called Atlantic salmon, is native to the Atlantic Ocean and is farmed in Norway, amongst other producing countries, while *Chinook* and *Coho* are Pacific species (Asche & Bjørndal, 2011).

The salmon roe is gathered from domesticated broodstock and hatched under controlled environments in January each year. The fry will feed on the contents of its yolk sack for the first month, before the human controlled feeding process is initiated. At a size of about 5 grams, the fry will reach the fingerling phase and develop the characteristics of salmon. The Atlantic salmon reaches the smoltification phase after 16 months, which is a complex physical change to adapt to the life in saltwater. The Atlantic salmon are then released to sea pens for the grow-out phase up to marketable weights of 2 to 8 kg during the course of 12 to 24 months. This is the most commercial important stage of the production as the most growth-relevant decisions are made. These decisions include time of release, harvesting time, feeding quantity and schedules, density and preventive lice and disease measures. All salmon species must be harvested before spawning, as the Pacific species will die, and the Atlantic salmon will experience a degradation of quality. This occurs about 28 months after the smoltification of Atlantic salmon and *Chinook*, and only 16 months for *Coho*, although large differences in spawning time may be observed within in the same year class (Asche & Bjørndal, 2011).

The value chain of salmon production consists of several stages; production, processing and sale to end user. Several fish farming companies are vertically integrated with their own production of fry and smolt, as well as their own feed production. After harvesting, the fish are slaughtered and processed into different consumer products like slices, filets and cutlets, before transported and sold to the end users (Teknologirådet, 2012). Several sectors are influenced by the aquaculture industry and include feed producers, breeders, equipment producers, research institutions and transportation service providers (Andreassen & Robertsen, 2014).

2.4 Growth Conditions for Salmon Farming

A variety of factors affect the growth of salmon during the grow out phase, among them water temperature, light, smolt quality, feeding, mortality, density, diseases and parasites.

2.4.1 Temperature and Daylight

Salmon is a cold-blooded animal, which means that temperature is one of the most important variables affecting growth, together with feed (Boeuf & Le Bail, 1999). The temperatures in Norway vary across seasons and geographic areas, translating to varying growth conditions for the fish farms (Thyholdt, 2014). The northern parts of Norway have lower sea temperatures than the areas further south, all year round, in addition to seasonal variations throughout the year. The average temperature for the 13 newly established production areas is shown in Figure 6 below. Production area 1 is the southernmost area, and thus the registered temperatures in this area are among the highest in the country reaching almost 17 °C in August, while production area 13 is the northernmost production area with the lowest registered temperatures, reaching only 10 °C in August.

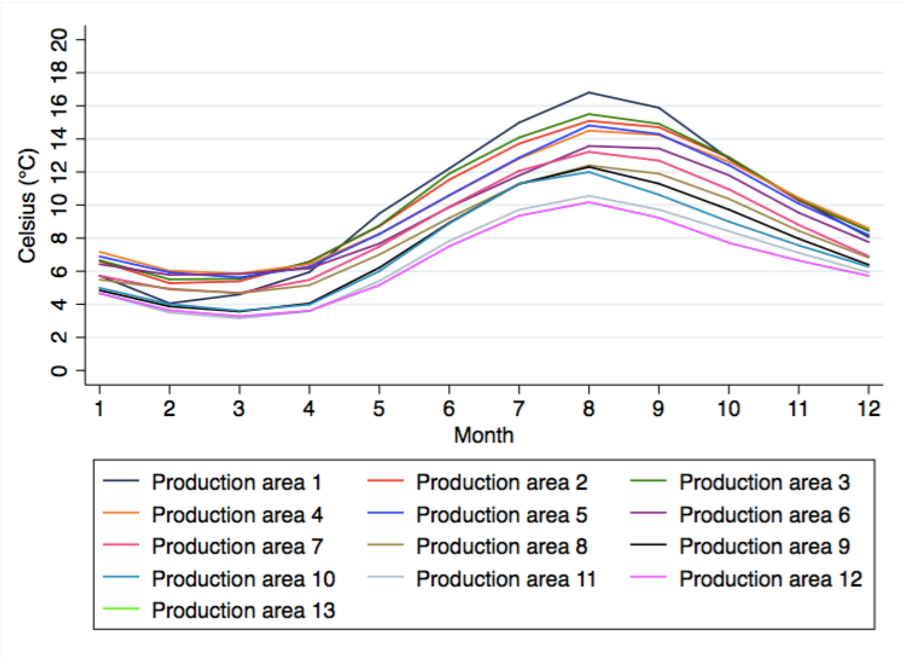

Figure 6 Average temperatures measured in Celsius in different production areas during a year (Barentswatch.no, 2017)

Recent studies show that the highest growth rate was achieved at temperatures around 13 °C (Jørgensen et al., 2014). At lower temperatures the fish has lower appetite and thus eats less, resulting in lower growth. At higher temperatures, on the other hand, challenges such as parasites, algae and oxygen levels become prevailing, resulting in higher mortality rates (Jørgensen et al., 2014).

Hours of daylight also influences the growth rate of salmon (Boeuf & Le Bail, 1999). Norway is a country with major variations in hours of daylight, both varying with seasons and with geographical areas. In the areas north of the Artic Circle the night is 24 hours from November until January, and nonexistent during summer, known as midnight sun (Yr, 2012). The fish farming industry has since the early 1980s stimulated the biological processes of the fish through manipulation of light conditions by using artificial light.

2.4.2 Feed

Feed is the other main explanatory variable for growth. The feed conversion ratio expresses how much feed that is needed to gain one kilo increased bodyweight for the fish (Marine

Harvest, 2017). Low feed conversion ratio means that the efficiency of feeding is high, i.e. large proportions of the feed amount results in increased weight, indicating small amounts of waste. The feed conversion is dependent on water temperatures, as aforementioned. Increasing weight reduces the feed conversion ratio (Skretting, 2012).

2.4.3 Density

Density, measured as kilos per cubic meter of water, also affects the growth of salmon (Calabrese, 2017). Research shows that high density increases the stress level of the fish and reduces the feed utilization. High density may also lead to aggressive behavior such as biting in the dorsal fin (Holm & Søreide, 1993).

2.4.4 Salmon Lice

Salmon lice is among the more recent challenges in the Norwegian industry. The lice problem causes the industry substantial costs, both directly through the cost of lice treatments, but also indirectly through reduced feeding. The fish are starved before treatment, resulting in lower growth, and the stress of treatment results in lower appetite in the time after. The lice may also cause stress, resulting in reduced growth, reduced swimming capabilities and sometimes death (Havforskningsinstituttet, 2017; Hjeltnes, Bang-Jensen, Bornø, Haukaas, & Walde, 2017).

2.4.5 Smolt

As mentioned, all smolts are hatched in January due to biological reasons. From there, the smolts are released to the sea either during spring or fall. The smolts released during the following fall are called zero years, while their siblings that are released during the spring the following year are called one years (Asche & Bjørndal, 2011). The growth of spring smolt is usually better than the growth of fall smolt due to favorable temperature conditions and higher survival rates when transferred to the sea.

3. Regulation of the Industry

To better understand the content and aim of the recently implemented Production Area Regulation, it is necessary to understand how and why the industry has been regulated in the past. In Section 3.1 and 3.2 we describe that the aim of regulation has varied from ensuring local ownership and jobs, to limiting production in order to clear markets, until today's focus on sustainable operations. Section 3.3 elaborates the operational characteristics of the MAB regulation, while Section 3.4 introduces the Production Area Regulation in detail.

3.1 1970 until 1996 Local Ownership

The first regulation of aquaculture in Norway was implemented in 1973 (Asche & Bjørndal, 2011). Since then, anyone who wanted to operate a fish farm needed a government license to do so. The aim of governmental regulation was at this point local ownership and jobs, and each company was only allowed to own one license (Schwach et al., 2015). The implementation of the regulation lead to the Norwegian Official report 1977:39, which argued that the environmental characteristics of Norway was ideal for the development of an extensive aquaculture industry, and that government regulation should promote this development (Lysø, 1977).

As a result, in 1981, the first permanent aquaculture act was passed, followed by an updated version in 1985. The local considerations were still strong, which became evident through the emphasis on local ownership and the desire to keep production spread out on many small companies. From this point, the licenses were to be given out through national licensing rounds (Fiskeridepartementet, 1979-1980). Until early 1990s new licenses were given out in large amounts, and existing licenses were granted increased capacity (PwC, 2016b). The rapidly increasing production lead to outbreaks of diseases. At the same time, prices started falling due to increased international competition, launching the Norwegian aquaculture industry into a crisis in the late 1980s and early 1990s.

Many of the aquaculture companies went bankrupt during this crisis, and the reaction from the government was a liberalization of the regulation regime (Aarset, Jakobsen, Iversen, & Ottesen, 2004). The main changes included removal of the rule that one company could only own one license and removal of requirements for local ownership. This resulted in increased consolidation of the industry, illustrated by the fact that in 1991 the ten largest companies produced only 8 % of the total production, while the same number was 46 % in 2001 and is 70 % today (Aarset et al., 2004; Nærings- og fiskeridepartementet, 2015; PwC, 2016b). No new licenses were granted in the period 1989 to 2002.

3.2 1996 until 2018 Market and Sustainability Focus

In 1996 a feed quota regime was implemented, as an attempt to regulate production after dumping accusations from the European Union (Aarset et al., 2004). The feed quota arrangement lasted until 1st of January 2005, when the maximum allowed biomass, abbreviated MAB, regime was implemented (Nærings- og fiskeridepartementet, 2015). The MAB regime introduced that a farmer could not, at any occasion, have more kilos living fish in seawater than their granted MAB.

The introduction of the MAB regime marks the start of a sustainability focus for state policies. The maximum allowed biomass was divided into two dimensions; farmers were granted a MAB limit on licenses, and another limit was set for the location. The MAB limit on licenses was set in order to control total national production, while the location MAB was set in order to consider the location's environmental capacity (Nærings- og fiskeridepartementet, 2015). The MAB capacity on licenses was set to 780 ton per license for all areas except Finnmark and Troms, where the limit was set to 945 ton due to poorer growth conditions.

Since 2002, compensation has been requested by the government for granting of new licenses, and from 2009 compensation was also requested for increased capacity on existing licenses. Up until this point the license regime was free of charge. The licenses have since the introduction of this system been granted in national rounds of licenses, with varying criteria depending on the political agenda of the government (Nærings- og fiskeridepartementet, 2015).

Since 2013, the environmental aspects of fish farming have been the main criteria for growth. The industry has experienced environmental challenges in regard to salmon lice, diseases, escapes, and emissions (Havforskningsinstituttet, 2017). The salmon lice have been the main focus for regulations, due to its influence on wild salmon stock (Miljødirektoratet, 2015).

3.3 Operational Characteristics of the MAB Regulation

To fully understand the MAB regime, and thus the operational changes followed by the Production Area Regulation, it is important to know that one license can be connected to several locations within an appointed region. The fact that licenses can be connected to several locations allows for optimal production planning for the companies that enjoy this flexibility. The system allows for better utilization of the MAB, e.g. as the license MAB may be used at other locations when one location has to lay fallow after the end of a production cycle. It is important to note that the location MAB is set independent of the license MAB, and thus may be above, the same, or below the total license MAB.

The companies that process a considerable share of their own fish in the districts of Norway are granted so-called maximum inter-regional biomass levels. This means that licenses that are normally tied to one specified geographic region can be utilized in more than one region (Akvakulturdriftsforskriften, 2008). This allows for further increased flexibility, and the argument behind this arrangement is that it is important to keep the value creating processing facilities in Norway to ensure jobs and local attachment.

As a result, the MAB-utilization for firms in the industry varies. Conditions such as temperature, fish health and productivity also influence how well each firm is able to fully utilize the MAB (Nærings- og fiskeridepartementet, 2015). Because of natural conditions such as temperature, it is difficult for industry players to fully utilize the MAB all year (Marine Harvest, 2017).

On average, a farmer is able to produce around 1 200 ton gutted weight equivalent per year per license. Larger companies enjoy more flexibility than smaller ones and are therefore, in theory, able to optimize production so that licenses are fully exploited to a larger degree. However, the fact that larger companies have a much more complex production planning process may lead to less capacity utilization, because it becomes challenging to optimize all parts of the production system at the same time. From this line of argument, smaller players may utilize their capacity more efficiently. Kontali Analyse and Sintef estimated in 2013 that if all farmers produced as efficiently as the five best performers in the industry did on average from 2010 to

2012, the total national production could reach 1.5 million ton with the licenses granted per 2013 (Nystøyl et al., 2013).

3.4 About the Production Area Regulation

The Production Area Regulation was passed by the Ministry of Trade, Industry and Fisheries and became effective on the 15th of October 2017. The process leading up to the final regulation started in April 2014 when the government announced the start towards a new regulation regime regarding growth in the aquaculture industry (Regjeringen, 2014).

The purpose of the regulation is stated in §1 which can be summarized as ensuring the advancement of the aquaculture industry within the parameters set for sustainable development. The regulation shall also contribute to value creation along the coast, by creation of production areas, and through regulation of production capacity for salmon, trout and rainbow trout (Produksjonsområdeforskriften, 2017).

The main idea when the process was initiated, was to ensure predictable and sustainable growth for the industry. Up until today, the assignment of growth has been done on ad-hoc basis, making the growth potential uncertain for industry participants. The previous growth regimes have also allowed for political latitude, thus not necessarily ensuring sustainable growth (Nærings- og fiskeridepartementet, 2015).

3.4.1 Main Content of the Regulation

The Production Area Regulation changes how the industry is regulated in two main ways. First, the industry is divided into 13 production areas which are rated as red, yellow or green based on the calculated level of environmental threat the area constitutes. The areas are regulated jointly, as opposed to previous regulation regimes, where the locations were regulated on an individual level. Second, the industry growth or reduction is based only on chosen environmental indicators.

Today, the chosen indicator is the risk of mortality of wild salmon populations due to lice infestation. This mortality is estimated by the Institute of Marine Research based on models that encompass emigration patterns for wild stocks, probability of death for small and large fish, infestation pressure models, and real-life observations, e.g. lice counts from fish farms and sea temperatures. The critical limits and effect of the regulation for the different production areas are shown in Table 1 (Nærings- og fiskeridepartementet, 2015). The industry, represented by the Norwegian Seafood Federation, The Federation of Norwegian Industries, and The Norwegian Seafood Association, made a consultative statement in September 2016 where they criticized the model and argued that it was not sophisticated enough to constitute the premises for the management of the Norwegian aquaculture industry (Sjømat Norge et al., 2017). The chosen environmental indicator may change over time, as new challenges become prevailing.

Table 1 Critical limits and effects of the Production Area Regulation

	Low risk/influence	Moderate risk/influence	High risk/influence
Criteria	It is probable that <10 % of the population dies due to lice infection	It is probable that 10-30 % of the population dies due to lice infection	It is probable that > 30 % of the population dies due to lice infection
Effect of the regulation	2 % growth on existing MAB 4 % growth offered through auction	No change in MAB	6 % reduction in MAB

The Ministry of Trade, Industry and Fisheries (2015) state that the challenges regarding salmon lice cannot be solved by regulating the industry on location level like previous regulation has done, but needs to be handled through an overall management linked to acceptable environmental exposure for a defined area. The defined areas have been determined based on dispersion analysis done by the Institute of Marine Research. The analysis quantified the level of salmon lice infection between the fish farms. As a result, the coast of Norway was divided into 13 areas as shown on the map in Figure 7. The environmental status of the areas will we evaluated every second year.

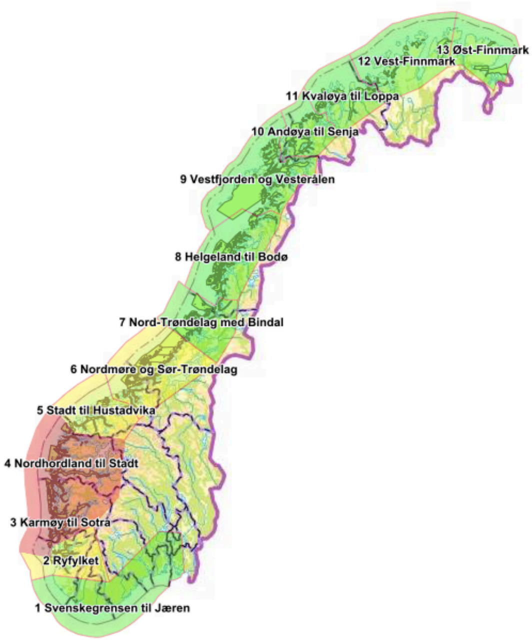

Figure 7 The newly established production areas and their given status per January 2018

The area status is the decision variable for changes in production capacity, operationalized as change in license MAB. No changes are made to location MAB, so companies that are restricted by this will have to apply for increased location capacity as before. This is not discussed in further detail here, as the Production Area Regulation only regulates license MAB.

If an area is given green status, meaning that the threat to wild salmon is considered to be low, the farms in the area may grow. The price of growth is set to 120 000 NOK per ton (Forskrift om kapasitetsøkning for tillatelser til akvakultur 2017–2018, 2017). The existing farms in the green areas are granted 2 % growth if they choose to apply for it. An additional 4 % growth is auctioned out, allowing for new entrants to be established. Companies could in January 2018 apply for growth for the first time since the implementation of the Production Area Regulation. 47 companies choose to do so, amounting to a total of 7 898 ton of growth distributed on 449 out 461 potential licenses in the areas. The auctioning of the remaining 4 % will be completed before the summer of 2018 (Fiskeridirektoratet, 2018a).

If an area is given yellow status, meaning that the threat to wild salmon is considered to be moderate, no changes in MTB is initiated, and the locations in the area can keep operations going as before.

If an area is given red status, meaning that the threat to wild salmon is considered to be high, the production capacity is reduced by 6 % (Nærings- og fiskeridepartementet, 2015). The reduction will not be realized in the ongoing round of capacity adjustment, as the companies in the red areas are to be given time to adjust to the new regulation. Downward adjustments will be completed in 2019 if the area is still assessed to be red (Regjeringen, 2017).

To sum up, the industry has been regulated in different ways since the beginning of the 1970s. The current MAB regime was introduced in 2005, making living biomass in sea the most important constraining parameter for fish farmers. The Production Area Regulation introduced in the end of 2017 has changed the way the industry is regulated by tying future growth to the chosen environmental indicator and dividing the coastline into 13 production areas. The goal of the regulation is to create a framework for predictable and sustainable growth. The regulation has been partially implemented, and the first round of application for growth has been undertaken. Decreased production capacity in red areas will only be enforced from 2019.

4. Theoretical Framework

This chapter introduces the theoretical framework which will constitute the bioeconomic foundation for our later analysis. In Section 4.1, we conduct a literature review which introduces the past and current literature on optimal harvesting, before moving on to the introduction of the optimal rotation problem as proposed by Asche and Bjørndal in Section 4.2 (2011). Lastly, we propose two extensions to the model; introducing the concept of capacity constraints and deriving an expression for willingness-to-pay for capacity increase, in addition to introducing fallowing to the model.

4.1 Literature Review

Bjørndal (1988) developed the first optimal harvesting model for aquaculture, founded on the tree rotation work done by Faustmann in the 1850s (Asche & Bjørndal, 2011). Faustmann developed a model for determining the optimal rotation length for forestry and propose that a tree should be cut when the marginal increase in the value of the tree is equal to the alternative cost of investment in trees and land. In his model, Faustmann assumes that a new rotation can start immediately after a rotation is finished (Guttormsen, 2001).

Bjørndal creates a biological model defining release of smolts, growth rate and mortality rate before introducing economic aspects such as costs and interest rate, creating a bioeconomic model for determining the optimal harvesting time in aquaculture (1988). He does not take into account the rotation problem, and thus only analyze a one-time investment in fish. The model assumes that a fixed amount of fish is released at time *t*, and that over time some fish die, and the others grow according to a defined growth function. The model suggests that a farmer should harvest when the proportional increase in the biomass is equal to the interest rate, known as the Fisher rule in forestry literature (Bjørndal, 1988). In his initial work, Bjørndal further introduces several variable costs such as feed costs, harvesting costs, insurance costs and release costs to the optimization problem (1988).

The model introduced by Bjørndal has later been extended by several authors. Arnason (1992) introduced dynamic behavior in regard to feeding schedules, while Heaps introduced density independent (1993) and density dependent growth (1995). Asche and Guttormsen (2002) analyzed weight dependent prices, concluding that there are cycles in the relative prices for different sizes of farmed fish. These price cycles were incorporated into the bioeconomic model by Guttormsen in 2001. In addition, Guttormsen extended the model to take into account that smolts cannot be released all year round due to biological constraints regarding availability of smolts, implying that a new rotation cannot necessarily be initiated when the previous one is over. The conclusion of this work is that both relative price cycles and limited access to smolts influence the rotation length and the weight per fish at harvest (Guttormsen, 2001).

4.2 The Optimal Rotation Problem

In The Economics of Salmon Aquaculture (2011), Asche and Bjørndal present a bioeconomic model for determining the optimal harvesting time for farmed salmon. The model assumes that variable costs are the only costs relevant for the decision, and salmon prices are fixed to simplify the analysis. Uncertainty in the parameter values is not considered, neither is the stochastic fluctuations in growth.

4.2.1 Number of Fish

The fish that are released into a pen is called a year class. In the model, the number of fish released for each year class is considered exogenous. Assuming a constant mortality rate, the number of fish can be expressed as:

$$N(t) = Re^{-M(t)} \quad (1)$$

The model assumes that at time 0 a given number of fish are released in the pen, denoted R for recruits in the equation above, and that the number of fish is reduced by the mortality rate M over time.

4.2.2 Weight per Fish

The weight per fish at time *t* is denoted w(t). The change in weight over time is expressed as:

$$w'(t) = g(w(t), N(t), F(t)) \ (2)$$

The change in weight is here given by the growth function, which is a function of weight per fish, number of fish and feed quantity. The growth model can also be extended to take other factors such as light and water temperature into account. The individual fish will grow towards a maximum value, where $w'(\tilde{t}) = 0$.

4.2.3 Total Biomass

Now, the total biomass B(t) for the year class can be expressed as a function of number of individuals and weight:

$$B(t) = N(t)w(t) = Re^{-Mt}w(t) \ (3)$$

All individuals are assumed to have the same weight in this model. In reality, this may not be the case, as fish grow at different rates in the pen, but it works as a representation of the average fish. The change in biomass, B'(t) can be expressed as:

$$B'(t) = \left[\frac{w'(t)}{w(t)} - M\right] B(t) \ (4)$$

Where the first term in the bracket is the relative growth rate of the fish. In the beginning, this rate is assumed to be higher than the mortality rate, so that biomass increases over time, i.e. $B'(t) > 0$. When the relative growth rate equals the mortality rate, the biomass is at its maximum. The time *t* when biomass reaches its maximum is denoted t_0, i.e. $B'(t_0) = 0$. The total biomass will reach its maximum before the individuals reach their maximum weight, because individual growth is here cancelled out by the mortality rate, $w'(t)/w(t) < M > 0$.

4.2.4 Value of Total Biomass

The model is initially developed with zero costs, and the value of the biomass is expressed as:

$$V(t) = B(t)p(w(t)) = p(w(t))Re^{-Mt}w(t) \ (5)$$

Where p(w(t)) is the price per kilo fish, which normally varies for different sizes of fish. Assuming that the price is higher for larger fish, we have that p'(w) > 0. This is the case for reasonable weights, and thus the assumption is valid (Fishpool). The number of recruits and the growth curve are here considered exogenous variables. The time when biomass reaches its maximum value is given by t_{max} when $V'(t_{max}) = 0$. The biomass reaches its maximum value at the same time or later than the maximum weight of the year class, depending on price for different weight classes. If price is higher for larger fish, then $t_{max} > t_0$, as opposed to the situation where price is independent of size which gives $t_{max} = t_0$.

In sum, the following relation exists; the individuals reach their maximum weight at the same time or later than the total year class reaches its maximum weight, due to mortality. The value of the biomass reaches its maximum earlier or at the same time as the year class reaches its maximum weight, depending on price conditions, i.e. $t_{max} \leq t_0 \leq \tilde{t}$.

Deriving equation (5) and rearranging the terms results in the following equation:

$$V'(t) = \left\{\frac{p'(w)}{p(w)} w'(t) - M + \frac{w'(t)}{w(t)}\right\} V(t) \quad (6)$$

Where the first term in the brackets expresses the change in price due to growth, the second the natural mortality rate, and the third the growth rate.

4.2.5 Optimal Rotation Length

The model is further developed to the find optimal rotation length taking into account an infinite number of rotations. Optimal rotation length is the time *t* which maximizes the net revenues for all future rotations.

To enable an evaluation of the farmers investments, one must calculate the present value of the investments. The discounting term $\frac{1}{e^{rt}-1}$ is thus introduced. Assuming that production capacity is constant over time, and that the parameter values are constant, the fish farmer will maximize the present value of the biomass over infinite rotations, expressed as:

$$\pi(t) = \frac{V(t)}{e^{rt}-1} \quad (7)$$

Where t is the rotation length. The first order condition is given by:

$$\pi'(t) = \frac{V(t)re^{rt} - V'(t)(e^{rt} - 1)}{(e^{rt} - 1)^2} = 0 \text{ (8)}$$

Which can be simplified to:

$$\frac{V'(t^*)}{V(t^*)} = \frac{r}{1 - e^{rt^*}} \text{ (9)}$$

Rewriting the expression so that it expresses change in the value of the biomass, it becomes clear that the last term is the present value of future profits:

$$V'(t^*) = rV(t^*) + r\frac{V(t^*)}{e^{rt^*} - 1} \text{ (10)}$$

Optimal harvesting is given by the point in time where the marginal increase in the fish stock is equal to the opportunity cost, expressed as:

$$V'(t^*) = \left\{\frac{p'(w)}{p(w)}w'(t^*) - M + \frac{w'(t^*)}{w(t^*)}\right\}V(t^*) = rV(t^*) + r\frac{V(t^*)}{e^{rt^*} - 1} \quad \text{(11)}$$

Which can be rewritten as:

$$\left\{\frac{p'(w)}{p(w)}w'(t^*) + \frac{w'(t^*)}{w(t^*)}\right\} = r + M + \frac{r}{e^{rt^*} - 1} \text{ (12)}$$

This expression illustrates that optimal harvesting time is given when the marginal revenue of keeping fish in the sea is equal to the marginal cost.

4.2.6 Production Costs per Kilo

Introducing production costs into the model, the value of biomass can be modified to:

$$V(t) = B(t)p(w(t)) - B(t)C \text{ (13)}$$

Where C represents the production cost per kilo. This, in turn, changes the profit function from equation (7). The updated profit function can be expressed as:

$$\pi(t) = \frac{B(t)p(w(t)) - B(t)C}{e^{rt} - 1} \quad (14)$$

Optimal harvesting time is then expressed as:

$$\left\{\frac{p'(w)}{p(w) - C} w'(t^*) + \frac{w'(t^*)}{w(t^*)}\right\} = r + M + \frac{r}{e^{rt^*} - 1} \quad (15)$$

If p'(w) = 0, i.e. the price is independent of weight per fish, the introduction of production costs does not change the optimal harvesting time. If p'(w) > 0, the optimal harvesting time increases, as the first term in the equation is reduced.

4.3 Extensions to the Model

4.3.1 Capacity Constraints

One of the elements disregarded by the model presented, is capacity constraints. To our knowledge, no other authors have addressed this issue either. For a Norwegian fish farmer, the capacity constraint is an important decision variable which influences the harvesting time. The model assumes that the farmer harvests when the marginal revenue is equal to the marginal cost, at time t^*. In a scenario with capacity constraints, one may find that a farmer is forced to harvest earlier than what is optimal according to the theory. The capacity constraint, imposed by the fact that total biomass cannot exceed MAB limit at any time can be expressed as:

$$B_t \leq MAB \quad (16)$$

For farmers facing a binding capacity constraint, an increase in capacity can be realized by either increasing rotation length, or by releasing more recruits. In this model, the number of recruits is considered given, so the interesting change is the potential gain from increased rotation length. From equation (6), we can see that the effects of increased rotation length on the value of biomass, is driven by several effects. Given that mortality remains unchanged with increased rotation length, the profitability of increased capacity is driven by two effects; a pure volume effect and a price effect. The pure volume effect is reflected in the third term of the equation, where increased weight leads to increased value of biomass. The price effect is reflected in the first term of the equation, where the fact that the characteristics of the price function influences the profitability of increased rotation length. In scenarios where price is increasing with weight per fish, the farmer gains both the pure volume effect of being able to postpone harvest and thus harvest larger fish, and the price effect of increased price for larger fish.

Further, we define a farmer's willingness-to-pay for change in capacity as θ, which can be calculated as:

$$\theta = \frac{\Delta\pi}{\Delta capacity} \quad (17)$$

This expression defines that a farmer's willingness-to-pay per capacity increase is the change in profits divided by the change in capacity. The unit for θ is NOK per kilo.

Rewriting the expression, the change in profits is expressed as:

$$\Delta\pi = \theta * \Delta capacity \quad (18)$$

We note that other indirect effects such as changes in costs, prices, investment levels or other factors is not included in the calculation of change in profit.

4.3.2 Fallowing

For an infinite number of rotations, the famers aim at maximizing the profits. The profits can initially be expressed as:

$$Max\ \pi(t) = V(t)e^{-rt} + V(t)e^{-2rt} + \cdots + V(t)e^{-nrt} \quad (19)$$

Introducing the concept of fallowing, assuming a fallow period of 2 months duration for each production cycle, the expression can be adjusted to take this into account. The following expression can be deduced:

$$Max\ \pi(t) = V(t)e^{-r(t+2)} + V(t)e^{-2r(t+2)} + \cdots + V(t)e^{-nr(t+2)} + \text{(20)}$$

Which in turn can be rewritten:

$$Max\ \pi(t) = V(t)(e^{-r(t+2)})^1 + V(t)(e^{-r(t+2)})^2 + \cdots + V(t)(e^{-r(t+2)})^n \text{ (21)}$$

This, in turn, changes the profit function to:

$$\pi(t) = \frac{V(t)}{e^{r(t+2)-1}} \text{ (22)}$$

5. Data

We will in this chapter give an introduction to the data set, which will be used to create a growth model for each production area and a price model. This will be used to estimate the average weight per fish and consequently the economic effects of the Production Area Regulation in Chapter 8. Section 5.1 is devoted to the process of creating the data set with a short description of relevant variables included. Next, we describe the data filtration and cleaning procedure, which has been highly crucial to obtain valid regression results. We present descriptive statistics in Section 5.3 and discuss the uncertainty of the variables in Section 5.4.

5.1 Creation of Data Set

For the analysis, we have created a panel data set consisting of monthly biomass related observations for 945 fish farming locations in Norway. Biomass data have been forwarded by the Norwegian Directories of Fisheries for the period of 2005 to 2016 under a research license. All fish farming companies are obligated to report at the end of each month biomass per pen per fish farming location, as well as feed usage and loss per pen (Akvakulturdriftsforskriften, 2008; Akvakulturloven, 2005). The biomass data are summarized over all pens for each location, and we aggregate the different species of salmon and trout into one common species of salmonid. Production data is not reported to the Directorate of Fisheries if a location has been fallowed in a given month, and we have thus created monthly observations with zero biomass, feed usage and loss for these months to secure a continuous time frame in the data set.

Norwegian fish farming companies are obligated to report average lice counts per fish on all locations on a weekly basis, as well as suspicion of or detection of pancreas disease (PD) and infectious salmon anemia (ILA), in addition to different types of lice treatment and temperature (Forskrift om lakselusbekjempelse, 2012). This data have been downloaded from BarentsWatch for the period of 2012 to 2016 (Barentswatch.no, 2017). The weekly lice count and temperature observations are averaged on a monthly basis, while disease and lice treatment are classified on a monthly basis by various indicator and continuous variables.

Price data are obtained from the Nasdaq Salmon Index as weekly reported exporter's selling price for head on gutted salmon at different size intervals, where we added a categorial variable for month and year for the period of 2005 to 2016 (Fishpool; Nasdaq). The price data is adjusted for inflation with 2015 as the reference year. Data on the Norwegian consumer price index is obtained from Statistics Norway (Statistisk sentralbyrå, 2018d).

The 945 fish farming locations represented in the data set are locations that have been allocated to a given production area according to the Production Area Regulation (Nærings- og fiskeridepartementet, 2017). A list of allocations has been downloaded from the Directories of Fisheries, including information on maximum allowed biomass per license and location (Fiskeridirektoratet, 2018f). By restricting the data set to the above-mentioned locations, we are focusing the analysis on operational fish farming locations that are producing edible salmon and salmon trout, thus excluding locations that have been closed within the time period, in addition to locations that are producing broodstock and research facilities.

The data set is a panel data set consisting of 136 080 observations and 49 variables with fish farming location as cross-sectional variable and monthly date per year as time variable. An overview of the most relevant variables in the data set is presented in the table below.

Table 2 Overview of the Most Relevant Variables in the Data Set

Biomass	Reported biomass at the end of each month	Kg
Fish	Number of fish reported at the end of each month	Fish
W_t	Average weight per fish	Kg
Lice_grown	Average number of grown lice per fish	Lice
Fish_per_pen	Average number of fish per pen	Fish
Time	Time periods after release	Month
Location	Location ID	Categorical
Year	Year	Categorical
Month	Month	Categorical
Prod_area	Production area	Categorical

5.2 Data Filtration and Cleaning

We have conducted several filtration procedures in the data set in order to conduct a valid estimation of weight per fish. To achieve this objective, we had to identify individual generations of fish per location, as well as the time periods where the fish were growing. The identification of each generation could easily be done visually by plotting the amount of biomass against time for a given location. Biomass development for one representative location is illustrated in the plot below.

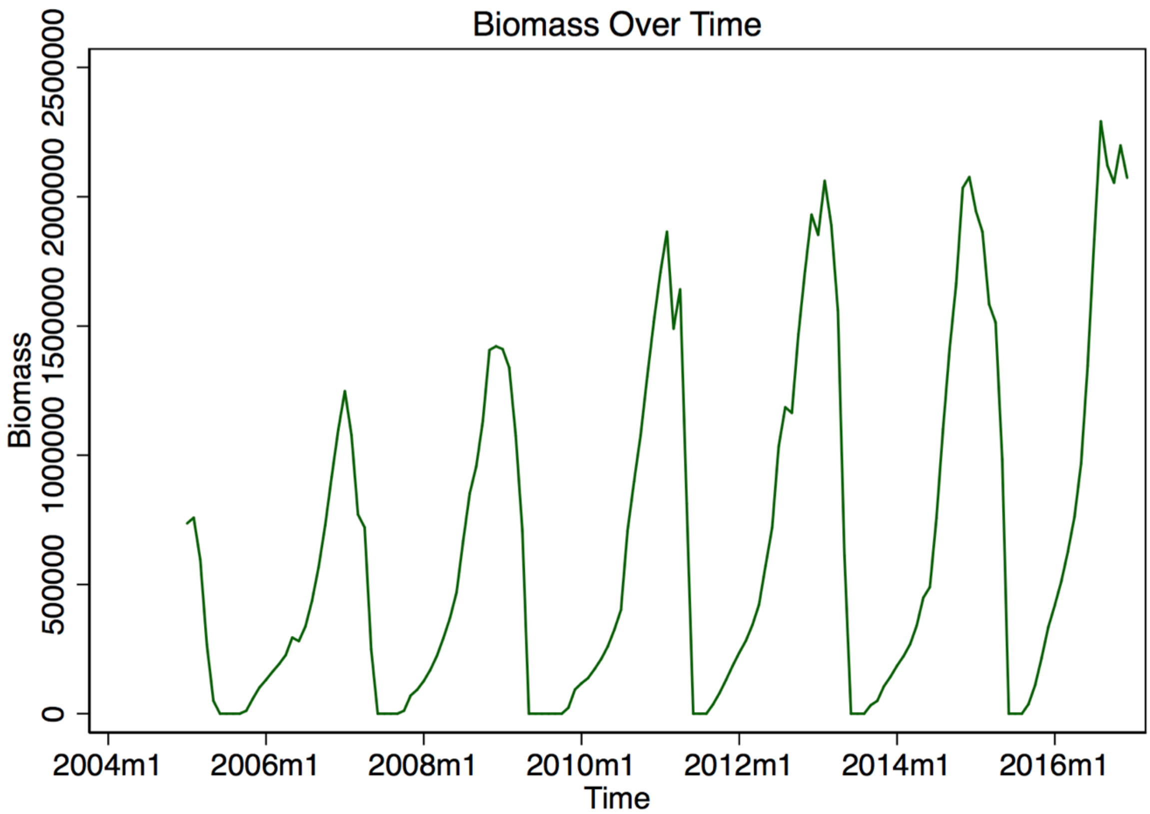

Figure 8 Biomass development over time (Fiskeridirektoratet, 2018c)

The individual generations of fish can be observed from the plot, as well as the periods were the location was fallowed. Running an estimation of weight per fish as function of time on this data would give a false interpretation of biomass growth, as periods where the biomass was reduced due to harvesting would be interpreted as negative growth, and thus affect the regression coefficients negatively.

To solve the above-mentioned challenge, we had to identify the periods of harvest to remove all time periods where the biomass was not growing. To achieve this objective, we started by identifying the periods where the smolt was first released for each generation by identifying an increase in the amount of fish after a period with zero biomass. This made us also able to classify the release as a fall or spring release. We were then able to generate a time variable counting the time after release and until the location became fallowed. Based on the time variable, we generated a unique generation ID, and we were now able to correctly identify 4 172 unique generations of fish.

Next, we had to generate a variable which identified the time periods where the biomass was growing for each location and drop all periods with no biomass growth. This objective was achieved by identifying and indicating the observations with intermediate biomass increase per generation and dropping all other observations. Furthermore, we had to drop all observations within a generation with a lower biomass compared the previous period, as dropping all observations that were not classified as growth did not remove all observations with intermediate biomass reduction. The number of observations after these procedures was 46 829. To finalize the data set, we created a variable for the average weight per fish in a given time period for each generation and removed all outliers with weight above 10 kilograms. This procedure removed 93 observations. We also removed generations with a rotation length under 6 time periods, as generations with missing values would result in a misclassification of generation length. This procedure removed 1 637 observations and 517 potentially misclassified generations. Finally, we considered all generations with length above 34 months to be outliers and removed the respective observations. This procedure removed 146 observations and 10 generations.

5.3 Descriptive Statistics

We will in this section present descriptive statistics to provide a better understanding of the magnitude of the data set. A table of summary statistics for relevant variables is presented in Table 3, with overall variation between locations and time, time-independent variation between locations and time-dependent variation within locations.

The overall mean is the mean of all observations in the data set, with the corresponding minimum and maximum values being reported. The overall standard deviation constitutes a comparison of a given location's observed value at a given time period and the mean of all locations over all time periods.

The between standard deviation is interpreted as the variation in unit-level average between fish farming locations and constitute a comparison of a location's mean with the mean of all locations independent of time. A between variation equal to zero means that all locations take the same value at a given time period. The reported minimum and maximum values are the lowest and highest observed location specific mean.

The within standard deviation is calculated as the unit-level variation over the sample period and constitute a comparison of a location's observed value at a given time period and its mean for all time periods. The corresponding within minimum and maximum values represent the lowest and highest observed time-dependent difference for the whole sample. The minimum can become negative by definition, as a location may have a lower observed value at a given time period compared to its mean. A within variation equal to zero means that all locations take the same value in all time periods, although the value taken may vary between locations.

Table 3 Summary Statistics

Variable		Mean	Std. Dev.	Min	Max
Biomass	Overall	1092695	1069291	2340	1.39e+07
(Kg)	Between		550221	38337	4644155
	Within		938122	-3449350	1.04e+07
Number of fish	Overall	782071	438451	5851	5485820
(Fish)	Between		361643	35042	3063494
	Within		276065	-1444465	3204397
Weight per fish	Overall	1.487	1.274	0.038	9.722
(Kg)	Between		0.448	0.198	3.975
	Within		1.230	-1.749	9.768
Rotation length	Overall	18.10	4.842	6	34
(Months)	Between		3.748	6	30
	Within		3.840	-1.159	34.37
Number of lice	Overall	0.122	0.260	0	6.583
(Lice)	Between		0.113	0	1.3
	Within		0.244	-0.761	6.274
Fish per pen	Overall	114684	55051	3862	543681
(Fish)	Between		42392	18757	274419
	Within		36272	-73784	453318

The mean value of biomass is 1 092 695, which constitutes an average between all locations and in all time periods. We can see that the amount of biomass varies a lot compared to the overall mean, both between and within locations. We find this observation to be natural, as fish farming locations vary considerably in size. In addition, the biomass will increase substantially during the life time of the fish.

Similar to biomass, the mean value of the number of fish constitute an average between all locations in all time periods. The overall maximum illustrates the size of one of the largest fish farming locations, which can hold up to 5.5 million fish. The overall variation between fish farming locations illustrates a large difference in sizes between locations, while a high within variation is natural due to harvesting or mortality.

The average weight per fish of all locations in all time periods after release is 1.49 kg, which does not seem to vary to a large degree between locations. The maximum size of fish observed is 9.72 kg, which is considered to be high compared to commercial sizes. We note that weight observations above 10 kg are considered to be outliers and removed from the data set. We can observe that the weight per fish varies to a large degree within locations, which is natural due to fish growth.

It is highly interesting to look at the descriptive statistics of rotation length. We note that the rotation length in this case is defined as the number of months in the grow-out phase from release until harvesting is first initiated. The overall average rotation length is 18.10 months with an overall standard deviation of 4.84 months. The highest observed rotation length is 34 months, which is considered to be high, but realistic under certain growth and market conditions. We also find it interesting that the rotation lengths within locations varies with an average of 3.84 months, indicating that the decision of harvesting is influenced by time-dependent factors like current market conditions.

The overall average amount of grown female lice per fish is 0.12, which is below the regulative limit of 0.50 (Forskrift om lakselusbekjempelse, 2012). The overall standard deviation of 0.26 illustrates, that on average, the number of lice on a given location does not exceed the limit. It is important to keep in mind that the fish farmers seek to minimize the lice level in order to not exceed the regulative limit. We can observe that the number of lice varies significantly between and within locations.

Looking at the overall mean of the number of fish per pen, we can observe that it is under the regulative limit of 200 000 fish per pen, and the overall observed maximum of 543 681 fish is forbidden according to current regulations (Akvakulturdriftsforskriften, 2008). The overall standard deviation indicates that the average deviation from the mean does not result in a violation of the limit. We have to keep in mind that the number of fish is usually reduced due to natural mortality or harvesting, and that the overall mean does not represent the average number of fish per pen at the time of release of a generation. The between standard deviation indicates considerable differences in sizes between fish farming locations, while the within standard deviation indicates that the fish stocks are usually reduced during the rotation period and at harvesting.

5.4 Uncertainty in Variables

As mentioned, it is compulsory for all locations to report total biomass in the sea at the end of each month. The reported biomass numbers are estimates, as it is challenging for fish farmers to know exactly how many fish there are in each pen, and how much each fish weight. It is reason to believe that the measurement error is noise that may bias our estimates. The biomass estimation is today based on growth models, section tests, and data from biomass measuring frames (Høy, Sunde, & Vanhauwaert Bjelland, 2013). The estimations prove to be quite accurate in sum, illustrated by work done by SINTEF in 2013, where 240 selected pens in sum had a deviation between reported biomass and harvested biomass of 604 ton out of 134 608 harvested ton, i.e. a deviation of 0.45 % (Høy et al., 2013). With this being said, the accuracy varies between pens, and 50 % of the pens had more than 3 % deviation in biomass estimation.

The data provided from the Directorate of Fisheries were presented on a pen level. The data have been aggregated to location level, allowing for the removal of noise in the data set resulting from the relocation of fish between pens within the same location. When estimating weight per fish at a given location, we are assuming that the individuals at a location remain unchanged during the production cycle, i.e. that fish are not moved between locations.

As the goal is to create a growth model, we considered adjusting total biomass for the weight of released fish, to avoid that the model identified release of recruits as growth. This incorrectly identified biomass growth could potentially make the coefficients skewed. From the data set we were able to identify when recruits are released by identifying the observations where the number of fish increased from one month to the next. Often, recruits are released over 2 to 3 months continuous, and they are usually part of the same generation, either spring or fall smolts. The conclusion after adjusting biomass for release, with an assumed weight per recruit, is that the adjustment introduces more uncertainty into the data set than it improves it, and that this procedure is not favorable for our purpose.

Each location reports the number of fish in the sea at the end of each month. The number of fish is most often an estimate, as it is challenging to know the exact number of fish in a cage. The estimation is based on continuous bookkeeping, where the stock is reduced in the event of harvest or death. More accurate counts are done when the fish are released, and thereafter in the event of treatment, or relocation of the fish (Høy et al., 2013).

The variable fish per pen is defined as the average number of fish per active pen at a location, where an active pen is considered to be a pen with reported biomass above zero. The practice of moving fish between pens within a location is widespread, and the number of active pens may change during the period of a rotation. It is thus important to keep in mind that intermediate changes in the variable may occur due to changes in the number of active pens, and not necessarily due to changes in the fish stock. As with the variable for total number of fish per location, the variable for fish per pen is based on bookkept numbers or estimation of the total number of fish at a given time period, which contain some degree of uncertainty.

6. Empirical Framework

We will in this chapter present the empirical growth and price model which is derived from the data set. In Section 6.1, we introduce the structural growth and price model, while Section 6.2 and 6.3 are devoted to the discussion of potential challenges with multicollinearity, heteroscedasticity and serial correlation.

6.1 Structural Models

6.1.1 Growth Model

We have created a growth model for an individual fish' weight, which enables the estimation of the willingness-to-pay for change in capacity. The model considers a fish' weight as a function of time after release, and the functional form, as suggested by Asche and Bjørndal (2011), is a third-degree polynomial with interception set to zero and no first-degree component. We will in this section present and evaluate the following model:

$$w_{it} = \beta_1\, time^2 + \beta_2\, time^3 + \beta_3\, time^2 * prod\_area + \beta_4\, time^3 * prod\_area + \beta_5\ lice_{it} + \beta_6\ density_{it} + \delta\, month + \lambda_t + \alpha_i + \varepsilon_{it}$$

The dependent variable is the weight of an individual fish w_{it} at a given fish farming location i and in a given year and month t, which is a function of the number of time periods *time* after the release of a generation and a set of control variables. The variable *time* is measured as the number of months after the release of a generation. We find and support that a third-degree polynomial with interception equal to zero is a good fit for the data. In reality, the interception would equal the size of the smolt in the period of smolt release, which we are not able to account for. We have included interaction terms between the second- and third-degree component of the time variable and production area, to obtain unique growth coefficients per production area. The variables $lice_{it}$ and $density_{it}$ are included in the regression as control variables. $Lice_{it}$ is the average monthly number of lice per fish for a given location in a given month and $density_{it}$ is the average number of fish per pen for a given location in a given month. The parameters λ_t, α_i and ε_{it} are error components.

Having the dependent variable in logarithmic form has been considered as an alternative functional form, where an increase in time represents a relative intermediate change in biomass. However, this model would yield a considerable overestimation of biomass when running post-regression analysis and a higher estimation error compared to having the dependent variable at level form.

The model is estimated using dummy variables for month, which allows us to control for endogeneity related to month specific unobserved factors being correlated with the explanatory variables. In addition, including indicator variables for month removes any month-dependent variation in the dependent variable. These effects are given by the parameter δ. By controlling for time and location fixed effects, we are able to control for endogeneity related to unobserved common macro effects that changes over time, as well as unobserved fixed effects between locations.

An example of unobserved common macro effects are disease or climatic conditions that affect the growth conditions negatively for the whole industry, thus leading to a below-average growth rate for all fish farming locations in a given year. Location specific fixed effects may be caused by differences in individual efficiency of different fish farmers, or geographical climatic differences leading to heterogeneity in growth rate. By partial out the fixed effects, as well as the variation related to the control variables, we are able to utilize the residual variation in growth to isolate the true intermediate growth in biomass from one period to another on an average level represented by the estimated regression coefficients for the time variable.

Assessing Potential Explanatory Variables

We emphasize the fact that other unobserved factors, which are necessarily not correlated with the explanatory variables, should be included in a true growth model to be able to estimate the weight of an individual fish more accurately. As earlier presented, several factors are relevant to determine the growth rate of salmon, and variables such as daylight, salinity, density and diseases are known examples. However, we have not been successful in obtaining adequate data on these factors.

We have data on temperature together with lice, PD and ILA in our data set. In addition, we created a variable for the total number of fish per pen at a given location in a given time period.

One may argue that this variable is correlated with the density of fish in a pen. The relationship between the above-mentioned variables and the dependent variables can be assessed by drawing a plot showing binned scatterplots. Each point represents the mean of the x-axis and y-axis for 100 equal sized bins of the x-axis variable, which improves readability compared to an ordinary scatterplot. The red line is a linear fit between the two variables in the plot. The dependent variables are demeaned after controlling for month, as well as time and location fixed effects. The left-hand side plots illustrate the relationship between the variables with the dependent variables in level form, while the dependent variables are in logarithmic form in the right-hand side plots.

Looking at the relationship between the dependent variable and the number of fish per pen, as shown in Figure 9, one can observe that it is negative correlated with a significant downward sloping trend. This is as expected, as higher density reduces the fish' growth conditions negatively, which thus leads to relatively lower biomass at a given time period after release. One would expect the respective regression coefficient to be negative if the variable is included in the growth model. However, the plots also illustrate the fact that the fish is relative small when the number of fish is relatively large, which is at the point of release. The number of fish will be reduced due to mortality as the time increases, while the remaining fish grow in biomass. As we may not be certain if the variable explains the real effect of density on a fish' individual weight, we choose to include the variable in the regression model only to control for the variation related to the amount of fish per pen, but we will not use the variable for post-regression weight estimations.

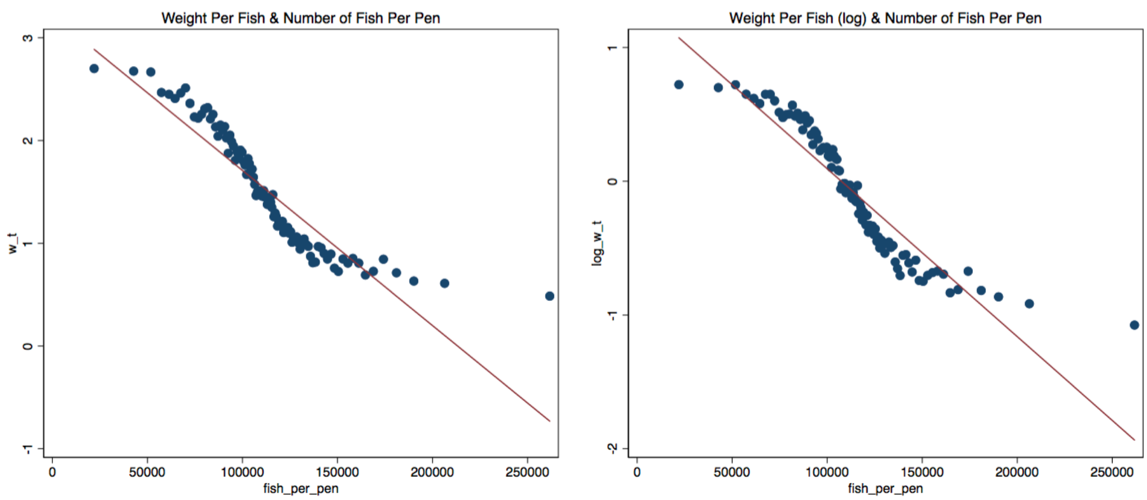

Figure 9 Scatterplot of weight per fish against fish per pen

The relationship between the dependent variable and the average number of lice per fish at a given location in a given time period is positive, as shown in Figure 10, thus expecting to yield a positive regression coefficient if the variable is to be included in the growth model. An increase in lice thus corresponds to an increase in weight in the data set, which is contradicting to our expectation of lice preventing biomass growth. For that reason, we choose only to include the variable as a control variable, and not use the variable for post-regression estimation.

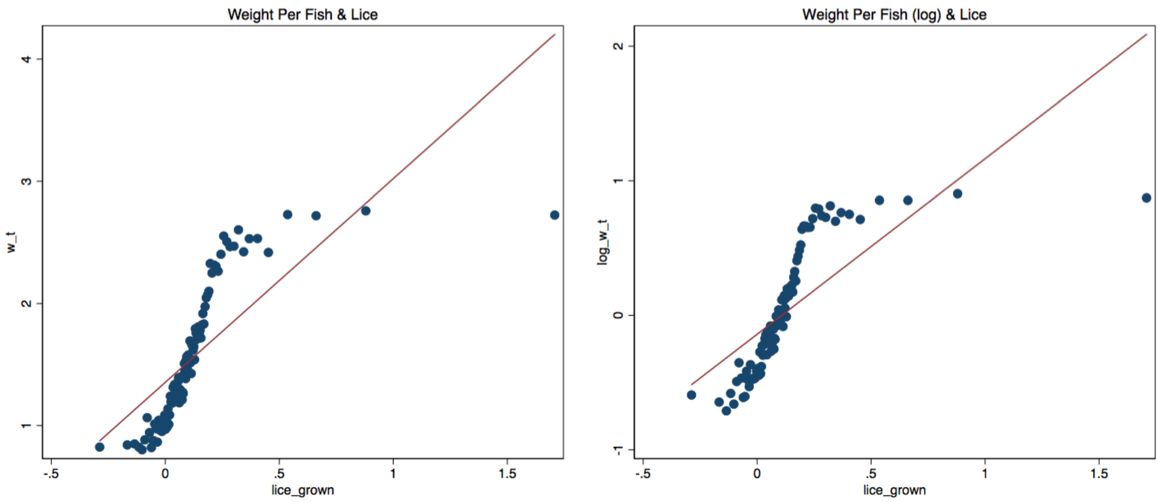

Figure 10 Scatterplot of weight per fish against lice

One would expect, from a biological perspective, that the growth rate increases when the temperature increases up to a certain level, and we would expect to observe a relative higher weight per fish at relatively higher temperatures in the plots below. Although the red linear regression line indicates an upward sloping trend, we visually conclude that the relationship between the variables is ambiguous. The regression coefficient of temperature would be positive if the variable was included in the growth model, but we choose to exclude it for the above-mentioned reason.

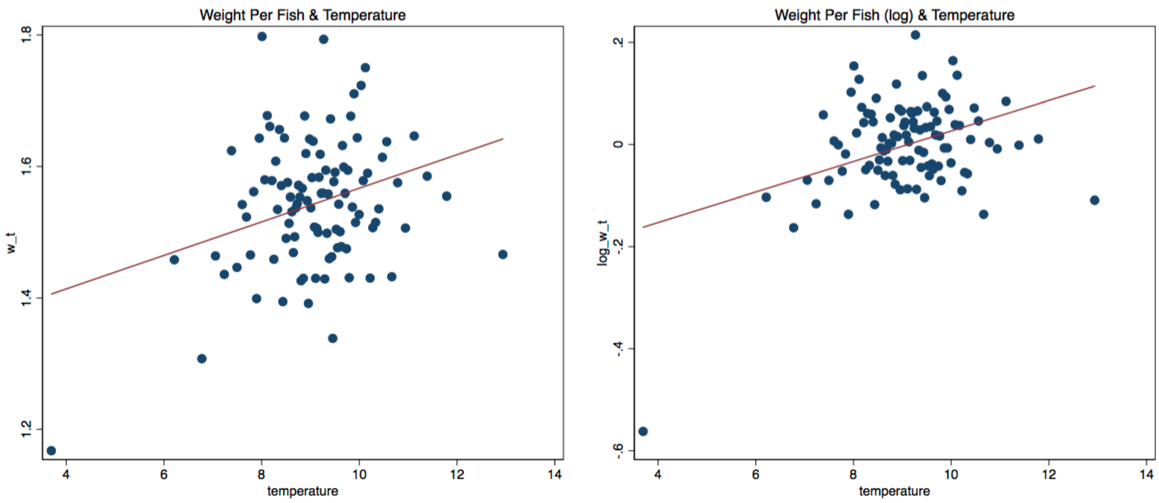

Figure 11 Scatterplot of weight per fish against temperature

We have indicator variables for the diseases PD and ILA in our data set, indicating disease outbreak at a given fish farming location. Their respective regression coefficients, if included in the growth model, are positive, which is contradicting to our expectation of diseases, in general, affecting fish growth negatively. The variables are excluded from the model, as we have a lot of missing values for most production areas.

One would expect that feed usage is a relevant explanatory variable in the growth model. However, including feed as an explanatory variable introduces a simultaneity problem in the regression and potentially biased coefficients caused by endogeneity, as feed usage is expected to explain a fish's weight and growth, while weight and growth is also expected to explain the feed usage. We have not been successful in finding a good instrument for feed usage and thus concluded to exclude the variable from the regression model.

As earlier described, controlling for month and location fixed effects is expected to remove month-dependent and geographic unobserved factors. It is well known that climatic factors, as temperature, daylight and salinity vary significant with month of the year and location. We are therefore confident that excluding the above-mentioned variables constitute a valid simplification of the true growth model, allowing us to estimate the intermediate change in biomass from one period to another.

6.1.2 Price Model

The estimation of optimal rotation length according to the bioecological theory of Frank Asche and Trond Bjørndal (2011) requires an assumption of the price of salmon, which is suggested to be a function of weight. We have calculated our own empirical price function using historical price data in the period of 2005 to 2016 from the Nasdaq Salmon Index, which contains weekly reported exporters' selling price for head on gutted salmon at different size intervals (Fishpool; Nasdaq). The prices are adjusted for inflation with 2015 as the reference year. Looking at the binned scatterplot below of the relationship between prices per kilogram and weight, we can observe that a quadradic function seems to be a reasonable fit to the data.

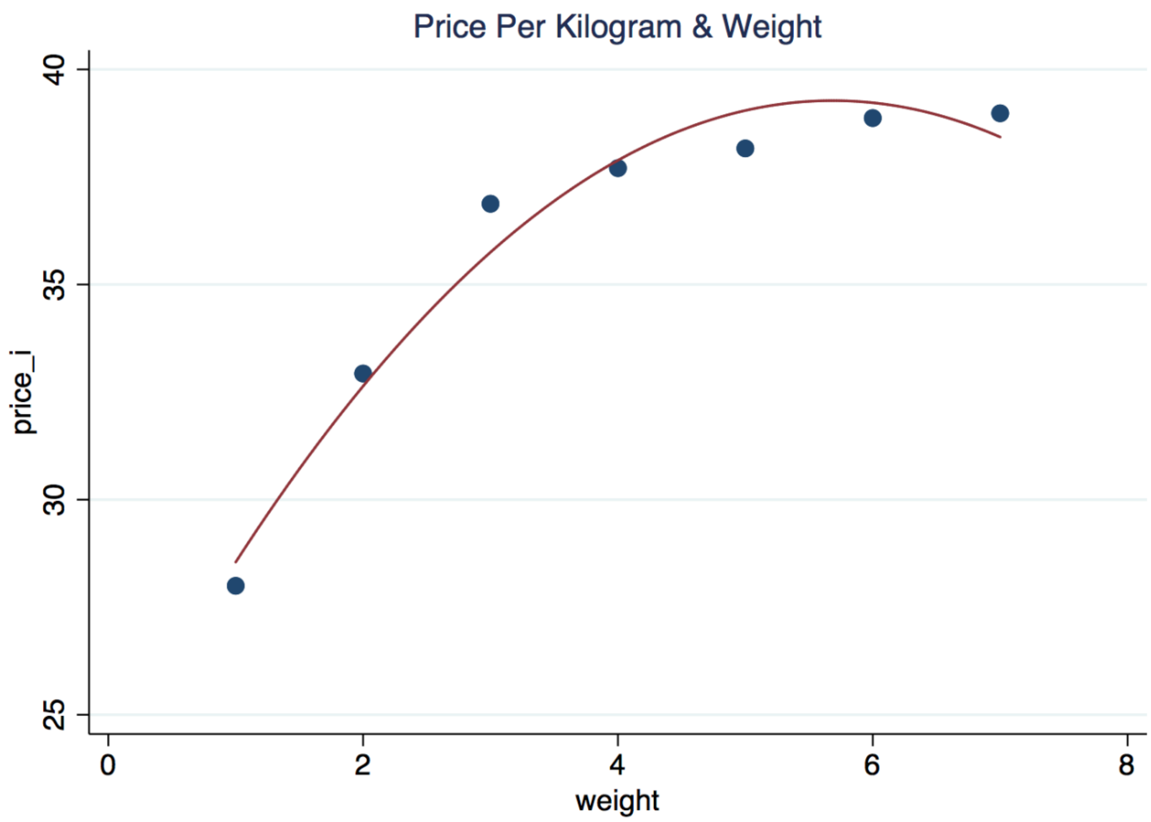

Figure 12 Price per kilogram against weight in kilogram

The price function thus takes the following form:

$$p(w) = \beta_1 + \beta_2\, w + \beta_3\, w^2 + \delta\, month + \lambda\, year + \varepsilon$$

We have that price per kilogram p(w) is a linear function of the first- and second-degree component of weight w, with the constant term β_1. We choose to control for month represented by the parameter δ, as it is shown that relative prices between different weight classes follow different month-dependent price patterns (Asche, 2002). We also control for time fixed effects represented by the parameter λ. The parameter ε is the error term.

6.2 Multicollinearity

Potential multicollinearity can be assessed by looking at the correlation between the explanatory variables, which is illustrated in the correlation matrix below. We can observe a significant high correlation between the second- and third-degree component of the time variable, while little correlation between the other variables. We are confident that multicollinearity does not bias the estimated standard deviations of the time variables, as they are correlated by construction.

Table 4 Correlation Matrix

	$Time^2$	$Time^3$	Lice	Fish per pen	Month	Year
$Time^2$	1					
$Time^3$	0.972^{***}	1				
Lice	0.249^{***}	0.216^{***}	1			
Fish per pen	-0.215^{***}	-0.208^{***}	-0.117^{***}	1		
Month	-0.0496^{***}	-0.0270^{***}	0.0431^{***}	-0.0215^{**}	1	
Year	-0.00824	-0.0207^{**}	-0.0387^{***}	0.0365^{***}	-0.0565^{***}	1

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

6.3 Adjusting for Heteroscedasticity and Serial Correlation

It is reason to expect the existence of both heteroscedasticity and serial correlation in the regression model, which can potentially bias the standard deviations and making model inference invalid. Heteroscedasticity is present if the variation in the error terms is not constant, thus violating the multiple regression assumption of homoscedastic error terms. Serial correlation is present if an error term in one period is correlated with the error term in another period, which will violate the multiple regression assumption of independent error terms errors (Hill et al., 2012). To assure unbiased standard deviations in the regression model, we choose to report Newey-West standard deviations which are robust to both heteroscedasticity and serial correlation (Newey & West, 1987).

7. Model Evaluation

We will in this chapter present and evaluate our growth and price model based on the significance level of the regression coefficients, the model's overall goodness-of-fit and prediction errors. We add control variables, time and location fixed effects stepwise in the models to investigate the respective effects. Finally, in Section 7.2, we comment on the validity of using the models for analytical purposes. We note that for simplicity, we evaluate the growth model for the industry as a whole by excluding the interaction terms between the time variables and production area when estimating the regression coefficients.

7.1 Regression Results

7.1.1 Growth Model

The regression results for the structural growth model are presented in Table 5. All regression coefficients are significant at the 99 % level, with the coefficient for the second-degree component of time being positive and the coefficient for the third-degree component of time being negative. The direction of the coefficients is as expected, considering a concave growth function as time increases after a given cuspidal point. This means that the weight per fish will decline when the third-degree component becomes sufficiently large, which is not realistic. In reality, the fish will grow asymptotically towards its maximum weight. We wish to highlight that the size of the coefficients is challenging to interpret without running weight estimations in a spreadsheet.

The first regression considers weight per fish as a function of time without control variables, month and year dummies, as well as location fixed effects. The goodness-of-fit for the first regression is considered to be good with an adjusted R-squared of 0.78. We observe that the explanatory power increases significantly when adding control variables in the second regression. Regression (1) and (2) yield higher coefficients for the time variable in absolute term compared to the regressions with month and year dummies in regression (3) and (4). Including month and year fixed effects increases the goodness-of-fit to 0.85. Compared to regression (3) and (4), we observe that the size of the coefficients for the time variable increases in absolute term when adding location fixed effects in regression (5), together with a decrease in goodness-of-fit to 0.77. The direction of the control variables is as discussed in Chapter 6, except from the positive direction of the coefficient of fish per pen in regression (2). We conclude that the main effects of the regressions, represented by the coefficients of the time variables, are highly significant and very robust. The conclusion is supported by a high explanatory power of all of the regressions.

Table 5 Main Regressions of Growth Model

	(1)	(2)	(3)	(4)	(5)
$Time^2$	0.0275***	0.0226***	0.0183***	0.0182***	0.0206***
	(0.000349)	(0.000480)	(0.000626)	(0.000637)	(0.000598)
$Time^3$	-0.000885***	-0.000653***	-0.000465***	-0.000458***	-0.000529***
	(0.0000213)	(0.0000274)	(0.0000354)	(0.0000362)	(0.0000364)
Number of grown female lice		0.824***	0.666***	0.666***	0.333***
		(0.0679)	(0.0585)	(0.0583)	(0.0372)
Number of fish per pen		0.00000133***	-0.00000272***	-0.00000276***	-0.00000524***
		(0.000000119)	(0.000000311)	(0.000000310)	(0.000000508)
Controls	No	Yes	Yes	Yes	Yes
Month FE	No	No	Yes	Yes	Yes
Year FE	No	No	No	Yes	Yes
Location FE	No	No	No	No	Yes
N	45314	20811	20811	20811	20805
Adj. R-sq.	0.78	0.83	0.85	0.85	0.77

Standard errors in parentheses. Month and year dummies not reported. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

7.1.2 Price Model

The regression results for the quadratic price model are presented in Table 6, with a stepwise inclusion of year and month fixed effects.

Table 6 Main Regressions of Price Model

	(1)	(2)	(3)
Weight	5.557***	5.557***	5.557***
	(0.344)	(0.201)	(0.192)
Weight^2	-0.489***	-0.489***	-0.489***
	(0.0447)	(0.0253)	(0.0241)
Constant	23.48***	16.44***	15.00***
	(0.535)	(0.367)	(0.489)
Year FE	No	Yes	Yes
Month FE	No	No	Yes
N	4382	4382	4382
Adj. R-sq.	0.11	0.73	0.76

Standard errors in parentheses. Month and year dummies not reported. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The constant and the coefficients of the first-degree component of weight is, as expected, both positive and significant at the 99 %-level, while the second-degree component of weight is negative and also highly significant. The first regression yields an adjusted R-squared of 0.11, with a significantly increase in adjusted R-squared when adding year and month fixed effects. The inclusion of the fixed effects decreases the interception, while the coefficients of weight remain unchanged. We can observe a slightly increase in explanatory power when adding month fixed effects in regression (3) compared to regression (2). We conclude that the quadratic price model explains the relationship between price per kilogram and weight quite good, after controlling for month-dependent price patterns and year fixed effects.

7.2 Model Validation

7.2.1 Growth Model

To further validate our growth model, we run post-regression predictions of weight per fish using all five regressions and calculate their respective prediction errors. We use observations from year 2005 to 2014 to estimate the regression coefficients and observations from year 2015 and 2016 to make weight predictions. The predictions are estimated using only the parameters of the time variable, not taking into account control variables and fixed effects. The mean absolute error, abbreviated MAE, and mean absolute percentage error, abbreviated MAPE, for all five regressions are presented in the table below.

Table 7 Prediction Errors of the Growth Model

	(1)	(2)	(3)	(4)	(5)
MAE	0.522	0.552	0.636	0.635	0.556
MAPE	40.10	39.44	42.54	42.52	39.72

The first regression has the lowest value of MAE compared to the other regressions, while the second regression has the lowest value of MAPE. The mean absolute error implies that the average absolute error in weight estimation is between 0.522 and 0.636 kilogram, while the mean absolute percentage error implies that the weight predictions deviate with 39.44 % to 42.54 % from the real observed value. The error measures do not indicate whether the deviation is due to over- or underestimation.

We plot the predicted values against the observed values to investigate if the errors are due to over- or underestimation. The binned scatterplot below would align along the diagonal line if the predicted values were equal to the observed values. We can observe from the plot that the weight predictions from all five regressions are slightly underpredicted, with the first regression giving the visually best model fit.

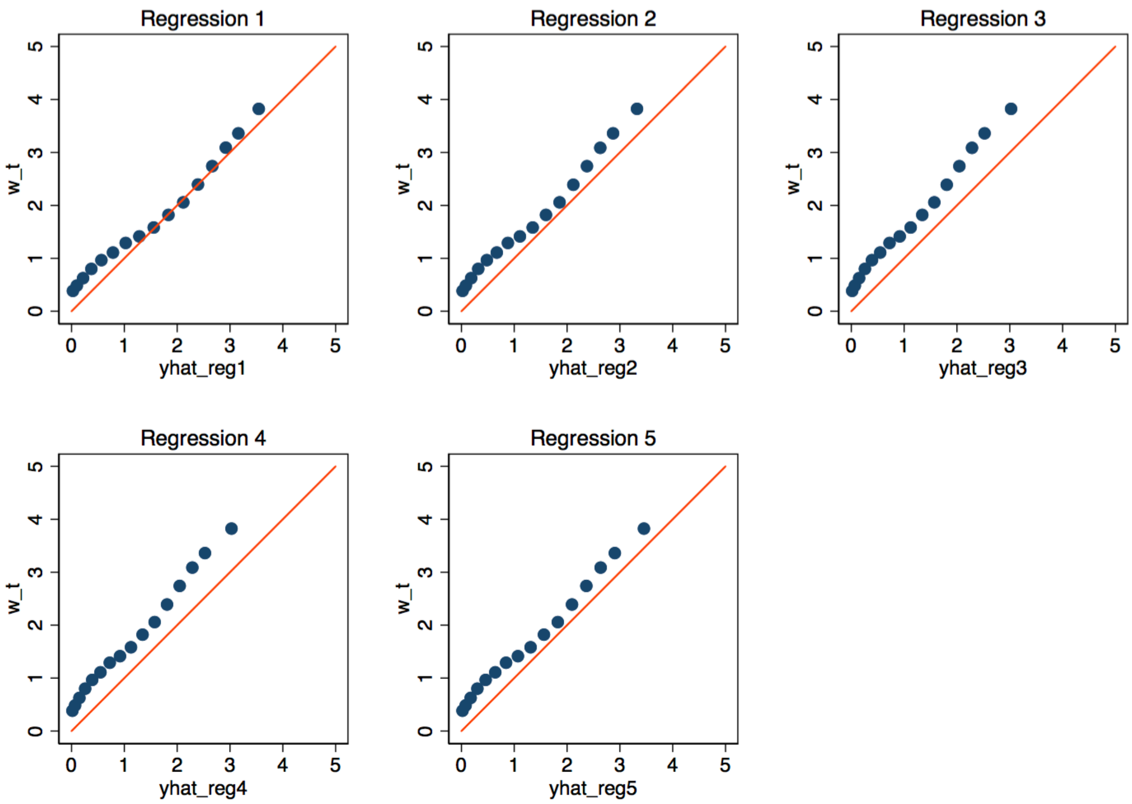

Figure 13 Prediction plot of the growth model

The magnitude of the prediction errors is satisfying taking into consideration that we are predicting an average fish' weight at a given time period after release in a highly heterogeneous industry. It is thus expected that each weight observation deviate from the mean to a certain degree. As the predictions are consistently underpredicted, we may be confident that this leads to a relatively lower biomass estimation, which in turn leads to underestimated economic effects of the Production Area Regulation.

We would expect the fifth regression to be the most accurate, but we note that the model's adjusted R-squared is smaller compared the other regressions. Although regression (2) yields better model fit in terms of predictions errors compared to regression (5), we conclude that the difference in predictions errors between the regressions, both numeric and visually, is small, making the five regression results quite similar. We may then be confident in using the fifth regression for analytical purposes, as including month, year and location fixed effects are expected to yield more valid regression coefficients.

7.2.2 Price Model

The prediction errors of the price model are displayed in Table 8. We do not find it relevant to divide the data set into a separate estimation and prediction part, as the price level has been considerably higher towards to end of the data period. Making out-of-sample predictions in this case would lead to an underprediction of price. Similar to the evaluation of the growth model, we use only the parameters of the weight variable to make the predictions.

Table 8 Prediction Errors of the Price Model

	(1)	(2)	(3)
MAE	8.087	8.952	9.647
MAPE	23.18	21.60	23.07

The first regression has the lowest value of MAE, while the second regression has the lowest value of MAPE. We find the regression errors, in general, to be adequate. Whether the errors are due to over- or underprediction is illustrated in Figure 14.

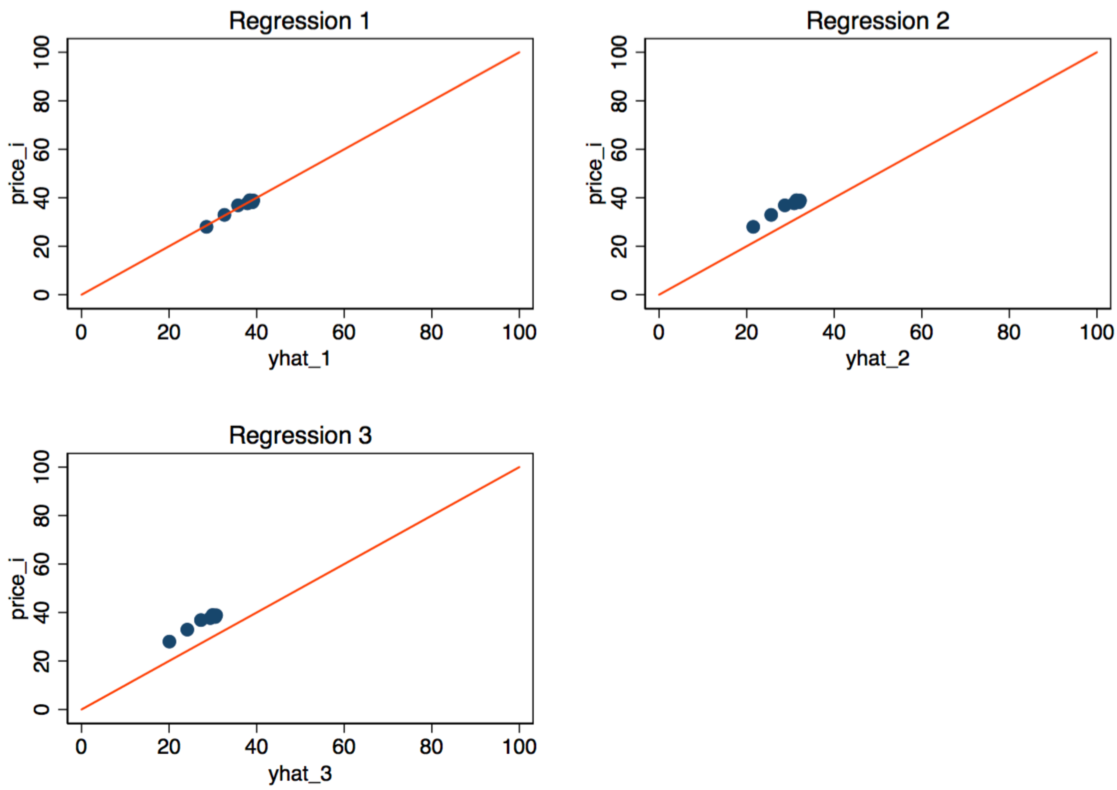

Figure 14 Prediction plot of the price model

We can observe from the plot that the predictions are underpredicted for the second and third regression, while the first regression has the visually best fit. The inclusion of month and year fixed effects is expected to yield more valid regression results and we thus choose to use the third regression for analytical purposes. It is important to note that the underprediction of price will in turn lead to an underestimation of the economic effects of the Production Area Regulation.

8. Analysis

In this chapter, we will estimate rotation length, weight per fish at harvest, willingness-to-pay and profit for changes in capacity constraint per license in each production area. In Section 8.1, we present the initial model setup and introduce the relevant parameters. In Section 8.2, optimal production without capacity constraints is estimated, before capacity constraints are implemented in Sections 8.3 and 8.4. The model is further developed to take into account fallowing in Section 8.5. The regulative status of the production areas and the implications for profits is discussed in Section 8.6. Heterogeneity in the economic effects is discussed in Section 8.7, where changes are made to the initial assumptions regarding number of recruits, mortality rate, price, costs and interest rate. In Section 8.8, the model is updated to reflect a more recent price and cost level in the industry, before we move on to a more general discussion of our findings. Lastly, the limitations of the analysis are discussed.

8.1 Initial Model Setup

8.1.1 Willingness-To-Pay

The objective of the analysis is to estimate optimal rotation length as proposed in the theoretical model in Chapter 4, and the corresponding willingness-to-pay, expressed as θ in equation (17):

$$\theta = \frac{\Delta\pi}{\Delta capacity}$$

The willingness-to-pay expresses how much companies in the industry should be willing to pay per kilo for increased capacity, or alternatively to avoid capacity reduction.

8.1.2 The Profit Function

The total profit with an infinite number of rotations is calculated as expressed in equation (7):

$$\pi(t) = \frac{V(t)}{e^{rt} - 1}$$

When examining the functional form of the profit function, as seen in Figure 15, for the production areas displayed in Figure 7, it becomes evident that the return on increased capacity is declining after a given cuspidal point as farmers approach optimal production, indicating diminishing returns on capacity increase on the concave part of the curve. We thus understand that the willingness-to-pay is highly dependent on the deviation from optimal harvesting time.

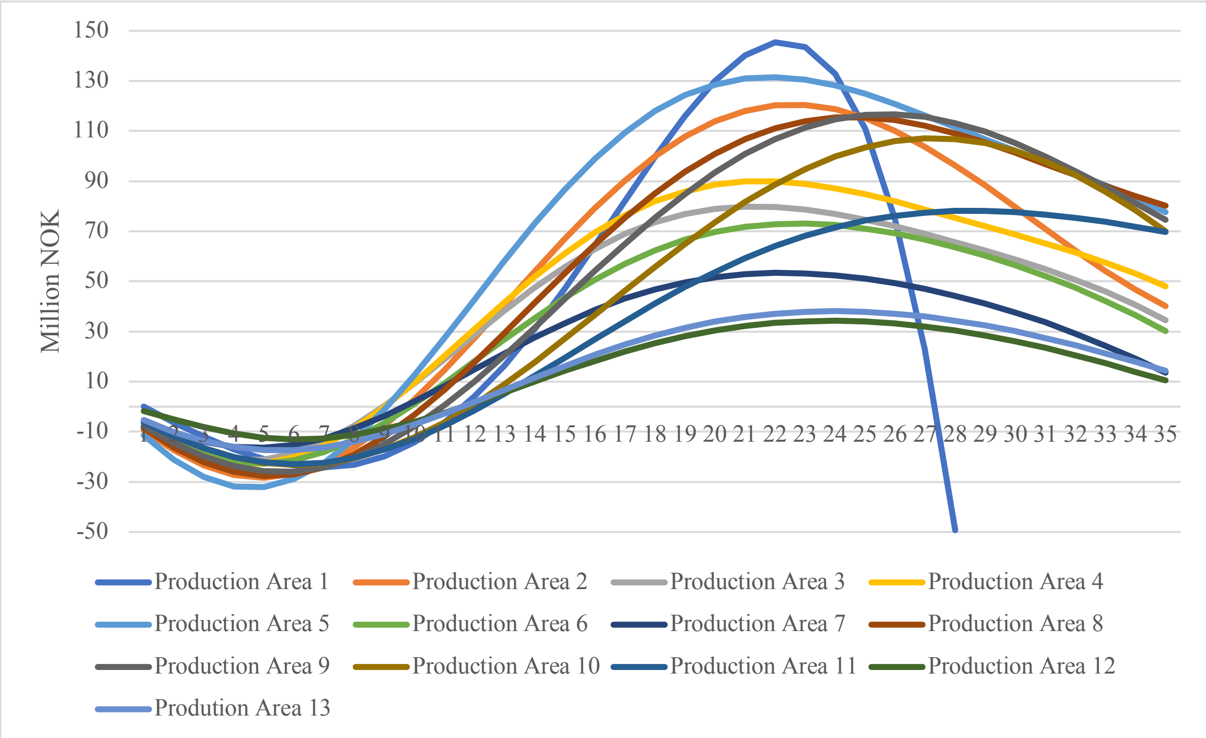

Figure 15 Present value over time of infinite rotations for all production areas, numbers in million NOK

8.1.3 MAB Constraints

The model maximizes the profit per production license by changing the rotation length, under the constraint that total biomass cannot be higher than MAB at any time, as expressed in equation (16). For production areas 1 to 9, the initial license MAB is set to 780 ton, while the MAB is set to 945 ton for production areas 10 to 13. We further assume that the license capacity is fully utilized at all times. Full capacity utilization implies that a new rotation is started immediately after a rotation has ended. We further assume that in the cases where both location MAB and license MAB are binding restrictions, the increase in license MAB is followed by a corresponding increase in location MAB, so that the capacity increase can be fully realized.

In the analysis, a change in MAB is operationalized through a change in rotation length, and not through changes in the number of recruits. This simplification is not necessarily an unrealistic delimitation, as it is reasonable to assume that farmers release as much smolt as possible, both from a regulatory perspective and according to the supply of smolt.

8.1.4 Growth Function, Mortality Rate and Number of Recruits

The growth function is derived for each production area as described in Chapter 6, and is expressed as:

$$w_{it} = \beta_1\, time^2 + \beta_2\, time^3$$

The coefficients of the growth function for each production area are estimated and displayed in the table below. Mortality is assumed to be constant over time and is derived from the data set. The number of recruits per license is calculated based on release data from the Directorate of Fisheries (Fiskeridirektoratet).

Table 9 Model Parameter Values per Production Area

Area	Time^2	Time^3	Mortality Rate	Recruits per license
1	0.0117	0.0001	0.0114	375 593
2	0.0065	-0.0004	0.0131	375 593
3	0.0111	-0.0006	0.0110	251 964
4	0.0107	-0.0006	0.0103	271 895
5	0.0102	-0.0006	0.0094	386 142
6	0.0076	-0.0006	0.0112	294 997
7	0.0087	-0.0006	0.0081	203 852
8	0.0049	-0.0004	0.0095	380 873
9	0.0028	-0.0003	0.0082	380 873
10	0.0003	-0.0003	0.0085	373 548
11	0.0006	-0.0003	0.0100	373 548
12	0.0032	-0.0005	0.0131	268 589
13	0.0031	-0.0004	0.0141	268 589

To illustrate the growth model coefficients, the growth of a representative fish in each production area is illustrated in the figure below.

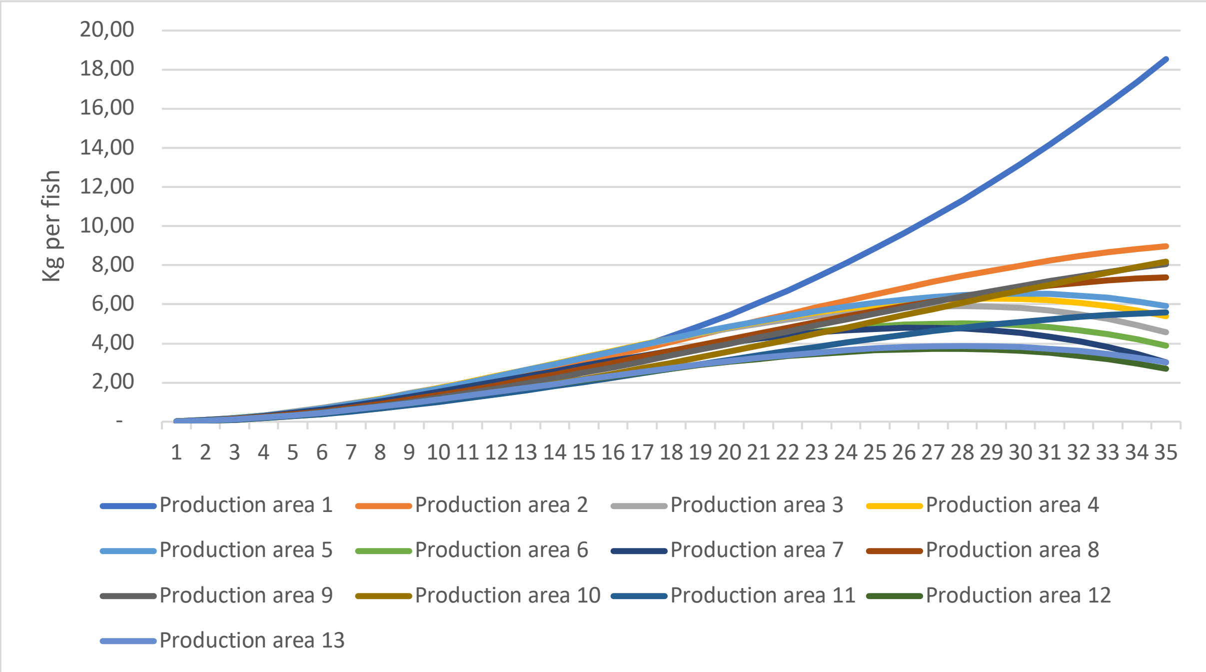

Figure 16 Growth function for each production area

From Figure 16 it becomes clear that the growth functions are highly heterogeneous across the production areas. It is worth noticing that production area 1 has a convex growth function for all values of time, and that it predicts unrealistically large fish as time increases. It does, however, yield valid results within reasonable intervals of the time variable.

8.1.5 Price Function

Furthermore, the price function derived from the data set is, as described in Chapter 6, expressed as:

$$p(w) = \beta_1 + \beta_2\, w + \beta_3\, w^2$$

Where $\beta_1 = 15.00$, $\beta_2 = 5.557$ and $\beta_3 = -0.489$

8.1.6 Interest Rate and Costs

The interest rate is set to 6 % to reflect expected return on investments in the Norwegian market (Kinserdal, 2017; PwC, 2016a).

We further assume a production cost per kilo of 22 NOK, which is the average production cost from 2008 until 2016 (Fiskeridirektoratet, 2017b). To simplify the analysis, the production cost is assumed to be constant over the whole production cycle. The cost term is incorporated into the model as illustrated in equation (13). Note that we do not take into account a potential change in cost due to changes in MAB in the analysis, such as an increase in cost of capital due to necessary investments in production equipment.

A summary of the initial setup parameters is shown in Table 10.

Table 10: Summary of Model Parameters

Growth function	Derived from the data set for each production area
Price function	Derived from the data set
Mortality	Average mortality rate per production area
Recruits	Average number of recruits per license per production area
Interest rate	6 % p.a.
MAB	780 ton in production area 1 to 9
	945 ton in production area 10 to 13
Capacity increase	2 %
Capacity decrease	6 %
Production costs	22 NOK/kg

8.2 No Capacity Constraints

As a benchmark result for later analysis, optimal rotation length, weight per fish at harvest and total profit over infinite rotations with the given parameters and without capacity constraints, are displayed in Table 11.

Table 11 Results Without Capacity Constraint

Area	Rotation length	Weight per fish	Profits
1	21.28	6.24	145 726 412
2	22.58	5.71	120 574 252
3	21.34	5.09	79 878 707
4	21.56	5.26	90 028 856
5	21.82	5.36	131 508 881
6	22.71	4.57	73 140 474
7	22.22	4.45	53 465 650
8	24.56	5.54	115 548 232
9	25.70	5.74	116 735 104
10	27.29	5.86	107 163 251
11	28.57	4.89	78 188 148
12	23.67	3.54	37 401 805
13	23.96	3.65	38 181 614

We can observe from the table that average rotation length is 23.64 months with an average expected profit of 91 349 337. Good growth conditions in production area 1 corresponds to the highest expected value of future biomass, while the northernmost areas can expect a considerably lower profit. This is both a result of different growth conditions, as well as different number of recruits.

8.3 Introducing Current MAB Constraints

In this section, we introduce the MAB constraints to the model. The estimation of rotation length, weight per fish at harvest and total profits over an infinite number of rotations are shown in Table 12. The numbers displayed in parenthesis are percentage change compared to the optimal production scenario displayed in Table 11.

Table 12 Results from Introduction of Current Capacity Constraints

Area	Rotation length		Weight per fish		Profits	
1	13.63	(-35.93 %)	2.42	(-61.18 %)	40 915 923	(-71.92 %)
2	13.24	(-41.39 %)	2.47	(-56.71 %)	43 847 541	(-63.63 %)
3	16.31	(-23.58 %)	3.70	(-27.26 %)	64 870 249	(-18.79 %)
4	15.15	(-29.74 %)	3.35	(-36.24 %)	62 513 973	(-30.56 %)
5	11.83	(-45.78 %)	2.26	(-57.90 %)	40 160 956	(-69.46 %)
6	16.45	(-27.56 %)	3.18	(-30.40 %)	53 595 184	(-26.72 %)
7	22.22	(0.00 %)	4.45	(0.00 %)	53 465 650	(0.00 %)
8	13.67	(-44.36 %)	2.33	(-57.93 %)	37 391 363	(-67.64 %)
9	14.28	(-44.44 %)	2.30	(-59.90 %)	34 716 766	(-70.26 %)
10	17.76	(-34.93 %)	2.94	(-49.79 %)	53 522 452	(-50.06 %)
11	19.62	(-31.32 %)	3.08	(-37.14 %)	51 540 719	(-34.08 %)
12	23.67	(0.00 %)	3.54	(0.00 %)	37 401 805	(0.00 %)
13	23.96	(0.00 %)	3.65	(0.00 %)	38 181 614	(0.00 %)

Comparing Table 11 and Table 12, it becomes evident that rotation length decreases substantially when capacity constraints are introduced for all production areas where the capacity constraint is binding, i.e. the farmers are forced to harvest the fish earlier than what is optimal due to the MAB constraints. In production area 7, 12 and 13, the capacity constraint is not binding, and rotation length thus remains unchanged. On average, the rotation length when introducing the MAB constraints is reduced by 27 %, which equals a 6.5 months reduction, with production area 5 experiencing the relatively largest reduction in rotation length of more than 45 %. Weight per fish at harvest is correspondingly reduced as a result of decreased time in the sea. On average, the fish are harvested 2.02 kg before optimal, which translates to a weight reduction of 36.5 % when introducing capacity constraints.

8.4 Introducing 2 % Increase in MAB Constraint

A 2 % increase in MAB is further introduced, which illustrates a scenario where all production areas are classified as green according to the Production Area Regulation. The results are displayed in Table 13, including changes in rotation length, weight per fish at harvest and profits compared to the previous scenario displayed in Table 12. We note that willingness-to-pay is abbreviated WTP in this table, and in all other tables in this chapter.

Table 13 Results from Increased Capacity Constraints of 2 %

Area	WTP	Rotation length		Weight per fish		Profits	
1	146.32	13.77	(1.02 %)	2.48	(2.16 %)	43 198 460	(5.58 %)
2	147.90	13.41	(1.30 %)	2.52	(2.23 %)	46 154 710	(5.26 %)
3	107.57	16.58	(1.70 %)	3.79	(2.31 %)	66 548 394	(2.59 %)
4	126.80	15.38	(1.53 %)	3.43	(2.24 %)	64 492 045	(3.16 %)
5	153.58	11.99	(1.30 %)	2.31	(2.15 %)	42 556 786	(5.97 %)
6	114.02	16.73	(1.73 %)	3.25	(2.33 %)	55 373 863	(3.32 %)
7	0.00	22.22	(0.00 %)	4.45	(0.00 %)	53 465 650	(0.00 %)
8	136.02	13.84	(1.30 %)	2.38	(2.17 %)	39 513 349	(5.68 %)
9	129.06	14.46	(1.25 %)	2.35	(2.15 %)	36 730 083	(5.80 %)
10	113.86	17.99	(1.28 %)	3.01	(2.20 %)	55 674 423	(4.02 %)
11	98.40	19.94	(1.60 %)	3.15	(2.32 %)	53 400 460	(3.61 %)
12	0.00	23.67	(0.00 %)	3.54	(0.00 %)	37 401 805	(0.00 %)
13	0.00	23.96	(0.00 %)	3.65	(0.00 %)	38 181 614	(0.00 %)

It becomes evident when comparing Table 12 and Table 13 that the increased MAB increases rotation length for all production areas where the capacity constraint is binding. For production area 7, 12 and 13, where the current MAB constraint is non-binding, the capacity increase of 2 % does not change the result of the model, as farmers in these areas are not able to utilize the existing capacity fully.

On average, the rotation length increases by 1.08 %, translating to 5 extra days in the sea and an average weight increase of 5 gram per fish. The total profits over an infinite number of rotations is on average increased by 3.46 % per license, all else equal. It is important to emphasize the heterogeneity of the results, where the change in profits resulting from the capacity increase ranges from 0 % to 5.80 % per license.

It is worth noticing that the average willingness-to-pay is 99.10 NOK/kg and that this is lower than the price for capacity increase, which is set to 120 NOK/kg. The commercial aspect of buying growth will be further discussed in Section 8.6.

8.5 Introducing Fallowing

The model is further modified to account for two months fallowing at the end of a rotation by using the profit function displayed in equation (22):

$$\pi(t) = \frac{V(t)}{e^{r(t+2)} - 1}$$

The results from this modification are showed in Table 14, with changes from Table 13 displayed in parenthesis.

Table 14 Results When Introducing 2 Months Fallowing

Area	WTP		Rotation length		Weight per fish		Profits	
1	130.08	(-11.10 %)	13.77	(0.00 %)	2.48	(0.00 %)	37 534 288	(-13.11 %)
2	132.17	(-10.63 %)	13.41	(0.00 %)	2.52	(0.00 %)	39 967 013	(-13.41 %)
3	102.28	(-4.92 %)	16.58	(0.00 %)	3.79	(0.00 %)	59 094 364	(-11.20 %)
4	117.86	(-7.05 %)	15.38	(0.00 %)	3.43	(0.00 %)	56 791 362	(-11.94 %)
5	135.05	(-12.06 %)	11.99	(0.00 %)	3.43	(48.66 %)	36 291 894	(-14.72 %)
6	106.95	(-6.20 %)	16.73	(0.00 %)	3.25	(0.00 %)	49 218 422	(-11.12 %)
7	0.00	(0.00 %)	22.51	(1.32 %)	4.50	(0.95 %)	48 834 069	(-8.66 %)
8	121.67	(-10.55 %)	13.84	(0.00 %)	2.38	(0.00 %)	34 355 809	(-13.05 %)
9	115.77	(-10.30 %)	14.46	(0.00 %)	2.35	(0.00 %)	32 108 591	(-12.58 %)
10	105.22	(-7.59 %)	17.99	(0.00 %)	3.01	(0.00 %)	49 856 617	(-10.45 %)
11	92.58	(-5.91 %)	19.94	(0.00 %)	3.15	(0.00 %)	48 292 685	(-9.57 %)
12	0.00	(0.00 %)	23.90	(0.96 %)	3.56	(0.60 %)	34 329 695	(-8.21 %)
13	0.00	(0.00 %)	24.20	(0.99 %)	3.67	(0.65 %)	35 078 864	(-8.13 %)

The fact that willingness-to-pay is reduced when introducing fallow periods becomes evident when comparing Table 13 and Table 14. On average, the willingness-to-pay is reduced by 6.64

% as a result of reduced present value of increased capacity, resulting in an average reduction in profit of 11.24 %. Rotation length and weight per fish at harvest remains unchanged in all areas where the capacity constraint is binding. For the production areas where capacity is non-binding, the willingness-to-pay remains 0, while rotation length and weight per fish at harvest increase. This is due to the reduced value of future rotations, and thus a reduced opportunity cost of keeping the fish in the sea for a longer period.

An increase in discount period reduces the present value of future profit, and the corresponding reduction in willingness-to-pay reflects that increased capacity is worth less when full capacity utilization is not possible due to fallowing. Using this line of argument, it is worth reflecting upon the fact that capacity utilization in the industry varies, and that larger firms enjoy larger flexibility than smaller ones, as a result of a large volume of licenses and locations. The large firms can therefore, in theory, to a larger degree plan and optimize production so that capacity is utilized to a maximum extent at all times, e.g. by operating locations with alternating fallow periods. On the other hand, complex production systems and logistics management, together with decreased ownership when a company becomes large may lead to reduced capacity utilization. The industry participants that manage to optimize production so that capacity is fully utilized at all times have the highest profit from buying growth, and thus the regulation awards the efficient firms through the use of homogenous prices.

To sum up the findings so far; the rotation length is drastically reduced when introducing capacity constraints, and on average Norwegian fish farmers harvest 27 % before optimal, which translates to over 6 months. The introduction of capacity constraints does not change rotation length in production area 7, 12 and 13, as the MAB constraint never becomes binding. The average willingness-to-pay for 2 % capacity increase is 99.10 NOK/kg assuming that all areas are classified as green, with variations from zero to 153.58. The rotation length is increased by 1.08 % in this scenario and profits are increased by 3.64 % per license. The introduction of fallowing reduces the willingness-to-pay, as restricted use of the production license reduces the present value of future biomass.

8.6 Evaluation of the Current Status

In the previous sections, all areas where assumed to have a green status to illustrate the different areas' willingness-to-pay for capacity increase. Now, we evaluate the net effect per license of the Production Area Regulation based on the current color of each area. The calculation is based on the model without fallowing.

Table 15 displays the average net effect per license of each area. As illustrated in Figure 7 in Chapter 3, area 1 and 7 to 13 have been classified as green, 3 and 4 as red and 2, 5 and 6 as yellow. The net effect for the green areas is calculated as the economic gain of increasing capacity by 2 % subtracted the price for capacity increase of 120 NOK/kg. The net effect for the red areas is the economic loss of an imposed capacity reduction of 6 %, while the net effect for yellow areas is equal to zero due to no changes in capacity.

Table 15 Total Effect of the Production Area Regulation

Area	WTP	Change in profits	Net effect
1	146.32	2 282 536	410 536
2	147.90	0	0
3	116.41	-5 448 147	-5 448 147
4	132.78	-6 214 179	-6 214 179
5	153.58	0	0
6	114.02	0	0
7	0.00	0	-1 872 000
8	136.02	2 121 986	249 986
9	129.06	2 013 317	141 317
10	113.86	2 151 970	-116 030
11	98.40	1 859 741	-408 259
12	0.00	0	-2 268 000
13	0.00	0	-2 268 000

From the table it becomes evident that the red production areas incur a loss in profits, while the green areas with binding capacity constraints increase the profits. Weighing the average over number of licenses per area, not taking into account the price of growth, The Production Area Regulation leads to change in profits of -829 883 per license over infinite rotations. The green areas gain an average of 1 334 044, while the red areas lose 5 865 679. The calculation assumes 2 % growth in green areas and 6 % reduction in red. If one assumes that the additional 4 % increase will be bought by existing license owners and that the additional increase does not lead to increased costs, the total change in profits resulting from the regulation is 410 486 on average. The green areas then gain 3 979 908 per license over infinite rotations.

Further, examining the net effect in Table 15, the results imply that within the green areas the investment in increased capacity is only profitable, on average, for fish farming companies with licenses located in production areas 1, 8 and 9. The remaining green areas have a negative net effect from buying growth, as the price of capacity increase is higher than their willingness-to-pay. In areas 7, 12 and 13 the capacity constraint is non-binding, resulting in a willingness-to-pay equal to zero. This implies that their capacity utilization should be increased on existing capacity before they apply for additional growth. Buying growth in these areas results in a negative net effect equal to the price paid for the capacity increase. Even so, we witness a high demand for capacity increase today, as applications for growth has been received on a total of 449 out of 461 licenses in the green areas.

Why farmers in green areas choose to buy increased capacity when our analysis suggests that it is not profitable may be explained by several factors. One explanation is that farmers have different assumptions when evaluating the profitability of capacity increase. Higher prices, lower cost levels and better growth conditions are some of the factors that could potentially increase the willingness-to-pay. Another explanation may be that farmers are risk averse, and that certain growth today is better than uncertain growth in the future. The Production Area Regulation opens for future changes in the environmental factors that constitute the criteria for growth over time, meaning that licenses that qualify for growth today may not qualify for growth tomorrow. A third explanation may be that the increased capacity will be operationalized in a different production area, as large companies are able to realize the growth through sophisticated production planning and the use of interregional biomass limits. This is not accounted for in our model. One last explanation may be that the price for capacity increase is below the perceived market value of capacity, meaning that buying capacity increase is considered to be a good investment with high future returns.

Production area 3 and 4 have been given a red status, and we can observe from the table that the corresponding economic loss of the imposed capacity reduction of 6 % is considerably large without any reversal in the long run. In addition to lost revenue due to reduced biomass, one should take into account the occurring costs of increased lice treatment and a potential depreciation in the valuation of the companies when assessing the total effects of the imposed capacity reduction. It is worth noticing that both production areas have a high potential gain of capacity increase if the areas were to be given a green status in the future, and that fish farmers in these areas have a relatively high willingness-to-pay to avoid capacity reduction by reducing the infestation pressure of lice, and thus become classified as yellow or green in the future.

Production area 2, 5 and 6 have been given a yellow status, which imply neither a potential capacity increase nor an imposed capacity decrease. From Table 13 we know that area 2 and 5 have a willingness-to-pay above the price for capacity increase, and the areas are thus incentivized to reduce the infestation pressure of lice.

The changes in capacity imposed by the Production Area Regulation combined with the price of growth results in a weighted average net effect per license of -1 789 175. Production area 1 has the largest potential gain from the regulative regime with an increase in profits over infinite rotations of 410 536, while production area 4 incur the greatest loss of -6 214 179. It is important to emphasize that the assumptions underlying the model influences the magnitude of the results to a large degree. Still, the fact that the economic effects imposed by the Production Area Regulation are highly heterogeneous becomes evident.

8.7 Heterogeneity in the Economic Effects

We observe from our results in the previous section that the economic effects of the Production Area Regulation are highly heterogeneous between production areas. We will in this section discuss the assumptions underlying the analysis and illustrate how changes in the respective parameters affect the results. The results from these scenarios are compared to the results displayed in Table 13, with percentage change in parenthesis.

8.7.1 Changes in Biomass

From equation (3) it is evident that total biomass is a function of two elements; the number of fish and the weight per fish. In our model, this means that the willingness-to-pay for each production area is a result of number of recruits per license per year, mortality rate and the growth function for each area. We will in this subsection analyze how changes in the number of recruits and mortality rate changes the willingness-to-pay for capacity increase. Changes in the number of recruits change the interception, while a change in mortality rate translates to a change in the slope of the curve resulting from equation (3).

Changes in Number of Recruits

Looking at Table 13, we see that in production areas where a large number of recruits are released, the willingness-to-pay is higher than in areas with a smaller number of recruits. To illustrate; production area 5 has the largest number of recruits and the highest willingness-to-pay for capacity increase. In this area, the capacity constraint becomes binding as early as after 12 months, and a representative farmer in this area thus harvests 10 months before optimal. Production area 7, on the other hand, has the lowest number of recruits, and the willingness-to-pay for capacity increase is equal to zero due to non-binding capacity constraint. Farmers in production area 7 thus harvest at their optimal harvesting time.

If one sets an equal number of recruits for all production areas, isolation of the magnitude of growth coefficients on willingness-to-pay becomes feasible. The number of recruits is in this scenario set to the industry average of 323 543. The results are displayed in Table 16. When comparing Table 13 and Table 16, it becomes evident that for production area 5, this results in a reduction in number of recruits by 16.21 %, a reduction of willingness-to-pay by 4.45 % and an increase in rotation length by 12.65 %. For production area 7, the number of recruits is increased by 58.71 %, resulting in an increase in willingness-to-pay to 130 NOK/kg and a decrease in rotation length by 34.03 %.

Table 16 Results with Number of Recruits set to 323 543

Area	% Δ R	WTP		Rotation length		Profits	
1	-13.86 %	145.76	(-0.38 %)	14.87	(7.98 %)	53 359 775	(23.52 %)
2	-13.86 %	140.53	(-4.98 %)	14.81	(10.47 %)	55 663 799	(20.60 %)
3	28.41 %	145.97	(35.69 %)	13.62	(-17.86 %)	56 635 179	(-14.90 %)
4	19.00 %	147.01	(15.94 %)	13.53	(-12.04 %)	56 090 766	(-13.03 %)
5	-16.21 %	146.74	(-4.45 %)	13.50	(12.65 %)	55 066 403	(29.40 %)
6	9.68 %	126.46	(10.91 %)	15.49	(-7.44 %)	51 553 967	(-6.90 %)
7	58.71 %	130.00	-	14.66	(-34.03 %)	49 874 856	(-6.72 %)
8	-15.05 %	129.96	(-4.46 %)	15.44	(11.51 %)	49 513 447	(25.31 %)
9	-15.05 %	124.73	(-3.35 %)	16.05	(11.01 %)	46 423 888	(26.39 %)
10	-13.39 %	102.23	(-10.21 %)	19.77	(9.89 %)	62 115 038	(11.57 %)
11	-13.39 %	77.83	(-20.90 %)	22.55	(13.08 %)	57 531 931	(7.74 %)
12	20.46 %	0.00	(0.00 %)	23.67	(0.00 %)	45 054 267	(20.46 %)
13	20.46 %	0.00	(0.00 %)	23.96	(0.00 %)	45 993 626	(20.46 %)

From the table, we observe that for the areas with binding capacity constraint, the profit increases when the number of recruits is reduced and decreases for areas where the number of recruits is increased. This might seem somewhat contradictory, but the increased rotation length thus outweighs the effect of the reduced number of fish as a result of increased weight and a corresponding realization of higher prices.

The change in willingness-to-pay is influenced by whether the farmer is further away from, or closer to optimal rotation length, after the number of recruits is changed. In the areas where the number of recruits is reduced and thus the rotation length is increased, the willingness-to-pay for growth decreases. An example of one such area is area 11, where the rotation length is increased by 13.08 % and the willingness-to-pay is reduced by 20.90 %. On the contrary, the willingness-to-pay is increased in the areas where the rotation length is reduced due to increased number of recruits. This illustrates the functional form of the production function as displayed in Figure 15, and from this the diminishing returns on capacity increase.

This scenario also illustrates that in areas with relatively high growth rates, e.g. area 1 and 2, the willingness-to-pay is higher compared to areas with relatively low growth rates, such as area 11 and 12. This seems intuitive, as farmers in areas with good growth rates will risk hitting their MAB earlier than farmers in other areas. This further implies that willingness-to-pay for capacity increase should be influenced by whether the farmer releases spring or fall smolts. One may argue that the willingness-to-pay for capacity increase should be higher for farms with spring generations compared to farms with fall generations due to better growth conditions.

Changes in mortality rate

An increase in mortality rate results in a reduced number of fish, and thus a reduction in total biomass, while the opposite is true for a decrease in mortality rate. A reduction in biomass further implies a reduction in present value of future rotations, everything else held equal. To illustrate, an increase in mortality rate by 10 % and keeping the rotation length fixed in production area 1, results in a decrease in profit. This scenario is displayed in Table 17.

Table 17 Increase of 10 % in Mortality with Fixed Rotation Length

Area	WTP	Rotation length	Weight per fish	Profits
1	146.32	13.77 (0.00 %)	2.48 (0. 00 %)	42 528 065 (-1.55 %)

If rotation length is not held fixed on the other hand, we find that increased mortality rate results in better production optimization for all areas where the capacity constraint is binding due to increased rotation length for the fish that survive. The increased mortality is thus outweighed by better prices for the larger fish that live until harvest. These results are displayed in Table 18.

Table 18 Increase of 10 % in Mortality

Area	WTP		Rotation length		Weight per fish		Profits	
1	147.26	(0.65 %)	13.88	(0.81 %)	2.52	(1.73 %)	44 346 417	(2.66 %)
2	148.45	(0.37 %)	13.57	(1.17 %)	2.58	(2.01 %)	47 406 277	(2.71 %)
3	103.39	(-3.88 %)	16.85	(1.62 %)	3.87	(2.17 %)	66 828 671	(0.42 %)
4	124.70	(-1.65 %)	15.58	(1.25 %)	3.49	(1.82 %)	65 032 981	(0.84 %)
5	154.17	(0.38 %)	12.08	(0.75 %)	2.33	(1.24 %)	43 452 460	(2.10 %)
6	111.47	(-2.23 %)	17.02	(1.70 %)	3.33	(2.26 %)	55 992 773	(1.12 %)
7	0.00	(0. 00 %)	22.15	(-0.29 %)	4.44	(-0.22 %)	52 515 466	(-1.78 %)
8	136.54	(0.38 %)	13.96	(0.87 %)	2.42	(1.46 %)	40 414 240	(2.28 %)
9	129.58	(0.40 %)	14.57	(0.76 %)	2.38	(1.31 %)	37 513 827	(2.13 %)
10	113.50	(-0.32 %)	18.17	(1.00 %)	3.06	(1.72 %)	56 486 142	(1.46 %)
11	96.87	(-1.55 %)	20.27	(1.65 %)	3.22	(2.38 %)	54 186 796	(1.47 %)
12	0.00	(0. 00 %)	23.58	(-0.38 %)	3.53	(-0.25 %)	36 263 659	(-3.04 %)
13	0.00	(0.00 %)	23.86	(-0.44 %)	3.64	(-0.30 %)	36 913 914	(-3.32 %)

In production areas where the introduction of capacity constraints leads to a relatively large reduction in rotation length, i.e. areas which are far away from their optimal production and on the convex part of the profit curve, the increased mortality leads to increased willingness-to-pay. On the opposite side, areas which are closer to their optimal production and on the concave part of the profit curve reduces their willingness-to-pay when introducing increased mortality. The increased rotation length compensates for the increased losses in both cases, which results in higher profits. This observation also indicates that the assumed number of recruits in this scenario is higher than that optimal number of recruits for all areas with binding capacity constraint. We can also observe that areas with non-binding capacity constraint will reduce their rotation length, while experiencing a profit loss.

In sum, the economic effects of the Production Area Regulation will be larger in magnitude in areas which are furthest from optimal production, as they have the most to gain from a capacity increase. The high number of recruits in most production areas results in short rotation lengths. Production areas which find themselves far away from optimal production can increase profits by decreasing the number of recruits or increasing mortality. Rationally speaking, the only option here is releasing less fish, as it makes little sense to release the same amount of fish and kill off larger amounts during the rotation. The total smolt costs will be reduced when reducing the number of recruits, which is also an advantage. Areas which are closer to optimal production are willing to pay relatively less for capacity increase when mortality rate increases. In areas 7, 12 and 13 the number of recruits is among the lowest in the industry. Combined with poorer growth conditions in the northernmost parts of Norway, these areas never reach their MAB limits and the areas realize lower profits when mortality increases.

8.7.2 Changes in the Price Function

The present value of future biomass is increasing in the parameters of the price function, which in turn leads to higher willingness-to-pay for capacity. Table 19 displays a numeric example with a 10 % increase in the parameters of the price function, which represents an upward shift in the function.

Table 19 Increase in Coefficients of the Price Function by 10 %

Area	WTP		Rotation length		Weight per fish		Profits	
1	294.29	(101.13 %)	13.77	(0.00 %)	2.48	(0.00 %)	72 766 740	(68.45 %)
2	275.27	(86.12 %)	13.41	(0.00 %)	2.52	(0.00 %)	76 720 190	(66.22 %)
3	176.14	(63.74 %)	16.58	(0.00 %)	3.79	(0.00 %)	94 021 613	(41.28 %)
4	219.28	(72.93 %)	15.38	(0.00 %)	3.43	(0.00 %)	93 452 175	(44.90 %)
5	290.49	(89.15 %)	11.99	(0.00 %)	2.31	(0.00 %)	75 948 077	(78.46 %)
6	184.22	(61.57 %)	16.73	(0.00 %)	3.25	(0.00 %)	81 537 314	(47.25 %)
7	0.00	(0.00 %)	21.07	(-5.16 %)	4.27	(-4.21 %)	73 489 711	(37.45 %)
8	255.91	(88.14 %)	13.84	(0.00 %)	2.38	(0.00 %)	68 573 884	(73.55 %)
9	246.66	(91.12 %)	14.46	(0.00 %)	2.35	(0.00 %)	64 405 836	(75.35 %)
10	210.50	(84.87 %)	17.99	(0.00 %)	3.01	(0.00 %)	84 415 455	(51.62 %)
11	165.03	(67.72 %)	19.94	(0.00 %)	3.15	(0.00 %)	79 547 456	(48.96 %)
12	0.00	(0.00 %)	21.94	(-7.33 %)	3.34	(-5.57 %)	53 827 895	(43.92 %)
13	0.00	(0.00 %)	22.20	(-7.37 %)	3.44	(-5.81 %)	54 533 728	(42.83 %)

We observe that the increase in price results in an average increase in willingness-to-pay of 80.65 % for all production areas where the capacity is binding, while the rotation length and weight per fish at harvest remain unchanged. The increase in price makes it more lucrative for areas with available capacity to reduce their rotation length as they are able to realize a relatively higher price for smaller fish and thus increase the number of rotations in the long run. The decision of buying additional capacity depends heavily on the fish farmers' expectations of future price levels, and our model confirms that the economic effects of the Production Area Regulation varies according to the price development in the market.

8.7.3 Changes in Cost

Fish farmers' expectations about future cost development will also affect the profitability of buying additional capacity, as a higher cost level decreases the present value of future biomass and the corresponding willingness-to-pay for capacity increase. We find that an increase in cost by 10 % results in an average reduction in willingness-to-pay of 7 % for locations with binding capacity, while the corresponding rotation length and weight per fish at harvest remain unchanged. Areas with available capacity find it more optimal to increase rotation length to realize a higher price, and thus reduce the decrease in profits when the costs increase.

Table 20 Increase in Cost by 10 %

Area	WTP		Rotation length		Weight per fish		Profits	
1	131.35	(-10.23 %)	13.77	(0.00 %)	2.48	(0.00 %)	17 949 595	(-58.45 %)
2	137.21	(-7.22 %)	13.41	(0.00 %)	2.52	(0.00 %)	20 204 701	(-56.22 %)
3	104.61	(-2.75 %)	16.58	(0.00 %)	3.79	(0.00 %)	45 729 982	(-31.28 %)
4	120.99	(-4.59 %)	15.38	(0.00 %)	3.43	(0.00 %)	41 981 119	(-34.90 %)
5	141.55	(-7.83 %)	11.99	(0.00 %)	2.31	(0.00 %)	13 421 174	(-68.46 %)
6	111.38	(-2.32 %)	16.73	(0.00 %)	3.25	(0.00 %)	34 747 737	(-37.25 %)
7	0.00	(0.00 %)	22.78	(2.52 %)	4.53	(1.77 %)	38 942 352	(-27.16 %)
8	125.65	(-7.63 %)	13.84	(0.00 %)	2.38	(0.00 %)	14 404 149	(-63.55 %)
9	118.44	(-8.23 %)	14.46	(0.00 %)	2.35	(0.00 %)	12 727 499	(-65.35 %)
10	105.93	(-6.97 %)	17.99	(0.00 %)	3.01	(0.00 %)	32 500 687	(-41.62 %)
11	94.92	(-3.54 %)	19.94	(0.00 %)	3.15	(0.00 %)	32 593 468	(-38.96 %)
12	0.00	(0.00 %)	24.49	(3.45 %)	3.61	(2.00 %)	24 986 983	(-33.19 %)
13	0.00	(0.00 %)	24.79	(3.47 %)	3.73	(2.14 %)	25 915 741	(-32.13 %)

From this, it becomes evident that differences in cost level between fish farmers lead to heterogeneity in the effects of the Production Area Regulation. Cost efficient fish farmers will experience a relatively higher gain or loss related to the corresponding increase or decrease in capacity compared to less efficient fish farmers.

8.7.4 Changes in Interest Rate

To illustrate the model's sensitivity for changes in interest rate, a scenario where the interest rate is increased by 4 % is displayed in Table 21.

Table 21 Increase of 4 % in Interest Rate

Area	WTP	Rotation length	Weight per fish	Profits
1	87.05 (-40.51 %)	13.63 (0.00 %)	2,48 (0.00 %)	25 802 830 (-40.27 %)
2	87.93 (-40.55 %)	13.24 (0.00 %)	2,52 (0.00 %)	27 584 608 (-40.23 %)
3	62.86 (-41.57 %)	16.31 (0.00 %)	3,79 (0.00 %)	39 571 062 (-40.54 %)
4	74.65 (-41.12 %)	15.15 (0.00 %)	3,43 (0.00 %)	38 422 399 (-40.42 %)
5	91.62 (-40.35 %)	11.83 (0.00 %)	2,31 (0.00 %)	25 492 153 (-40.10 %)
6	66.85 (-41.37 %)	16.45 (0.00 %)	3,25 (0.00 %)	32 918 588 (-40.55 %)
7	0.00 (0.00 %)	22.09 (-0.58 %)	4,43 (-0.44 %)	31 503 411 (-41.08 %)
8	80.83 (-40.57 %)	13.67 (0.00 %)	2,38 (0.00 %)	23 598 976 (-40.28 %)
9	76.62 (-40.63 %)	14.28 (0.00 %)	2,35 (0.00 %)	21 915 073 (-40.33 %)
10	66.93 (-41.21 %)	17.76 (0.00 %)	3,01 (0.00 %)	33 030 404 (-40.67 %)
11	57.38 (-41.69 %)	19.62 (0.00 %)	3,15 (0.00 %)	31 581 626 (-40.86 %)
12	0.00 (0.00 %)	23.56 (-0.48 %)	3,53 (-0.31 %)	21 986 061 (-41.22 %)
13	0.00 (0.00 %)	23.84 (-0.51 %)	3,63 (-0.35 %)	22 433 801 (-41.24 %)

It becomes evident that the increased interest rate decreases the present value of future rotations substantially due to higher discounting of future profits. On average, the future profits are reduced by 40.60 %. Willingness-to-pay is correspondingly reduced for all production areas where capacity is binding, while the rotation length and weight per fish at harvest remain unchanged. In the areas where capacity is non-binding the rotation length decreases as a result of the increased interest rate. This is due to the fact that the marginal return on keeping fish in the sea reaches the level of the interest rate earlier than before, and thus the farmer should harvest earlier.

We have in this section discussed and evaluated how changes in the underlying parameters of our empirical framework affect the willingness-to-pay for capacity increase, rotation length, weight per fish at harvest and present value of future profits. We were able to isolate the significance of the growth coefficients by setting the same number of recruits for all production areas. This exercise proved that areas with more favorable growth conditions have a higher willingness-to-pay for capacity increase compared to areas with worse growth conditions. We also found that an increase in mortality rate resulted in a better production optimization for areas where the capacity constraint was binding, indicating a suboptimal number of recruits. The corresponding change in willingness-to-pay was in both cases dependent on the areas' deviation from optimal harvesting time.

Furthermore, we found that the economic effects of the Production Area Regulation depend heavily on the price and cost development in the market, with an increase in willingness-to-pay and present value of future profits as the price increases, and a decrease in the same parameters if the cost increases. Variation in price and cost levels between fish farmers leads to higher heterogeneity in the economic effects of the Production Area Regulation. Lastly, we found that the economic effects of Production Area Regulation depend heavily on the assumed interest rate, as a 4 % increase in interest rate reduced the present value of future profits with an average rate of 40.60 %.

8.8 Current Price and Cost Levels

The market situation today deviates considerably compared to the market perspective we presented in the previous sections in terms of prices and production costs. We will in this section present and comment on the results reflecting today's price and cost level.

Our original price function is derived using price data from 2005 until 2016, thus reflecting an average price over the last decade. In recent years, the salmon prices have been considerably higher, which directly increase the present value of future biomass. Price parameters reflecting the price level from January 2017 to February 2018 are shown in the table below (Fishpool).

Table 22 Updated Price per Kilogram

	(1)
	Price Per Kilogram
Weight	7.120***
	(0.479)
Weight^2	-0.571***
	(0.0599)
Constant	51.10***
	(1.565)
Year FE	Yes
Month FE	Yes
N	364
Adj. R-sq.	0.87

Standard errors in parentheses. Month and year dummies not reported. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Compared to the original price model, we observe that all the parameters are considerably higher in absolute value, resulting in relatively higher prices. All coefficients are highly significant, and the adjusted R-squared is good.

The Norwegian Directorate of Fisheries has calculated an average production cost per kilo of 30.60 NOK in 2016 (Fiskeridirektoratet, 2017a). The willingness-to-pay using today's price level and production cost is presented in the table below. Optimal rotation length, weight per fish at harvest and present value of future profits are calculated after a 2 % capacity increase with percentage changes from current to new capacity levels in parenthesis.

Table 23 Current Price and Cost Levels

Area	WTP	Rotation length		Weight per fish		Profits	
1	400.61	13.77	(1.02 %)	2.48	(2.16 %)	397 463 334	(1.57 %)
2	345.81	13.41	(1.30 %)	2.52	(2.23 %)	410 911 033	(1.31 %)
3	200.05	16.58	(1.70 %)	3.79	(2.31 %)	371 667 130	(0.84 %)
4	260.59	15.38	(1.53 %)	3.43	(2.24 %)	390 841 721	(1.04 %)
5	369.84	11.99	(1.30 %)	2.31	(2.15 %)	448 706 806	(1.29 %)
6	198.00	16.73	(1.73 %)	3.25	(2.33 %)	352 749 732	(0.88 %)
7	0.00	20.22	(0.00 %)	4.11	(0.00 %)	275 638 992	(0.00 %)
8	324.39	13.84	(1.30 %)	2.38	(2.17 %)	390 559 756	(1.30 %)
9	317.91	14.46	(1.25 %)	2.35	(2.15 %)	371 928 760	(1.33 %)
10	265.88	17.99	(1.28 %)	3.01	(2.20 %)	387 029 603	(1.30 %)
11	185.95	19.94	(1.60 %)	3.15	(2.32 %)	352 332 112	(1.00 %)
12	0.00	20.40	(0.00 %)	3.12	(0.00 %)	228 746 390	(0.00 %)
13	0.00	20.63	(0.00 %)	3.20	(0.00 %)	227 807 031	(0.00 %)

Similar to the scenario displayed in Table 13, we can observe that the increase in capacity results in an increase in rotation length with a corresponding increase in profit for all areas with binding capacity constraint. The average willingness-to-pay is 243 % higher compared to the results in Table 13, while the present value of future profit is, on average, 750 % higher. The standard deviation of willingness-to-pay is over twice as large compared to the willingness-to-pay in Table 13, and we can conclude that the magnitude of the economic effects, as well as the variation in the effects between the production areas, are considerably stronger under the price and cost assumptions made in this scenario.

8.9 Discussion

We will in this section provide a discussion of the profitability of buying growth, in addition to a discussion of the consequence of future regulative status of the production areas. Finally, we reflect upon the price of capacity increase from a socio-economic perspective.

8.9.1 Profitability of Buying Growth

The willingness-to-pay for capacity increase differs substantially when comparing the scenario introduced in Section 8.4 and the scenario introduced in 8.8. When the most recent price and cost levels constitute the foundation of the analysis, it becomes profitable for 10 out of 13 production areas to buy growth, as opposed to only 6 of 13 in the long-term perspective presented in Section 8.4. The fish farmers should consider the fact that the potential economic gain of investing in increased capacity will be realized over a long period of time. This aspect must be considered against the assumptions of price level and the future market development. Economic theory implies that profitable markets are a driver for market entries, leading to an increase in supply and a potential decrease in prices, which will reduce the producer surplus of each individual supplier.

It is also reason to consider that the technological development in the aquaculture industry will increase the cost efficiency of novel production methods, like offshore and land-based fish farming, which can also pose a threat to incumbents. These production methods may also disrupt the natural competitive advantage of Norwegian fish farmers in the long run, namely the long coastline with favorable conditions. We find it highly relevant to consider the future technical and economic development in the market when deciding upon investing in capacity increase.

Even though a positive change in profits implies that a potential investment in capacity increase is profitable, the fish farmers should consider a reasonable risk premium reflecting the uncertainty of future market development and their risk preference. When assessing the uncertainty of future market development, we also find it highly important to consider the risk of losing capacity if a production area becomes red.

8.9.2 Future Regulative Status

It is important to emphasize that the estimation of the present value of future profits only consider a one-time change in capacity, and that this capacity level remains fixed in all future time periods. In reality, the capacity may be adjusted in subsequent regulative periods, which will affect the present value of future profits accordingly. For example, green areas that experience an increase in capacity today, may expect additional capacity increases in the future and a higher expected value of future profits. In addition, the estimated economic loss may be lower for red areas that are imposed a capacity reduction today, as the reduction may be reversed if the infestation pressure decreases and the areas later become green. However, we find our empirical framework to be highly relevant to quantify the isolated economic gain or loss of a change in regulative status, given all available information. We find this simplification to be valid, as the expectation of future profits is highly uncertain and dependent on a large number of different factors.

We emphasize that the magnitude of the results should be interpreted with consideration to the underlying assumptions, as these assumptions influence the results to a large degree. Still, the results illustrate the heterogeneity of the production areas well and the fact that there are substantial differences when evaluating the effects of the Production Area Regulation. Individual growth conditions, number of recruits and mortality rate are the main differentiating factors between the areas.

Even though the magnitude of the effects is uncertain and dependent on the underlying assumptions, we find that our analysis is highly beneficial in estimating the expected net effect of commercial fish farmers' decision of buying capacity increase. The net effect constitutes the estimated change in present value of future profits, taking into account the price of capacity increase. One may then use our empirical framework to evaluate if the purchase of capacity is a profitable decision for the fish farmers, considering all available information at that point in time.

8.9.3 The Price of Growth

The price for capacity increase should regulate both the demand of capacity increase to a sustainable level, as well as the proper distribution of the return of our natural resources between the fish farmers and the Norwegian Government. We wish not to comment on the latter, as it constitutes a central topic within the political discussion of taxation. It is worth noticing, however, that the economic surplus of the society as a whole will increase if the salmon production is increased in all areas with a positive willingness-to-pay, regardless of the distribution of profit between the government and the fish farmers. However, this is only true if the benefits resulting from increased production exceeds the costs. Increased production may increase the socio-economic costs through increased lice levels or pollution for example, and these costs have to be taken into account when calculating the overall socio-economic effect of the regulation. The estimation of the socio-economic costs and benefits of the Production Area Regulation is an interesting topic for further research.

Our analysis suggests that the price level of capacity increase of 120 NOK/kg is set very high from a long-term perspective. Considering diminishing returns on capacity increase, one may argue that the price of capacity increase should be reduced for each round of allotment. It is also worth noticing that the steadily increasing cost level makes the industry more vulnerable for fluctuations in prices through lower margins. If the Production Area Regulation increases the cost level, both directly or indirectly, it might be a contributor to a more vulnerable Norwegian industry.

8.10 Limitations of the Model

It is important to emphasize that the model reflects an average license for each area. The industry participants are highly heterogeneous in size, efficiency, geographic location and cost levels to mention some differentiating factors. As our results are presented as area averages, we emphasize that individual considerations of the different assumptions should be made in order to apply the results to individual licenses. Uncertainty in the variables from the data set, e.g. number of fish, also introduces uncertainty in the results.

As described in Chapter 7, the growth and price model yield an underprediction of weight per fish and price, which in turn leads to an underprediction of change in the present value of future profit and willingness-to-pay. The underprediction of the economic effects leads to a larger potential gain of increased capacity, as well as a larger loss of an imposed capacity decrease. More accurate growth and price models should be used to further improve the economic analysis.

The industry is changing rapidly, and the time frame of the data set is only until the end of 2016. This means that the most recent data is not included, and the model should be updated to include these numbers when they become available to depict the most recent situation in the industry.

The model does not manage to capture all aspects of salmon farming, and there might be operational characteristics of the production that we have not been able to take into account. Large companies enjoy flexibility in production planning due to large volumes of locations and licenses. The largest players enjoy further flexibility through inter-regional biomass levels, which in reality means that they have the opportunity to realize the growth in a different area than the growth was granted for. Such conditions are not implemented in the model and might influence our conclusions.

The model fails to capture value creation from the industry as a whole, and we have to no degree aimed at estimating the socio-economic effects of the regulation. The results are therefore only fit to discuss the commercial effect of the regulation on license level. If aiming at determining the total effects of the Production Area Regulation, a broader approach should be undertaken, such as including the change in profits of suppliers and increased value creation through increased employment.

9. Conclusion

We have in this thesis aimed at estimating the economic effects of the Production Area Regulation on commercial fish farming companies. We introduced an extension to the bioeconomic theory by including capacity constraints, which has enabled us to calculate how optimal rotation length is affected by the Production Area Regulation. By using an empirical growth and price model combined with the theoretical framework, we were able to calculate the change in profits resulting from changes in capacity, and the corresponding willingness-to-pay for capacity increase for each production area.

The analysis highlights the fact that farmers are forced to harvest earlier than what is economically optimal when facing capacity constraints. On average, farmers harvest over 6.5 months before their optimal harvesting time, which translates to a 27 % reduction in rotation length. When introducing increased capacity of 2 %, the rotation length increases in all areas where the capacity constraint is binding, and the average willingness-to-pay for capacity increase is 99.10 NOK/kg.

Evaluating the current status of the production areas, our analysis suggests that the average change in profits per license independent of area is 410 485, assuming that the 6 % growth is operationalized on existing licenses and that all licenses in red areas are imposed a 6 % reduction. Given the price of 120 NOK/kg for capacity increase, we find that it is only profitable for farmers in area 1, 8 and 9 to buy growth.

Furthermore, we find that the economic effects of the regulation are diverse and driven by expectations regarding price level, costs, mortality rate, interest rate and growth conditions. Each farmer should therefor assess their own parameter values to determine their willingness-to-pay for capacity increase and the corresponding profitability of investment in growth.

References

Aarset, B., Jakobsen, S.-E., Iversen, A., & Ottesen, G. G. (2004). Lovverk, teknologi og etableringsbetingelser i norsk havbruk : fase I.

Akvakulturdriftsforskriften. (2008). *Forskrift om drift av akvakulturanlegg (akvakulturdriftsforskriften), FOR-2008-06-17-822*. Retrieved from https://lovdata.no/dokument/SF/forskrift/2008-06-17-822.

Akvakulturloven. (2005). *Lov om akvakultur (akvakulturloven), LOV-2005-06-17-79*. Retrieved from https://lovdata.no/dokument/NL/lov/2005-06-17-79.

Andreassen, O., & Robertsen, R. (2014). *Nasjonale ringvirkninger av havbruksnæringen*.

Arnason, R. (1992). Optimal Feeding Schedules and Harvesting Time in Aquaculture. *Marine Resource Economics, 7*(1), 15-35. doi:10.1086/mre.7.1.42629021

Asche, F. (2002). *Patterns in the relative price for different sizes of farmed fish* (Vol. nr 92). Bergen: Norges handelshøyskole, Senter for fiskeriøkonomi.

Asche, F., & Bjørndal, T. (2011). *The economics of salmon aquaculture* (2nd ed. ed.). Chichester: Wiley-Blackwell.

Barentswatch.no. (2017). Fiskehelse i norsk akvakultur. Retrieved from https://www.barentswatch.no/fiskehelse/locality/28976/2018/6

Bjørndal, T. (1988). *Optimal harvesting of farmed fish* (Vol. 7/1988). Bergen.

Boeuf, G., & Le Bail, P.-Y. (1999). Does light have an influence on fish growth? *Aquaculture, 177*(1), 129-152. doi:10.1016/S0044-8486(99)00074-5

Calabrese, S. (2017). Environmental and biological requirements of post-smolt Atlantic salmon (Salmo salar L.) in closed-containment aquaculture systems. In: The University of Bergen.

Fishpool. Nasdaq Salmon Index. Retrieved from http://fishpool.eu/price-information/reports/nasdaq-salmon-index-archive/

Fiskeridepartementet. (1979-1980). *Om offentlig medvirkning til utvikling i fiskeoppdrettsnæringen*. (71).

Fiskeridirektoratet. Laks, regnbueørret og ørret. Retrieved from https://www.fiskeridir.no/Akvakultur/Statistikk-akvakultur/Akvakulturstatistikk-tidsserier/Laks-regnbueoerret-og-oerret

Fiskeridirektoratet. (2009). Lønnsomhetsundersøkelse for matfiskproduksjon, 1986-2008.

Fiskeridirektoratet. (2017a). *Lønnsomhetsundersøkelse for produksjon av laks og regnbueørret, 2016*.

Fiskeridirektoratet. (2017b). Lønnsomhetsundersøkelse for matfiskproduksjon, 2008-2016.

Fiskeridirektoratet. (2018a). 47 oppdrettsselskap har søkt om vekst Retrieved from https://www.fiskeridir.no/Akvakultur/Nyheter/2018/0218/47-oppdrettsselskap-har-soekt-om-vekst

Fiskeridirektoratet. (2018b). Antall lokaliteter i sjø.

Fiskeridirektoratet. (2018c). Biomassedata.

Fiskeridirektoratet. (2018d). Lønnsomhetsdata.

Fiskeridirektoratet. (2018e). Matfiskproduksjon.

Fiskeridirektoratet. (2018f). Produksjonsområder. Retrieved from https://www.fiskeridir.no/Akvakultur/Tildeling-og-tillatelser/Kapasitetsoekning-2017-2018/Produksjonsomraader

Flåten, O., & Skonhoft, A. (2014). *Naturressursenes økonomi*. Oslo: Gyldendal akademisk.

Forskrift om kapasitetsøkning for tillatelser til akvakultur 2017–2018. (2017). *Forskrift om kapasitetsøkning for tillatelser til akvakultur med matfisk i sjø av laks, ørret og regnbueørret i 2017–2018, FOR-2017-12-20-2397*. Retrieved from https://lovdata.no/dokument/SF/forskrift/2017-12-20-2397.

Forskrift om lakselusbekjempelse. (2012). *Forskrift om bekjempelse av lakselus i akvakulturanlegg, FOR-2012-12-05-1140*. Retrieved from https://lovdata.no/dokument/SF/forskrift/2012-12-05-1140.

Guttormsen, A. G. (2001). *Faustmann in the sea : optimal rotation in aquaculture*. In Diskusjonsnotater fra IØS, Vol. D-11/2001.

Havforskningsinstituttet. (2017). *Risikorapport norsk fiskeoppdrett 2017*. Retrieved from https://www.hi.no/filarkiv/2017/05/risikorapport_2017.pdf/nb-no

Heaps, T. (1993). The Optimal Feeding of Farmed Fish. *Marine Resource Economics, 8*(2), 89-99.

Heaps, T. (1995). Density Dependent Growth and the Culling of Farmed Fish. *Marine Resource Economics, 10*(3), 285-298. doi:10.1086/mre.10.3.42629592

Heen, K., Monahan, R. L., & Utter, F. (1993). *Salmon aquaculture*. Oxford: Fishing News Books.

Hill, R. C., Griffiths, W. E., & Lim, G. C. (2012). *Principles of Econometrics* (4 ed.): John Wiley & Sons, Inc.

Hjeltnes, B., Bang-Jensen, B., Bornø, G., Haukaas, A., & Walde, C. S. (2017). *Fiskehelserapporten 2017*. Veterinærinstituttet.

Holm, J. C., & Søreide, P. I. (1993). *Tilrådd tetthet for laks*. Havforskningsinstituttet.

Høy, E., Sunde, L. M., & Vanhauwaert Bjelland, H. (2013). *Hvor mye laks er det egentlig i merden?* Retrieved from https://www.sintef.no/globalassets/upload/fiskeri_og_havbruk/havbruksteknologi/exactus/dokument/exactus-nfo-artikkel_paaskrift.pdf.

Jørgensen, S. M., Castro, V., Krasnov, A., Torgersen, J., Timmerhaus, G., Hevrøy, E. M., . . . Takle, H. (2014). Cardiac responses to elevated seawater temperature in Atlantic salmon. *14*(1). doi:10.1186/1472-6793-14-2

Kinserdal, F. (2017). Hva blir avkastningskrav og vekstforventninger når renten er lav? *Magma*(3), 16-19.

Ling, S.-W., & Mumaw, L. (1977). Aquaculture in Southeast Asia. A historical overview. *A Washington Sea Grant Publication (USA).*

Lysø, N. (1977). *Fiskeoppdrett : utredning fra et utvalg oppnevnt ved kongelig resolusjon 25. februar 1972 ; utredningen avgitt til Fiskeridepartementet i april 1977* (Vol. NOU 1977:39). Oslo: Universitetsforlaget.

Marine Harvest. (2017). *Salmon Farming Industry Handbook*. Retrieved from http://marineharvest.com/globalassets/investors/handbook/salmon-industry-handbook-2017.pdf.

Miljødirektoratet. (2015). Lakselus. Retrieved from http://www.miljodirektoratet.no/no/Tema/Arter-og-naturtyper/Villaksportalen/Pavirkninger/Lakselus/

Nasdaq. Retrieved from https://salmonprice.nasdaqomxtrader.com/public/home

Newey, W. K., & West, K. D. (1987). A Simple, Positive Semi-Definite, Heteroskedasticity and Autocorrelation Consistent Covariance Matrix. *Econometrica, 55*(3), 6.

Nystøyl, R., Kosmo, J. P., Liabø, L., Kongsvik Brandvik, R., Olafsen, T., Gisvold Sandberg, M., & Winther, U. (2013). *Produksjonsreguleringer i havbruk*. Retrieved from https://www.regjeringen.no/globalassets/upload/fkd/vedlegg/rapporter/2013/rapport_rullerende_mtb_v2.pdf

Nærings- og fiskeridepartementet. (2015). *Forutsigbar og miljømessig bærekraftig vekst i norsk lakse- og oppdrettsnæring*. (16).

Olafsen, T., Winther, U., Olsen, Y., & Skjermo, J. (2012). *Verdiskaping basert på produktive hav i 2050*.

Produksjonsområdeforskriften. (2017). *Forskrift om produksjonsområder for akvakultur av matfisk i sjø av laks, ørret og regnbueørret (produksjonsområdeforskriften)*, *FOR-2017-01-16-61.* Retrieved from https://lovdata.no/dokument/SF/forskrift/2017-01-16-61.

PwC. (2016a). *Risikopremien i det norske markedet*. Retrieved from https://www.pwc.no/no/publikasjoner/verdivurdering/risikopremien-2016.pdf.

PwC. (2016b). *Sustainable growth towards 2050*. (1). Retrieved from https://www.pwc.no/no/publikasjoner/pwc-seafood-barometer-2017.pdf.

Regjeringen. (2014). Regjeringen vil sikre vekst og konkurransekraft i havbruk [Press release]. Retrieved from https://www.regjeringen.no/no/aktuelt/Regjeringen-vil-sikre-vekst-og-konkurransekraft-i-havbruk/id754291/

Regjeringen. (2017). "Prøvekjøring" av det nye systemet for kapasitetsjusteringer i norsk lakse- og ørretoppdrett. Retrieved from https://www.regjeringen.no/no/aktuelt/provekjoring-av-det-nye-systemet-for-kapasitetsjusteringer-i-norsk-lakse--og-orretoppdrett/id2556793/

Schwach, V., Hovland, E., Møller, D., Haaland, A., Kolle, N., Hersoug, B., & Nævdal, G. (2015). Norges fiskeri- og kysthistorie. Bind 5: Over den leiken ville han rå : norsk havbruksnærings historie. *Historisk tidsskrift, 94*(2), 312-317.

Sjømat Norge, Norsk Industri, & NSL. (2017). *Høringsuttalelse om implementering av Meld. St. 16 (2015-2014)*.

Skretting. (2012). *For*. Retrieved from http://www.skrettingguidelines.com/readimage.aspx?pubid=cd8a45bd-0e6e-409c-a2ee-1da2b7d19b06.

Statistisk sentralbyrå. (2018a). 03214: Akvakultur. Oppdrett av laks, regnbueørret og andre marine arter. Personer i arbeid og timeverk, etter produksjonstype (F) 1986 - 2016. Retrieved from https://www.ssb.no/statbank/table/03214/tableViewLayout1/?rxid=d92fd3c2-e06a-4913-82f0-d029b811e045

Statistisk sentralbyrå. (2018b). 05278: Fangst, etter fiskeslag 1977 - 2016. Retrieved from https://www.ssb.no/statbank/table/05278/?rxid=0c6e721d-573e-4456-be48-7122ebd94eef

Statistisk sentralbyrå. (2018c). 07326: Akvakultur. Salg av slaktet matfisk, etter fiskeslag (F) 1976 - 2016. Retrieved from https://www.ssb.no/statbank/table/07326/?rxid=da455c34-ccd9-4525-9038-80daa5a0e2c3

Statistisk sentralbyrå. (2018d). 08981: Konsumprisindeks, historisk serie, etter måned (2015=100) 1920 - 2017. Retrieved from https://www.ssb.no/statbank/table/08981/?rxid=503a25df-dd4d-4894-95ac-5467acf8ce7b

Store norske leksikon. (2018). akvakultur. Retrieved from https://snl.no/akvakultur

Teknologirådet. (2012). *Fremtidens lakseoppdrett*.

The Food and Agriculture Organization of the United States. (2018). Global Aquaculture Production 1950-2015. Retrieved from http://www.fao.org/figis/servlet/SQServlet?file=/usr/local/tomcat/8.5.16/figis/webapps/figis/temp/hqp_2887548884868100064.xml&outtype=html

The World Bank. (2013). *FISH TO 2030 Prospects for Fisheries and Aquaculture*.

Thyholdt, S. B. (2014). The importance of temperature in farmed salmon growth: regional growth functions for Norwegian farmed salmon. *18*(2). doi:10.1080/13657305.2014.903310

Yr. (2012). Polar nights and midnight sun. Retrieved from http://om.yr.no/about/midnight-sun/