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Astrid Gunnarsson

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Astrid Gunnarsson

Supervisor: Katarina Elofsson, Swedish University of Agricultural Sciences,
Department of Economics

Examiner: Rob Hart, Swedish University of Agricultural Sciences,
Department of Economics

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Abstract

Current climate change is reducing precipitation in the southern Baltic Sea region, threatening agricultural production on the island of Gotland. The economy of Gotland is highly dependent on agriculture, as it employs 10% of the workforce. The sector produces vegetables that are popular on the mainland of Sweden. This thesis presents an investigation of the cost of predicted climate change in the Swedish region that includes Gotland, taking into account potential adaptation strategies in cropping patterns and irrigation. For this purpose, a farm profit maximisation model, where the net revenue was maximised given the limitations in water due to climate change, was developed. When the model was solved (in Ms Excel), the results showed that the net revenue risked decreasing even more if no adaptation measures were taken. The cost of maintaining the same level of production after climate change increased, suggesting that financial support is necessary to enable farmers to keeping producing as before. Arable crop production was most affected by climate change and would need particular support. These results can be useful for decision makers on Gotland regarding water use and production within the sector under climate change, but should not be used as a single tool due to uncertainty and sensitivity of the results. The results can also be applied to similar areas vulnerable to climate change-related water problems.

Contents

CO = carrots
GHG = greenhouse gases
Gmb = Götalands slättbygder (Götaland plains)
OA = oats
ON = onions
PE = peas
PO = potatoes
RS = rapeseed
SB = spring barley
SCB = statistics Sweden
SGU = Geological Survey of Sweden
SLU = Swedish University of Agricultural Sciences
SMHI = Swedish Meteorological and Hydrological Institute
SR = spring rape
SW = spring wheat
UN = United Nations
WB = winter barley
WW = winter wheat

1 Introduction

With predicted climate change, combined with global population growth and an alarming risk of resource scarcity, climate adaptation of existing production is becoming increasingly important. The cost of climate change can be high if no action is taken. A fear of rapidly growing water scarcity problems due to climate change is beginning to emerge in Sweden. In a recent report, the Geological Survey of Sweden (SGU) highlighted the problem of low groundwater levels, which means that water supplies are at risk and large amounts of precipitation are necessary to restore normal levels. In particular, water scarcity is becoming pronounced in southern Sweden, including the island of Gotland. This is due to the location not receiving normal levels of precipitation, which comes mainly from the west (SGU, 2017a).

Water is a fundamental input in agricultural production. Moreover, the agriculture sector on Gotland plays an important role, as it employs 10% of the workforce on the island, which is three times the average rate of employment in agriculture in mainland Sweden. Of the small companies on the island, one in three is an agricultural enterprise. The sector also contributes to the unique environment on Gotland, with pastures and open countryside, which is of interest to preserve. These surroundings promote tourism, which is also an important economic sector on Gotland (SWCA, 2017a).

The Swedish Meteorological and Hydrological Institute (SMHI) has produced several future climate scenarios for Sweden, which show a drier climate in the future affecting the environment substantially (Andréasson *et al.*, 2014). The main effect is predicted to be an increase in temperature, which will result in an arid climate in southern Sweden. Seasonal precipitation is also expected to change over Sweden, with an annual increase in the north and an annual decrease in the south. These expected changes in climate will directly affect the agriculture sector, since it is highly dependent on the climate. This means that new cultivation conditions for farming have to be considered in production.

1.1 Aim and delimitations

The economic problem of managing the changing climate within the agriculture sector on Gotland was evaluated in this thesis work. The aspect of decreased precipitation from climate change was considered and possible adaptation strategies in the form of changing cropping hectares and irrigation schedules were evaluated. The aim of the study was to evaluate the change in net revenue under different climate scenarios and the cost of climate adaptation.

The economic impact of climate change on agricultural production on Gotland was studied by a quadratic optimisation model, taking into account possibilities for adaptation through cropping systems and irrigation. Climate change was assumed to decrease precipitation, which in turn would affect the production of agricultural crops. This means that farmers would need to adapt to maintain the same productivity and net revenue.

The optimisation model considered the costs of, and income from, crop production and the net return was related to the amount of water applied. Through this relationship, it was possible to identify optimal allocation of resources under different scenarios. In classical economics, the producer examines the net income and produces the product with the highest net income. The same measure was used in this study.

Four different scenarios were considered. The *first* was status quo, which was used as reference for the other scenarios. The *second* scenario analysed climate change impacts on net revenue when there is no adaptation. The *third* investigated a scenario of climate change and the effects on net revenue with adaptation measures applied. The *fourth* scenario analysed the cost of maintaining the same production as in the status quo under climate change.

The hypothesis tested in the thesis was that productivity and net revenue in agriculture will decrease if no adaptation to climate change is made. If farmers opt to adapt to climate change, they will not lose as much due to their production being better fitted to the situation. Through adaptation within the sector, the losses from climate change may be smaller or even non-existent, depending on the relationship between income and costs of climate change.

The overall aim of this work was to contribute new findings in the area of climate change adaptation for the agriculture sector by analysing the monetary value of production. By knowing about possible adaptation strategies within the sector, farmers can be better prepared for future events and maintain the same revenue in their production.

1.2 Background to the problem

1.2.1 The island of Gotland and its climate

Gotland is Sweden's largest island. It is located in the Baltic Sea, around 100 kilometres east of the Swedish mainland, and is characterised by a lime bedrock, which supports a unique flora. When humans first moved to the island it mainly consisted of swamps, but these were drained in order to create farmland. The drained swamp areas made very good farming soils and the agriculture sector became important for Gotland. Farming activities have also resulted in an open landscape and areas that attract tourists (Gotland 1, 2016).

The climate on Gotland is beneficial for farming, as the Baltic Sea generates late springs and long autumns, and the number of sun hours is great. The precipitation on the island is on average between 500 and 600 mm. The bedrock is covered by loose layers of soil or weathering gravel, which means that the ground has little capacity to store water and the groundwater level can vary rapidly (SWCA, 2017a).

1.2.2 Agricultural production on Gotland

Gotland is the region in Sweden with most agricultural businesses (1504) and these play an important role for the economy on the island. The agriculture sector provides 10% of the employment on the island. The region has invested in the sector to make it attractive by constructing suitable buildings, providing financial support for businesses and providing physical support in transport of commodities to the mainland. At present, 80% of the commodities produced on the island are exported (SWCA, 2017a). Of the total land area on Gotland, approximately 70% is used in agriculture and forestry. Crop production had a value of 335 million SEK in 2013 (Holm, 2015).

1.2.3 Climate change

The Swedish Meteorological and Hydrological Institute (SMHI) has performed a climate analysis on how the frequency of drought in southern Sweden will change in the future due to climate change. The results for southern Sweden are shown in Figure 1. As can be seen, Gotland is predicted to experience a drier climate in the future. For example, the number of soil drying days on Gotland is estimated to increase by 19-35 days per year due to climate change, which is a doubling of the normal. Soil drying days is a measure of the depth to the groundwater during the growing period, where a dry day implies a dry soil.

The analysis conducted by SMHI was based on a hydrological model for future changes in soil drying days. They simulated two time perspectives, 2021-2050 and 2069-2098, and found that the number of days with dry soil could double already by the middle of this century compared with the reference period (Andréasson *et al*., 2014).

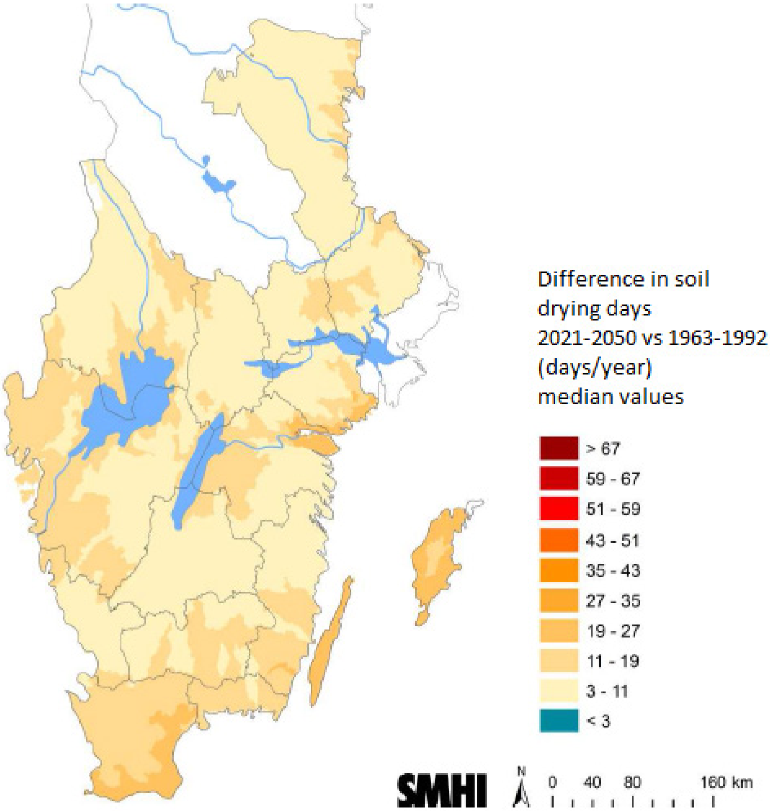

Figure 1. Future scenario of changes in soil drying days. Gotland is the larger and more northerly of the two islands located to the right, and shows a difference of between 11-27 days. Source: Andréasson *et al*. (2014).

Statistics on annual precipitation for Gotland show that the amount has decreased in recent years. The main change observed has been in the rainfall that usually comes during the period October to April, which has declined markedly. It is during this period that the groundwater level can rise due to rainfall, since in other periods most rainfall is taken up by vegetation (Rosengren, 2016). According to SMHI climate models, the prognoses show that the rainfall amount will be lower and contribute less to groundwater recharge, implying a drier climate in the area (Kihlberg, 2016).

In addition, SMHI has developed different climate scenarios for Sweden for 70 to 100 years in the future. Their main conclusions are that the future climate will be 3-6 degrees warmer, the growing season will be extended and annual rainfall will change. Winter, spring and autumn will be rainier and the summers will become drier (Hidås, 2010). The current deviation from the normal in groundwater levels in Sweden is shown in Figure 2. The red areas, where Gotland is included, indicate groundwater levels below the normal, implying dry areas. The data are from April 2016, highlighting the concerns about a drier climate in Sweden. With this severity of low groundwater level, the average precipitation would need to double in order to fill the reserves again, which would mean around 100 mm in three to four weeks (SGU, 2016c).

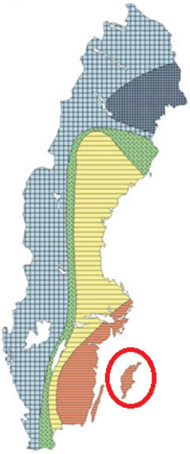

Figure 2. Groundwater levels in April 2016. The red areas show groundwater levels below normal and the blue areas groundwater levels above normal. Source: SGU (2016c).

There are several reasons why studies on environmental change focus on the agriculture sector. One is that agricultural production is directly exposed to changes in climate, for instance temperature and precipitation. The sector also plays an important role in the economy, since food consumption represents a large share of income for the consumer (Forssell, 2014). The debate concerning climate change is about the future risk that many countries will suffer a net loss due to lower yields and higher costs.

1.2.4 Climate adaptation possibilities within the sector

In response to decreased precipitation, farmers have the possibility to change their production systems. Alternative crop rotations or growing crops better suited to the new climate conditions are a logical choice for farmers in order to maintain the same level of productivity. The Swedish Board of Agriculture (SBA) has produced a report on the subject and has concluded that some crops are better suited than others. Irrigation experiments conducted in Sweden show that during a normal year, the yield increase from irrigation is around 20-25%. Crops like potatoes and vegetables are more dependent on an even level of applied water during the growing stages in order to yield high quality and large returns. They are also more vulnerable to drought. By examining alternative crop rotations or by using existing crop varieties better suited to the new climate conditions, farmers have the possibility to maintain the same productivity level and income (Berglund & Malm, 2007).

Investment in technology can ensure constant access to water resources and render famers less vulnerable to climate change. Investments are already currently planned on Gotland, in the form of a desalination plant and sewage treatment water plant (Nordstedt, 2016a; Nordstedt, 2016b). Irrigation ponds are also commonly used on Gotland, which is an alternative for the farmer in order to secure water availability (SWCA, 2017a).

1.3 Outline

The remainder of this thesis is organised as follows: Chapter 2 presents a theoretical perspective on the problem. This seeks to explain the problem, describes methods used in earlier studies and summarises findings on similar issues that have already been considered in research. Chapter 3 describes the methodology used in this thesis work, while Chapter 4 presents the data. Chapter 5 describes irrigation, cropping systems and net return under different climate scenarios. An analysis and discussion of the results are also presented in Chapter 5. Finally, Chapter 6 presents conclusions of the study and suggestions for further research.

2 Theoretical perspective and literature review

A literature review of the economics of climate change and adaptation within the agriculture sector was conducted. Background material on the topic and answers to related research questions are presented in this chapter, in order to give a picture of the past history, current situation and theory about the methodology used for this study. Relevant research areas used in the review were climate change effects on the agriculture sector, climate adaptation, economic impacts, managing resources and effects of irrigation.

2.1 Climate change effects

Roberts and Schlenker (2008) highlighted concerns about future climate change for the agriculture sector in the U.S. in a study examining crop choice, food supply and price change in response to climate change. A nonlinear regression analysis was used to explain the relationship between yield and climate effects. Those authors concluded that a slight increase in temperature will increase yield and benefit production, but if the temperature increases further there will be a steep decrease in yield and the environmental effects will be negative for the sector.

The International Food and Policy Research Institute published a report in 2009 about climate change impacts on agriculture and the costs of adaptation (Ahammad *et al.*, 2009). According to that report, food calorie production ability will be lower in the future due to the environment and, with higher prices for commodities, the demand will change. It was calculated that agricultural investments of US 71-7.3 billion are needed to raise calorie production enough to offset the negative impacts of climate change on health (ibid.).

2.2 Climate adaptation

Skinner and Smit (2002) grouped agricultural adaptation options into four categories: 1) Technological developments, 2) government programmes and insurances, 3) farm production practices and 4) farm financial management. The first two relate to planned adaptation and responsibility by public agents and agri-businesses. The latter two categories refer to farm-level decisions. Those authors conducted their research based on conditions in Canada and developed a typology of adaptation to systematically classify and characterise agricultural adaptation options to climate change. They also concluded that in order to implement adaptations to climate change in agriculture, there is a need to better understand the relationship between potential adaptation options and existing farm-level and government decision-making progress and risk management frameworks.

A report by the Swedish University of Agricultural Sciences (SLU) on climate change suggests different climate adaptation possibilities for farmers (Andersson *et al*., 2008). Crop choice is the main adaptation factor, since by changing crops farmers can adapt to changes in cropping season, increased demand for fertiliser and a change in pesticides. Adaptation strategies to cope with decreased access to water first mean accepting decreased productivity. Irrigation will be necessary otherwise, and the irrigation requirement will be as much as the decrease in precipitation (ibid.). Similar results are presented by Aboudrare and Debaeke (2004), who point out that farmers have the possibility to change crop management, which means changing sowing date, cultivar, fertilisation, irrigation and cultivar, in order to optimise their net revenue. The timing, intensity and predictability of future weather are important factors in choosing the optimal cropping management. Adapting to the climate by changing these variables means that net revenue can be maximised (ibid.).

2.3 Water effects

The agriculture sector is highly dependent on good water resources, since it is the largest consumer of water world-wide at present. The sector currently uses about 70% of all withdrawals and by 2030 around 50% of agricultural production is estimated to be irrigated (UN-Water, 2011). Variability in water availability increases the risks for farmers and means that farmers have an incentive to irrigate their fields. Semenov and Porter (1995) examined the risks farmers are facing due to climate change and climate variability. They used a nonlinear model, since they claim that this is most suitable when working with parameters that include variability. Their results showed that, as the climate variability increases, the risk increases.

The Intergovernmental Panel on Climate Change (IPCC) has projected that the global mean surface temperature will rise by 1.4-5.8 °C due to increases in carbon dioxide concentration. A study performed at farm level in California used the hedonic property value method to examine the benefit of having access to several water resources (Mukherjee & Schwable, 2015). The results showed that agricultural land values decrease if there is lower quality water and less reliable water access, highlighting the importance of water supply in agricultural production.

2.4 Cost of using limited resources

Ziolkowska (2015) evaluated the shadow price of irrigation in the U.S. agriculture sector of High Plains (Texas, Kansas, Nebraska) in 2010 and 2011. The shadow value was computed by comparative-statics analysis on farm level. The analysis concluded that water is currently under-priced and that there are future challenges in management of the resource. Higher water prices are beneficial for conserving water resources and securing future use, but will have a severe economic impact on productivity. Higher government subsidies are necessary if the same level of productivity as today is to be maintained (ibid.). The cost of using a natural resource captures the scarcity if priced right. Getting prices right and allocating water efficiently will become increasingly important as demand for food and water increases and as water scarcity becomes more of a problem (Johansson, 2000).

2.5 Modelling the economic impacts of climate adaptation

There are several techniques for examining the economic problem of managing resources under climate change conditions. Mathematical programming is a useful technique for system analysis when the best possible optimum should be chosen from among a set of feasible options. Deressa *et al.* (2009) discuss the two main types of economic impact assessment models in the literature, which are computable general equilibrium and partial equilibrium models. Partial equilibrium models consider a single market of a commodity or a sector of the market and can be classified as a production function. This approach is suitable for studying the economic impacts of adaptation measures on agriculture. The production function approach is based on an empirical or experimental production function that measures the relationship between agricultural production and climate change (Nordhaus *et al.*, 1994). The function includes environmental variables of interest such as temperature and precipitation as inputs which can then be projected. Through this approach, changes in yield can be calculated as changes in the environmental variables (Bocher *et al.*, 2000). The yield can then be multiplied by the market price and the economic effect can be evaluated. Farmers can adapt to climate change in order to maximise profit by changing the crops grown and their planting and harvesting dates. This response will in turn involve a cost for farmer, which is reflected in the net revenue. Therefore, a suitable way of calculating the cost of climate adaptation is by examining the net revenue or land value (Deressa *et al*., 2009).

Linear modelling is most commonly used in crop water relation modelling, as shown in studies by Kodal (1996), Gupta *et al.* (1997) and Kumar and Raju (1999) focusing on calculation of optimum cropping patterns. Amir and Fisher (1999) used linear modelling for analysing agricultural production. It is a popular method, since it is less demanding in terms of data and computation, but does not always capture the real relationship. The maximum net benefits will occur at the constraint, whereas the real world shows an optimal value within the feasible region. Through the nonlinear relationship, the marginal effects are captured and it is often the real image that is shown. Elango *et al.* (1998) used nonlinear programming in an optimisation study to identify optimal cropping pattern and optimal deficit irrigation schedule. Carvallo *et al.* (1998) also used a nonlinear approach in an optimisation study on optimal cropping patterns, while Benli *et al.* (2003) applied it in their study of optimal distribution of crop areas, irrigation water needs for crops and total profit for the farm.

The studies referred to above all used optimisation. Optimisation is a classical approach to economic problems with constraints. A static problem of this nature refers to the process of minimising or maximising the costs and benefits for an objective function for one instant in time only. Buzarovska (2012) examined the problem of yield reduction due to deficit irrigation by applying optimisation modelling to examine changes in cropping patterns and irrigation systems under climate change in Pelagonia, Macedonia. The modelling results revealed a loss in net farm returns caused by climate change.

Buzarovska (2012) used the Lagrangian approach for the optimisation process, as did Elango *et al.* (1998) and Carvallo *et al.* (1998). In this approach the Lagrangian multipliers can be computed, which gives relevant information about the marginal values of the constraints. The shadow prices obtained by Buzarovska (2012) showed a positive value for arable land, feasible area for irrigation and maximum area for barley, tobacco and grasses. A negative shadow price was estimated for minimum area of alfalfa, meadow, maize, winter wheat, barley and vegetables.

3 Method

The economic impact of climate change in the agriculture sector on Gotland was examined by a constrained optimisation model. This type of model was chosen in order to capture the influencing environmental impacts on Gotland's agricultural production. The optimisation model examined the difference in income and costs for farmers, *i.e.* the net revenue, subject to the constraints under climate change. The model applied was a partial equilibrium model, meaning that it only considered agricultural crop production for the specific area.

3.1 Conceptual framework

Optimisation techniques, such that used in this study, are applied to make optimal decisions for allocation resources, in this case land and irrigation applications. In this approach, the resource allocation problem is formulated as a mathematical programming model by defining the objective function, decision variables and constraints. The model considers decision allocation of resources during one year, calculated in Ms Excel.

The relationship considered for Gotland consisted of the following elements: the net return was the objective function and was the value of interest to optimise. The net return was defined as the sum of income from crop production minus the cost of production. Crop production was defined by a yield function and hectare usage. The yield function comprised the agronomic component in the model, which was crop yield response to climate (water). The economic component in the model considered the monetary value of yield based on net returns and allocated crop area. The model included the farmer's decision on hectare usage per crop and the decision on irrigation per crop. Based on these decisions, the maximising net return strategy can be chosen subject to resource availability.

3.2 Objective function

The first step in the method was to define the objective function, *i.e.* the net revenue function. The net revenue is the sum of all crop revenues and costs. The optimal allocation of resources is found by maximising the net revenue function subject to the constraints. The optimisation model used here was on aggregated level, so it captured the whole picture of the crop sector. By combining the yield function with prices of crops and costs for inputs, the net revenue was obtained. This also meant that the optimal cropping system for Gotland under climate change conditions was determined. The net revenue was calculated for Gotland in total and was defined by the following function:

$$Net\ income\left(x_i w_i^{irr}\right) = \sum_i^N (I_i - TC_i) = \sum_{i=1}^{12} x_i (P_i\, Y_i(W) + S_i - (P_w w_i^{irr} + VC_i)) \quad Eq.\ 1$$

where i represents the different crops included in the model. The following variables were defined:

P_i = the price the farmer receives from selling the crop (SEK/kg)
$Y_i(W)$ = the yield function, which depends on water added
W = total added water, *i.e.* the sum of precipitation and irrigation ($W = w_i^{prec}$ + w_i^{irr}) (m)
x_i = the total amount of hectares on which crop i is grown (ha)
P_w = cost of irrigation water (SEK/m/ha)
w_i^{irr}= total amount of added irrigated water for crop i (m)
VC_i = variable cost for crop i per hectare x_i (SEK)
S_i = subsidies for each crop i grown (SEK/ha)
$\overline{A}$ = total arable available land on all of Gotland (ha)
$\overline{L_i}$ = maximum allowable area for crop i (ha)
$\underline{L_i}$ = minimum allowable area for crop i (ha).

3.2.1 Decision variables, constraints and the exogenous precipitation parameter

Within the objective function, the producer, in this case the farmer, faces decision variables and constraints. The constraints will limit the farmer's ability to achieve profit maximisation and the decision variables will make it possible to choose the maximum net income based on the stated situation. To clarify the water parameters and the difference between them, irrigation was included in the model as a decision variable and precipitation as an exogenous parameter. In this section, the decision variables, the constraints and the exogenous precipitation parameter are presented.

The model designed in Excel provided the possibility for selecting irrigation (m) and hectares (ha) for the different crops in order to maximise net return for Gotland. The decision on number of arable hectares devoted to each crop was presented as x_i, where i=crop. The allocation of irrigation between crops was implemented as w_i^{irr}, where *i*=crop. Constraints were added to the model with the aim of mimicking the conditions on Gotland and restricting the use of available resources in the area, so that they are used in a sustainable way. The first restriction was on land area. Gotland has a total feasible area for production and the land available was therefore restricted to this area:

$$\sum_{i=1}^{12} x_i \le \overline{A} \qquad \textit{Eq. 2}$$

where $\overline{A}$ is total area of arable land (ha), which according to the restriction needs to be greater than or equal to the total sum of the area of cultivated crops. The next constraint applied was an agro-economic constraint, which restricted minimum and maximum allowable area per crop:

$$\sum_{i=1}^{12} \underline{L_i} \le x_i \le \overline{L}_i \qquad \textit{Eq. 3}$$

where $\underline{L_i}$ is the minimum allowable area for crop i and $\overline{L}_i$ is the maximum allowable area for crop i. Both variables are in hectares. Seasonal rainfall was added to the model as an exogenous determined parameter limiting the net revenue due to limitations in the resource. The amount of added annual rainfall was varied under different climate scenarios:

$$\sum_{i=1}^{12} w_i^{prec} \le \sum_{i=1}^{12} \overline{w}_i^{prec} \qquad \textit{Eq. 4}$$

where w_i^{prec} is the seasonal rainfall added to crop i (m), which equals $\overline{w}_i^{prec}$, the exogenous parameter of rainfall per year.

3.3 Lagrange optimisation

The optimisation problem can be handled using a Lagrange function to find the maximum net revenue subject to the constraints. The Lagrange function in the present case represented the net revenue from the farmer's production subject to the constraint imposed by the availability of inputs x_i and w^{irr} used in production (Debertin, 2012:139). The Lagrangian function for the present case was:

$$max_{x,w^{irr}} L(x_i, w_i^{irr}, \lambda_k) = \sum_{i=1}^{12} x_i(P_i Y_i(W) - (P_w w_i^{irr} + VC_i)) + \lambda_1(\overline{A} - \sum_{i=1}^{12} x_i) + \lambda_{2i}(\sum_{i=1}^{12}(\overline{L}_i - x_i)) + \lambda_{3i}(\sum_{i=1}^{12}(x_i - \underline{L_i})) \qquad \textit{Eq. 5}$$

where λ_k are the Lagrangian multipliers for the restrictions presented above and was interpreted as the implicit value of the last SEK spent on the input. It represents the worth of money spent on inputs if the inputs are allocated according to the expansion path conditions (Debertin, 2012:140). Note that the water constraint was not included in the Lagrange function, since it is an

exogenous variable and not a decision variable. All variables were as defined above except for the multipliers, which were defined as:
λ_1= Marginal value of a change in total area of 1 hectare
λ_{2i}= Marginal value of a change in restriction of maximum hectares per crop i
λ_{3i} = Marginal value of a change in restriction of minimum hectare per crop i.

3.3.1 Interior solution

An interior solution is a choice made by the agent (in this case the farmer) and is characterised as an economic optimum. The point can be found by setting all λ_k in the differentiated equations equal to zero. The following equations were then derived (Perloff, 1998:77):

$$P_i Y_i(W) = P_w w_i^{irr} + VC_i \qquad \textit{Eq. 6}$$

$$P_i \frac{\partial Y_i(W)}{\partial w_i^{irr}} = P_w \qquad \textit{Eq. 7}$$

as Eq. 6 shows, the interior solution is found at the point where the income from crop i equals the cost of producing it. Eq. 7 can be rewritten as:

$$P_i MPP_i = P_w \qquad \textit{Eq. 8}$$

where MPP_i is the marginal physical product of the input water, which together with the product price always equals factor price at the optimum point. The MPP can be computed at different levels of input use and the value changes as the use of input changes. At first, the productivity of using more water increases, and so does the marginal product and the corresponding MPP function. At a certain input use the inflection point is reached, which marks the maximum marginal product. After passing the inflection point, the marginal product of water declines, as does the MPP function. Therefore the MPP function is zero at the point of output maximisation (Debertin, 2012:26)

3.4 Yield function

The yield function used in this thesis described the yield response of water applied in the field. This relationship was used to describe the environmental effect on production and by that a monetary value of climate change was obtained. Since Gotland is a new study area for this kind of analysis, the yield function used in the present work was developed from existing studies and corrected for Gotland's local conditions by calibration. The calibrated function had the structure of a quadratic function:

$$Y = b_1 W - b_2 W^2 \qquad \textit{Eq. 9}$$

where Y is the yield, b_1 and b_2 are the calibrated parameters and W is the amount of water added in the field. This means that added water reaches an optimum point and thereafter has a negative impact on yield, see Figure 3. Quadratic functions are suitable to describe environmental effects on production. The quadratic variable in the function, *W*, represents water applied in crop production and is the sum of precipitation and irrigation. The relationship between water and yield is illustrated in Figure 3. As more water is added, there eventually comes a point where the effect will be negative. This is called the marginal effect of the decision variable in the objective function. An example of this is flooding, which damages the field crop and decreases the yield. Precipitation in the function is an exogenous variable, while irrigation is an endogenous variable. The farmer has the possibility to choose the optimal level of irrigation in order to maximise the quadratic relationship.

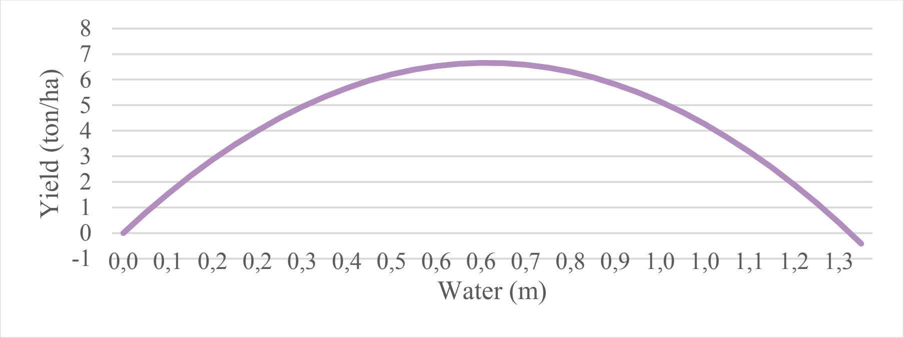

Figure 3. The quadratic relationship between added water and crop yield for winter wheat.

Calibration is an important part of model development, where a systematic adjustment is made to ensure that the model results correspond to local observations. In the present case, the function was calibrated and evaluated for the conditions on Gotland and was based on economic and environmental logic reasoning regarding where production takes place.

4 Data collection and presentation

This chapter provides a detailed description of the data used in the study, starting with the agronomic data and followed by the economic data. The calibration and parameters of the yield functions are also presented.

4.1 Agronomic data

The agronomic data used were mainly obtained from Agriwise and SBA. Agriwise is a cooperation website that supplies farmers in Sweden with relevant production information. The data on the environmental factor water were based on several sources, as presented below.

4.1.1 Choice of crops

In the decision on what crops to include in the model, several elements were considered. First, there had to be available data on the crops. Historical data from SBA were then analysed, in order to choose relevant crops for Gotland (see Appendix on cultivated areas for Gotland). Based on the findings, the crops presented in Table 1 were chosen for inclusion in the study. The crops were divided into two groups in the analysis, arable crops and vegetables.

4.1.2 Area data

Total feasible area for crop production, taken from SBA data for 2016, was 85,787 ha. Restrictions on minimum and maximum allowable arable area for the different crops were based on historical data from SBA and are presented in Table 1. The data evaluated were from the period 1991-2016 and were assumed to represent the cultivation conditions on the island. The lime-rich soils, sun hours and cropping time are factors on Gotland that create cultivation possibilities and limitations in production, which were assumed to be reflected in the areas studied. Note that the areas apply for Gotland as a whole and are presented in hectares.

Table 1. *Minimum and maximum arable area for all crops on Gotland. The data are presented as total number of hectares per year. Source: SBA and Agriwise database*

Arable crops	**Minimum area**	**Maximum area**
Winter wheat	4 000	15 000
Spring wheat	4 000	15 000
Winter barley	4 000	15 000
Spring barley	4 000	15 000
Rapeseed	1 000	15 000
Spring rape	1 000	15 000
Oats	1 000	15 000
Coarse feed	1 000	15 000
Peas	1 000	15 000
Vegetables		
Potatoes	500	12 000
Onions	20	500
Carrots	20	500

4.1.3 Precipitation and irrigation

According to historical data taken from the SMHI database, annual rainfall on Gotland it is around 500 mm, a value which was used in the model and for the yield function calibration. Above that, annual irrigation of 150 mm was assumed to be added to all vegetables, according to cropping information from Agriwise budget analyses for vegetables on the Götaland plains (region Gmb) 2017. The choice of irrigation level was also based on findings in a study by Ingvarsson (1992).

4.1.4 Expected decrease in precipitation

Expected decrease in precipitation is difficult to measure and reports give different and no exact values due to uncertainty. The value for decrease in precipitation used in this study was therefore built on data from several studies. Andersson *et al*. (2015) reviewed the state of knowledge in collaboration with sector agencies, with the aim of highlighting the coming risks and consequences of a changing climate. Comparing the past two decades with the period 1961-1990 showed decreased precipitation. The climate will become drier in southern Sweden due to higher temperatures, more evaporation and longer cropping seasons with more water-demanding crops. Axén-Mårtensson *et al.* (2015) analysed climate change in Sweden based on two scenarios developed by the United Nations (UN), one with low greenhouse gas (GHG) emissions and one with extreme levels of GHG emissions (three times the current levels). They concluded that there will be a decrease in water supply on Gotland, especially during summer, due to higher temperatures and increased evaporation. The term water supply, used to describe access to water in watercourses, is expected to decrease by 10-15%. SMHI's report on dry soil days in the future in southern Sweden states a decrease of 40-50%. They used a hydrological model to compute the future change and used 1963-1992 as their reference period. The two future scenarios examined were 2021-2050 and 2069-2098 (Andréasson *et al*., 2014). SGU, together with SMHI, has written a report about groundwater levels in a changing climate. The study examined data from several groundwater stations in Sweden and applied different climate scenarios to these data. The conclusion was that higher temperatures would give higher evaporation rates that exceed rainfall rates, which means that groundwater levels will fall and the climate will become drier (Dahné *et al*., 2010). SBA used SMHI's future climate scenarios in their analysis of the impact of climate change on the agriculture sector. Their study considered the period 2030-2035 and concluded that cropping season will increase, crops will become more demanding of water due to higher temperatures and precipitation will decrease during the summer (Albertsson *et al*., 2007). A study at SLU has also used SMHI's future climate scenarios to evaluate the effects on crop production within Swedish farming. The authors looked at the period 2071-2100 and used 1961-1990 as the reference period and calculated the mean values for these periods. The calculated water availability showed a decrease in Götaland (Gotland) and an increased irrigation requirement for some crops. Autumn-sown crops are expected to be favoured compared with spring crops. The calculated compensated irrigation requirement was 15-80 mm/year (Andersson *et al*., 2008). Based on these findings, precipitation was assumed to decrease by 20% in the main study, while a sensitivity analysis tested different levels above and below this value.

4.1.5 Available water for irrigation

There was no exact information on available water for irrigation on Gotland and therefore the availability was based on current information and statistics. The resource was assumed to come from several sources. The Statistics Sweden (SCB) database provides information about water use and states that Sweden purifies 1.5 billion m^3 water each year. By simple mathematics based on the population on Gotland, this amount should be enough by itself to cover the decreased precipitation on Gotland. In addition to this source, Gotland is currently constructing a desalination plant that will be ready in 2019 and will produce fresh water (Wesley, 2017a, b). Farmers also have the possibility to use sea water directly, since the salt level is low (0.6%), which means that sea water is a further water resource for Gotland's farmers (Ingvarsson, 1992). The studies presented in the subsection above also concluded that it may rain more during autumn and winter, which means that farmers can collect water during these periods and store it for later use during the cropping season. Thus based on existing information, the available water for irrigation will not be limited in the study period.

4.2 Economic data

Concerning economic data on crop production, Agriwise and SBA were used as data resources, since they do not influence the market and work independently of producers and consumers. The Agriwise database divides Sweden into different regions, and data for the Gmb region were used here since it includes Gotland. The SBA database instead divides Sweden into smaller regions, one of which is Gotland, data for which were used directly for this study. Data on peas and winter wheat were calculated as livestock feed.

4.2.1 Income data

The prices of crops were fixed in the model. Since Gotland is only a small part of Sweden, which in turn is only a small part of the world market, agricultural production on Gotland was assumed to have no market power and to be a price taker. Data on the prices for the different crops were taken from SBA and Agriwise databases, where the latest prices refer to 2016. The prices for the different crops are presented in SEK/kg in Table 2, where the crops are again divided into two subgroups depending on type. In addition to the income the farmers receive from production, they also receive an income in the form of subsidies. According to the Agriwise database, Gotland's farmers receive between 1500 and 2000 SEK per hectare. A similar value has been reported by the Swedish Parliament, which calculated the average value of support to farmers on Gotland to be 2000 SEK per hectare (Swedish Parliament, n.d., a). Based on this, a subsidy to the value 2000 SEK per hectare was added in the present analysis.

4.2.2 Cost data

The calculations of production costs were performed for each crop separately, in order to get specific production costs for each crop. The Agriwise tool for budget calculations was employed, using data collected in February 2017 and prepared according to the real method. The cost per hectare for each crop is presented in Table 2.

Table 2. *Hectare costs (SEK/ha) and prices (SEK/kg) for each crop in the study. Source: Agriwise database 2016 and 2017, area Gmb*

Arable crops	**Cost (SEK/ha)**	**Price (SEK/kg)**
Winter wheat	7242	1.07
Spring wheat	6240	1.22
Winter barley	6115	0.95
Spring barley	5117	0.95
Rape seed	8938	3.04
Spring rape	5076	3.04

Oats	4457	0.96
Coarse feed	8223	3
Peas	5726	1.44
Vegetables		
Potatoes	83841	3222
Onions	63208	3377
Carrots	129260	2156[1]

[1] Data obtained from SBA

4.2.3 Irrigation cost

Since the cost of irrigation was of interest, it was calculated separately from the other production costs. The cost of irrigation was included as a cost (SEK) of added water (m) due to the structure of the model. This cost arises since there is a cost of using the resource in production and capital investment is necessary in order to move water from natural water bodies to the irrigation site. Several sources were considered, to obtain a credible value. Agriwise includes the cost of irrigation in some of their budget calculations, based on data collected 2017 and including the cost of electricity, maintenance, depreciation, interest and extra work by the farmer. The average value reported by Agriwise for different crops is a cost of ~3357 SEK/ha. Abraham and Wesström (1993) estimated the irrigation cost of water from sewage plants to be 1100-1600 SEK/m. However, this value does not consider all costs related to irrigation. Hidås and Malm (2010) examined the investment cost of an irrigation pond and estimated it to be 16000-310000 SEK/m. Dahlgren (1974) looked at irrigation from groundwater sources in Sweden and computed the cost for different water sources to be around 245-822 SEK/ha. Based on these sources, a cost of 3000 SEK/m was used in the model.

4.3 Yield function calibration

The main focus of the calibration was to find a credible relationship between yield and water for the location Gotland. Crop yield depends on more factors than the environmental factor water, which were considered for added credibility. Several existing yield functions from previous studies were examined. In order to find a credible yield function for the present case, a review of the relevant literature was conducted. A number of papers were analysed, and the most pertinent are presented in the Appendix. Based on the structure of the yield functions used in these papers, the classic quadratic function was applied:

$$Y(w) = b_1W - b_2W^2 \qquad \textit{Eq. 10}$$

where b_1 and b_2 are the coefficients of interest to be calibrated for conditions on Gotland and

$$W = w^{prec} + w^{irr} \qquad \text{Eq. 11}$$

is the sum of precipitation and irrigation water applied in the field. This function gives a nonlinear relationship between applied water and yield. The first aspect compared in the papers was to identify similarities in the estimated parameters. An assumption was made for the function, which was that the yield is zero when no water is applied, meaning that the function does not have an intercept. The papers reviewed used similar variables, although some used more variables than applied water, such as applied nitrogen and salt effects. How the data were collected was also compared, with papers with data collected during a longer time frame in field experiments being considered more credible. Moreover, the functions were evaluated in terms of whether it was possible to correct them for the conditions on Gotland.

The calibration was also corrected for the conditions of the location. The mean yield and mean precipitation for Gotland were used, where mean yields for all crops are presented in the Appendix. To find a credible maximum point, the precipitation for the area Skåne in Sweden was used. Skåne has the largest yield per hectare in Sweden and therefore an assumption was made that applying the same precipitation as in Skåne to the case of Gotland would yield the maximum point. The calibration also considered the findings in Berglund & Malm (2007), where they expected yield to increase by 20-25% due to irrigation in Sweden. The calibrated yield function was thus based on a two equation system and was for arable crops:

$$\left.\begin{array}{l}\frac{Y_{imean}}{1.4} = b_{i2} \\ b_{i1} = b_{i2} * 3.1\end{array}\right\} \qquad \text{Eq. 12}$$

and for vegetables:

$$\left.\begin{array}{l}\frac{Y_{imean}}{1.4425} = b_{i2} \\ b_{i1} = b_{i2} * 3.1\end{array}\right\} \qquad \text{Eq. 13}$$

Vegetables were corrected for the fact that they are irrigated under the current climate and were therefore expected to have a higher mean water requirement.

4.3.1 Presentation of the yield functions

The calibrated coefficients for the yield functions are presented in Table 3. They are divided into two groups, since vegetables had additional water added to their function. As the table shows, vegetable crops were most affected by added water.

Table 3. *Presentation of the calibrated variables b_1 and b_2 in the yield functions for all crops*

Arable crops	**b_1**	**b_2**
Winter wheat	20.48	15.76
Spring wheat	14.05	10.81
Winter barley	16.53	12.72
Spring barley	14.27	10.98
Rape seed	11.95	9.19
Spring rape	5.98	4.60
Oats	12.24	9.42
Coarse feed	18.79	14.46
Peas	9.87	7.60
Vegetables		
Potatoes	100.26	77.12
Onions	75.82	58.32
Carrots	185.59	142.76

The relationship between added water and yield is presented in Figure 4. The first chart shows arable crops and the second shows vegetables. The two graphs have the same maximum point due to the assumption on maximum yield.

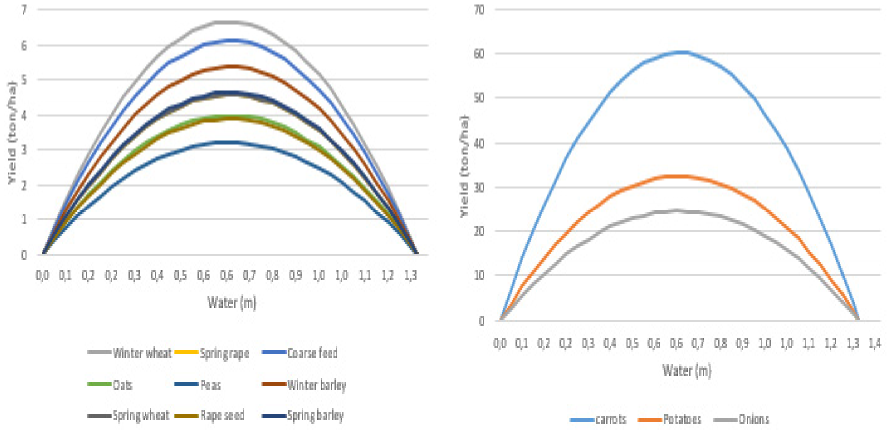

Figure 4. The calibrated yield function and its relationship to amount of water applied for all crops studied.

5 Results and discussion

This chapter describes in detail the four different scenarios used for the study. The results from the optimisation in terms of net return, irrigation and hectare usage for the different scenarios are then presented. The comparative statistics of the model are considered, followed by an analysis of the model, and the study results are compared with those of similar studies. The chapter ends with a discussion on suitable policy instruments for the economic research problem.

5.1 Defining the scenarios

The optimisation model allowed the annual precipitation to be varied, which was done to examine the effects of a drier climate. The following four scenarios were examined:

S0: Status quo, reference scenario

This scenario was used for comparison and reflected the current situation, where annual rainfall was set equal to mean annual rainfall. Precipitation was fixed at a value equal to current level (w_0^{prec}). Irrigation was also fixed at the current level, which is zero for arable crops and 0.15 for vegetables. The cost of irrigation was included. The farmer was assumed to choose to distribute the hectares available (x_i^{S0}) in the optimal way, *i.e.* to maximise net revenue.

S1: Climate change, no adaptation

Under this scenario, climate change was assumed to occur, but with no adaptation measures implemented by the farmer. Annual precipitation was decreased by 20%, but irrigation and hectare usage were fixed at the same levels as in scenario S0. In this scenario, the decrease in net revenue from climate change when no adaptation was made was measured.

S2: Climate change, with adaptation

The same climate scenario as in S1 was assumed, but possible adaptation alternatives were examined in this scenario by the optimisation model. The farmer was assumed to choose the optimal applied irrigation $\left(w_i^{irr,S2}\right)$ and hectare (x_i^{S2}) usage in order to optimise net revenue.

S3: The cost of maintaining production
In this scenario, the cost of maintaining the same production under climate change was examined. The farmer was assumed to have the opportunity to choose irrigation $(w_i^{irr,S3})$ to compensate for climate change, in order to have the same production as in the status quo (before climate change) $\sum_i^{12} y_i^{S0} x_i^{s0} = \sum_i^{12} y_i^{S3} x_i^{s3}$.

5.2 Net return

The net return was decided by the choice of hectare use and water variations in the scenarios and is presented in Figure 5 for Gotland as a whole. In S1, where no adaptation was conducted, the net return decreased by 2.37%. In scenario S3, where production was equal to that in S0, the net return decreased by 0.002%, indicating that the cost of maintaining the same level of production under climate change does not have a large impact on net return for Gotland in total. For the optimisation scenario (S2), the net return decreased by 0.01%.

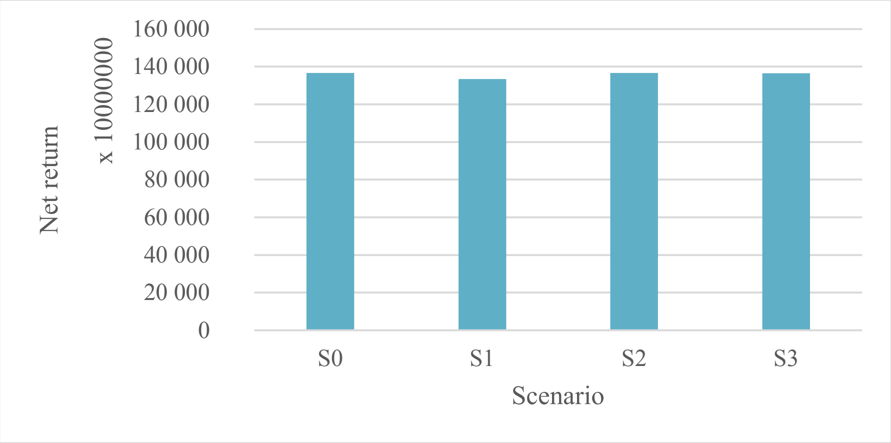

Figure 5. Net return (SEK) for each of scenarios S0-S3, total for Gotland.

5.3 Hectare usage

The allocated cropping area for scenarios S1 and S3 was fixed at the same level as for scenario S0. Therefore Figure 6 presents only the allocations for S0 and S2. Scenario S0 used all allowable land for production, whereas in S2 the land use decreased to 49,476 hectares, *i.e.* decreased by 42%. Cultivated land area decreased for the crops winter wheat, rapeseed, spring rape and coarse feed, whereas area of land allocated to oats and peas increased.

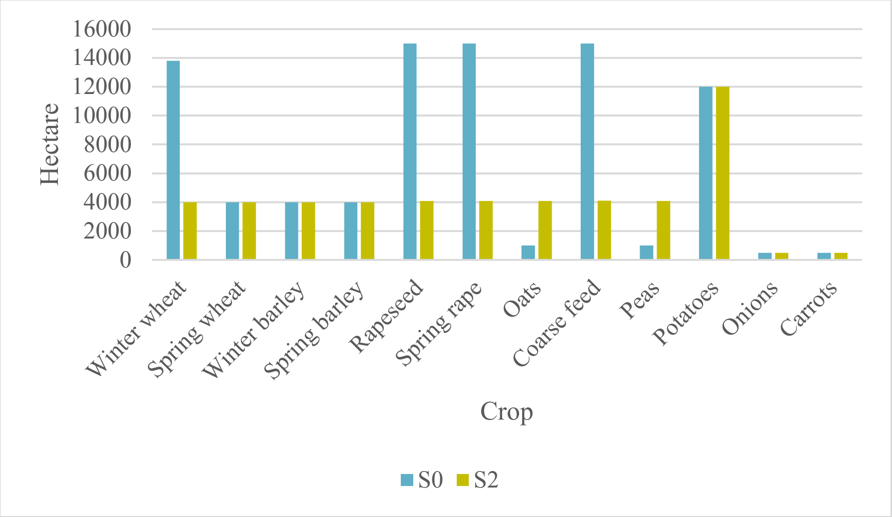

Figure 6. Hectare allocation for the different crops in scenarios S0 and S2, total for Gotland.

5.4 Irrigation

The choice of irrigation applied only for scenarios S2 and S3, while in the other scenarios the irrigation was fixed. Irrigation in the optimisation scenario (S2) is presented in Figure 7 in mm/ha. Only five crops were irrigated in the scenario, three of which were vegetables. The decision on irrigating these was based on the net return of the crops. These crops yield a profitable higher net return if irrigated and were therefore irrigated. For the remaining crops, it was not beneficial to apply irrigation water. In S3, the irrigation increased by 100 mm/ha for all crops, *i.e*. irrigation compensated for climate change in order to achieve the same productivity as in S0.

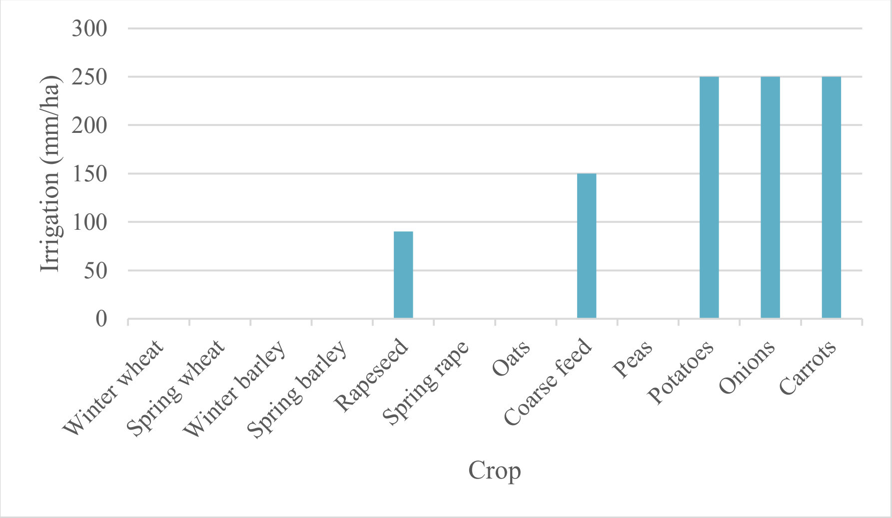

Figure 7. Irrigation (mm) per hectare for the different crops in scenario S2, total for Gotland.

The cost of irrigation in S3 was 300 SEK/ha, which thus represents the cost of compensating for climate change. The cost of irrigation in S2 was between 260 and 751 SEK/ha.

5.5 Comparative statistics

Due to the fact that expected precipitation was uncertain, different levels were tested in the model for scenarios S1 and S2. Figure 8 shows the net return at different levels of precipitation for the scenarios. In the case of S1, where the farmer did not compensate for climate change, the net return was dependent on precipitation and net return changed as precipitation changed. In the case of the optimisation scenario (S2), the farmer compensated for the lower precipitation with irrigation to a certain level to increase net return. At the precipitation level where more added water resulted in decreased net return, the farmer was assumed to stop irrigating (Figure 8). Even if there was a cost of irrigating the crops, the farmer chose to irrigate in order to increase net return.

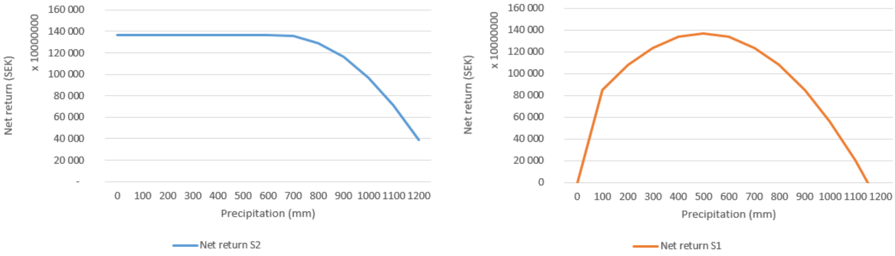

Figure 8. Net return in (left) scenario S1 and (right) scenario S2 at different levels of precipitation.

Varying the level of annual rainfall also had an effect on hectare usage in scenario S2. Decreasing the annual rainfall led to a decrease in hectare usage, since the net return per hectare was too low for the farmer to benefit from cultivating the land.

Since the cost of irrigation was also uncertain, different levels of cost for irrigation were investigated for S2. Increasing the cost of irrigation first triggered a reaction regarding arable crops, where the amount of added water was decreased. Increasing the price even more led to a decrease in cultivated area for arable crops, meaning that arable crops would suffer more than vegetable crops due to an increase in the cost of irrigation. Vegetable crops give a high net return, so it is still profitable to cultivate them at higher water input costs.

5.6 Shadow prices

The shadow prices for irrigation and hectares were analysed using MS Solver. The shadow price represents the marginal value of the input in terms of its contribution to revenue on the farm to its marginal cost. The analysis was conducted to test the credibility of the model and analyse the value of relaxing the constraints. The results revealed positive shadow values for irrigation and limited hectare usage in all scenarios. This means that the increasing restriction in water usage had a negative impact on net revenue for farmers, which was also shown in the results of the optimisation.

5.7 Discussion of the model

The choice of a partial equilibrium model has its benefits, as it is easy to use and less demanding in terms of data. The main drawback with the model is that it does not consider external variables that often affect an economic sector. The model thus only considers a small part of the economy and interactions are excluded. However, the model does capture the most relevant factors related to the study object. A nonlinear model was chosen here, since the relationship with environmental variables is often nonlinear. Previous studies have found that using a nonlinear model often results in a higher net revenue, an aspect that should be considered in interpretation of the results (Benli & Kodal, 2003).

The calibrated yield function obtained here was associated with some uncertainty. The procedure was based on assumptions about the real relationship and the calibration assumed the same optimum point, which might not be the optimum in reality. The yield function is a good way to show the relationship between water and yield when no data are available for an area, but the calibration is basically built on a simple quadratic relationship, whereas there may be more factors influencing the outcome. Nevertheless, based on the conditions, the yield function can be assumed to capture the relevant effects.

The optimisation model is very useful in capturing relevant farm-level decisions based on an economic problem. The costs can be reduced and the yield maximised by the model. Bearing this in mind, it might not be possible to accomplish as good results as the real scenario due to limited factors not included in the study. For instance, non-farm decisions and technical improvements are not included. According to SBA, the average Swedish farmer has 43 hectares of arable land and therefore technical improvements would have a relatively low effect on farm productivity within the time frame considered in the present thesis. Socio-economic factors such as growth, income and social development can also be considered to be irrelevant, since the model only considers a one-year period. This leads to the conclusion that the short time frame of the model is a weakness, since environmental changes often occur over a longer period.

5.8 Comparison with other studies

One weakness of using a mathematical programming model is that the model often provides a better solution than reality. There is thus a risk of a biased answer towards providing expected outcomes. The risk of a biased answer can be analysed by comparing the results with those of similar studies. Bhandarkar *et al.* (2001) examined a similar problem to that considered in this thesis, using a linear programming model. Their objective function had the following constraints: total available water and land, minimum area and the farmer's socio-economic conditions and preferences for specific crops. The results are similar to those obtained in this thesis, with the net return decreasing together with the amount of available water. Amir and Fisher (2000) used an optimisation model to examine water policy instruments in Israel and found that when water quotas are binding, an increase in the price of water price does not increase water productivity. The farmers in that study were assumed to choose a mix of crops that maximised the net return, given the availability of water. Similar results have been reported by Kaiser *et al.* (1993) and Li *et al.* (2011), where the estimated net return was expected to be affected by climate change.

Many previous studies within the research area consider evaporation in their calculations, such as those by Benli and Kodal (2003) and Buzarovska (2012). Evaporation is closely related to the availability of water for crops and is therefore often included. However, comparing the results in this thesis, where evaporation was not considered, with those reported by Buzarovska (2012) revealed that they were similar. The net return was expected to decrease by 11 to 22 % in the different climate scenarios examined if no adaptation was applied. The production of low profitability crops would thus be reduced, whereas high profitability crops (vegetables) would still be cultivated.

5.9 Policy implications

The increasing risk of limited water availability raises the question of relevant policy implications in the future. This thesis contributed relevant information about how farmers on Gotland would react in different scenarios if climate change occurs. Based on the results, relevant policy instruments can be formulated, such as subsidies to cover the increased production costs if the same level of productivity is to be achieved. Instruments limiting the use of the water resource so that it is used sustainably should also be considered.

In rainfed areas such as Gotland, farmers are strongly dependent on the rain parameter, which is beyond their control. The fact that the climate is changing and the outcome is uncertain increases the risks for farmers. In order to continue producing crops in the area, farmers might need some kind of security grant if there is a bad cropping year.

The analysis of varying the cost of irrigation in scenario S2 revealed that it resulted in the largest effect on arable crops, which are crops that are often used in the human food chain. If the same calorie production is to be maintained, a subsidy covering the irrigation cost for these crops is probably necessary.

The ethical aspects of the research question are also relevant in terms of policy implications. There are several aspects to consider, e.g. there should be instruments that increase the incentive to produce on Gotland in order to decrease transport of imports, as well as remaining cultural heritage. However, the aspect of sustainable use of the resource for future generations should also be considered. One of Sweden’s environmental targets is to have groundwater of good quality, which means that relevant policy instruments should be implemented. One suggestion is to have environmental labelling on production which tells the consumer how much water has been used and how much is recycled. Water consumption should also be priority for the production of food rather than products to ensure food security. Moreover, the question of a suitable consumer price should be considered in the future, since the production costs are estimated to increase. Increased consumer prices mean a decrease in welfare for low wage earners.

6 Conclusions

Using an optimisation model, this thesis evaluated the economic cost of climate change and adaptation for the agriculture sector on the Swedish island of Gotland. The main results for the different scenarios are presented in Table 4. Overall, all scenarios showed a decrease in net return due to climate change. If the expected climate change occurs, there is a risk for the farmer in the form of decreased revenues. In order to avoid a decrease in the standard of living for people on the island, policy instruments which can help farmers to obtain the same net revenue as at present will be necessary. The main findings confirmed the hypothesis that productivity and net revenue in agriculture will decrease if no adaptation to climate change is made.

Table 4. *Main conclusions of scenarios S1-S3 examined in this thesis*

Scenario	Conclusions
S1	Decrease in net return due to climate change and no adaptation.
S2	Decrease in net return due to climate change. Farmers choose to mainly irrigate vegetables and cultivate less.
S3	Decreased net return due to increased cost of water inputs in production.

The change in net revenue under different climate scenarios and the cost of adaptation were successfully evaluated. Some novel findings in the area of climate change and associated economic conditions were made. The results can help farmers and politicians to devise better adaptation strategies and to prepare for future climate variations, while still maintaining the same level of productivity and net return. The model provided a good reflection of the biology of farming systems and can be a good complement to enterprise-level simulation models, through considering a broader context and optimum use of resources.

6.1 Further research

This thesis assessed the monetary cost of effects of climate change on crop production on Gotland. The review of the literature showed that different future climate effects have been investigated at a similarly complex level using other climate models. The models can be improved in future analysis by applying them at an even higher level of complexity, through including factors such as fertilisers, soil quality, labour shortages, land ownership, pests, capital investments, livestock production, abilities and skills.

Location-specific research, as performed in this thesis, improves understanding of farm practices, needs and responses to climate change. Complementing the focus on farm-level decisions, further research should consider non-farm level decisions for the area. The cost of using the water resource depends on several factors, where policy makers play a major part. By extending the research on sustainable use of the resource, the financial, environmental and resource costs can be computed and the resource can be priced correctly and used efficiently. The long-term development and implementation of irrigation projects requires government planning, finance and initiatives, but such projects can significantly improve crop yields.

Since climate effects often appear over a number of years, one important feature is the period covered by the study. A good way to examine the effects of climate change would be to consider a longer period than applied in this thesis. Including socio-economic factors such as population, growth, income and economic development in a future model could also improve the results. Finally, use of an improved yield-water relationship function, determined by field experiments in the study area, in future analysis might give better fitted data for the area.

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Appendix

Table A1. Presentation of the papers used for finding a relevant yield function for the present study

Author	Year	Inter-cept	Coeff water	Square coeff water	Interaction between water and other coefficients	Other variables
A. Azizian, A.R Tavakoli, A.R Sepaskhah	2006	-4.28	11.78	-3.78		N=0.03 N^2=0.00000854
N.L. Castanheira, M.L. Fernandes, M.C. Goncalves, J.C Martins, A. Prazeres, T.B Ramos, F.L Santor	2008	681.87			WNa^+=0.000719	Year= 66.91 Na^+ =-0.5353 $(Na^+)^2$= -0.000102 Soil =-100.62 N=46.63 N^2=-1.7382
R.B Gardner, R.L Roth	1989	0.5065	0.000156	−0.0000001	WN= 0.00000138	N=0.00431
A.M. Featherstone, Richard V. Llewelyn	1996	194.12	206.22	-2.12	WN=0068	N=48.10 N^2=0.08
A. Dinar, P. Nash, J.D Rhoades, B.L. Waggoner	1991	-3.350	0.2064	-0.0014	QC=-0.071 QS=0.033	C=3.555 C^2=2.326 S=-2.031 S^2=0.823 CS=-2.754

Mean yield

There are two yield levels in Agriwise, '*norm*' which refers to the standard level and '*hög (high)*' which refers to 20% higher yield. In all calculations, the standard level was used. Carrots and onions did not have specific calculations for Gotland, and instead the area Gss in Agriwise was used.

Table A2. Mean yield values used in the calibration. Data presented in kg/ton

Arable crops	**Mean yield**
Winter wheat	6302
Spring wheat	4323
Winter barley	5087
Spring barley	4390
Rape seeds	3677
Spring rape	1841
Oats	3767
Coarse feed	5783
Peas	3038
Vegetables	
Potatoes	32 585
Onions[1]	24 642
Carrots[1]	60 318

[1] Data obtained from SBA

Modified enterprise budget

Table A3. Modified enterprise budget structure used to calculate income and costs in the thesis

Income variables
Income from crop
Subsidies
= total income
Cost variables
Seed
Fertilisers
Pesticides
Machinery, fuel and lubricants
Custom hire and rental
Operator and hired labour
Other variable costs
Operating interest
Insurance
Depreciation
Other fixed costs
= total cost variables excluding water
Water costs
= total cost variables for crop production

Cultivated crops on Gotland

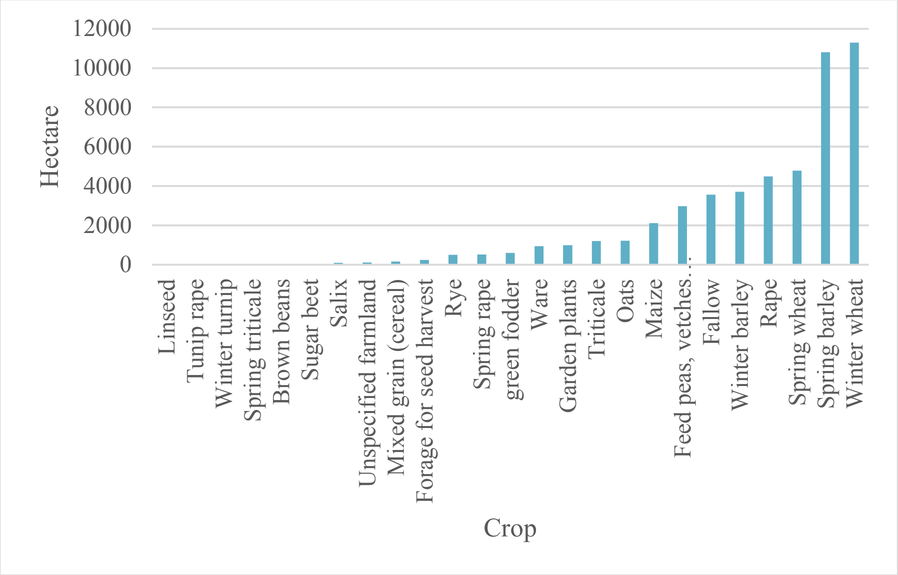

Figure A1. Usage of agricultural area on Gotland in 2016. The vertical axis shows the total areal use in hectares per cultivated crop. Source: SBA database.

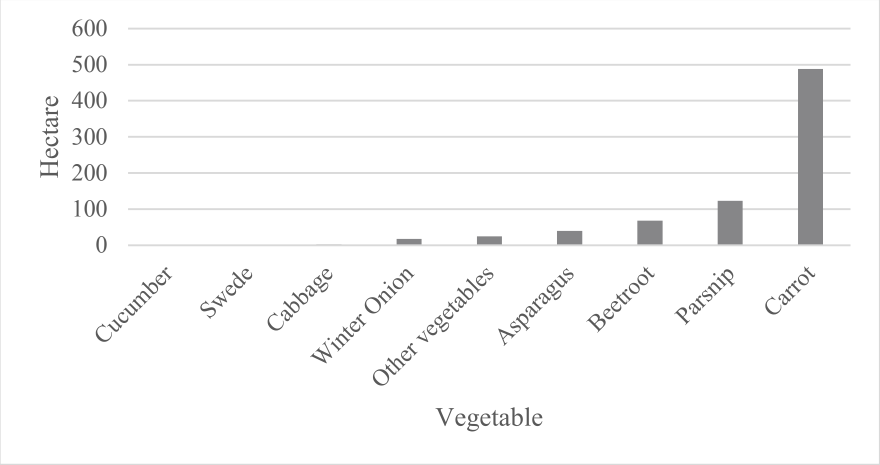

Figure A2. Usage of agricultural area for vegetables in 2014. The vertical axis shows the total areal use in hectares per cultivated vegetable crop. Source: SBA database.