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Department of Economics

Precision Agriculture
- A study of the profitability in a Swedish context

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Precision Agriculture

- A study of the profitability in a Swedish context

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Abstract

A comparison within the European Union (EU), reveals that the Swedish agricultural sector is at a lower rate than other comparable countries regarding competitiveness. The low rate of competitiveness is an adverse development for Sweden, and according to a yearly report created by LRF Konsult the profitability of Swedish grain farming is low (SJV, 2014; www, LRF, 2017). One method to improve the profitability in the agricultural sector is to apply precision agriculture to the operation (Zarco-Tejada *et al.*, 2014).

The study aims to examine the profitability of applying precision agriculture in a Swedish context. More specifically the study examines how the economic result is affected on a case farm by applying precision agriculture to the crop operation. To examine the profitability of precision agriculture in a Swedish context a mathematical optimization model is developed. This study applies a quantitative method with a deductive approach. The empirical data used is collected from a case farm in Västergötland.

Results from the study indicates that precision agriculture could be a profitable investment for the case farm in the study. The results differ from previous studies, compared to Lawes and Robertson (2011). This study shows a significantly higher profitability increase from implementing precision agriculture. Results display that the case farm would lose less yield under a nitrogen policy implication when using precision agriculture compared to conventional agricultural techniques.

Sammanfattning

Den svenska jordbrukssektorn är mindre konkurrenskraftig i jämförelse med många andra europeiska länder. Den svaga konkurrenskraften leder till en negativ utveckling för det svenska lantbruket, enligt en årlig rapport från LRF konsult är lönsamheten hos svenska växtodlare låg (SJV, 2014; www, LRF, 2017). Ett verktyg för att öka lönsamheten är enligt Zarco-Tejada *et al.* (2014) att implementera precisionsodling.

Studien syftar till att undersöka lönsamheten av att använda precisionsodling i en svensk kontext. Mer specifikt undersöks hur det ekonomiska resultatet påverkas på en fallgård av att implementera precisionsodling i växtodlingen. För att undersöka lönsamheten av precisionsodling utvecklas en matematisk optimeringsmodell.

Studien tillämpar en kvantitativ forskningsmetod med en deduktiv ansats. Den empiriska datan är inhämtad från en fallgård i Västergötland. Resultaten av studien visar att en investering i precisionsodlingsteknik kan vara lönsam för fallgården. Resultaten skiljer sig från tidigare studier, jämfört med Lawes and Robertson (2011) visar denna studie på betydligt högre lönsamhet vid en implementering av precisionsodling. Resultaten visar även att fallgården genom att implementera precisionsodling mer effektivt skulle kunna anpassa sig till en restriktion i kväveanvändning jämfört med än en gård med konventionell växtodlingsteknik.

Abbreviations

PA – Precision agriculture
CA – Conventional agriculture
VRA – Variable rate application
CTF – Controlled traffic farming
Barley – Refers to spring barley

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1 Introduction

1.1 Background

Grain production is of growing importance as the world population increases at an accelerating rate. When a more prominent part of the world population lives as middle class the demand for grain and meat will continue to grow (Godfray *et al.*, 2010). According to Gregory and George (2011), only about 20 % of the future increased food production will originate from the cultivation of land. The rest is dependent on new technology, higher crop intensity, and increasing yields. A problem highlighted by Gregory and George (2011) is the need for increased yield without making environmental compromises. According to Alexandratos and Bruinsma (2012), the grain production needs to increase by 50 % until 2015, visualized in figure 1.

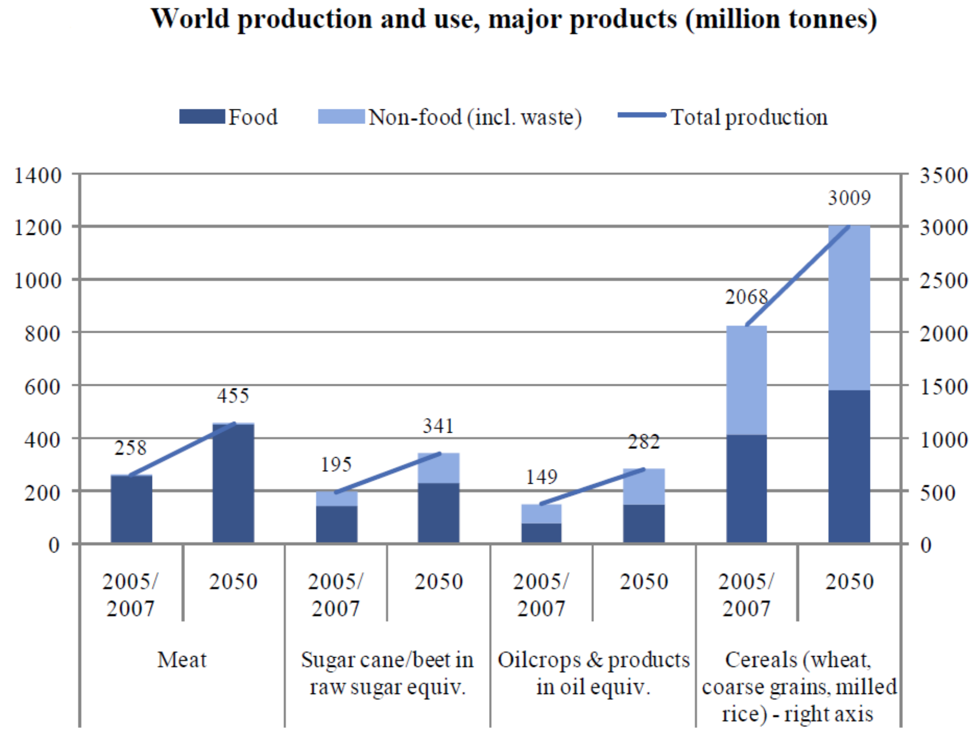

Figure 1: The calculated increase of the most significant product groups in the agricultural sector divided into direct food against feed, Energy and waste (Alexandratos & Bruinsma, 2012).

The market price of grain varies in cycles. When the demand increases the price increases as well. When the price reaches a higher level, the cultivated acreage in the world grows as the farmer's profitability increases. The consumption of grain is nearly constant, but the production can vary due to several factors such as weather. Small changes in the volume of grain produced can have significant effects on the price. This is partly the result of speculation in the futures market (Iwarson, 2012).

Swedish agriculture is dependent on grain production, and around a million hectares are grown on a yearly basis (www, Statens jordbruksverk 1, 2018). In Sweden, the production and consumption of grain are in level at around five million tons. All grain produced in Sweden is not consumed in the country. Major trade streams exist due to export and import (www, scb, 2018).

According to a report from LRF Konsult, the Swedish grain producers suffer from low margins and less to none profitability. The report also discusses the increased level of external funding within the agricultural sector due to increasing investments (www, LRF konsult, 2018). Swedish grain producers cannot effect the world market price of grain and therefore must work with other aspects of their operation to improve profitability (Zarco-Tejada *et al.*, 2014).

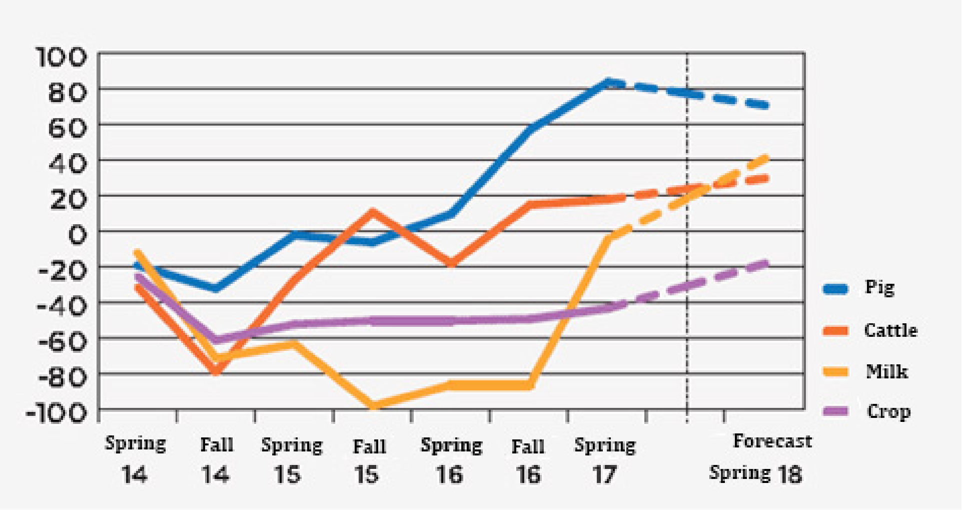

Figure 2: Profitability index (LRFkonsult, 2018).

One tool to increase the profitability in the agricultural sector is to apply precision agriculture (PA) to the operation (Zarco-Tejada *et al.*, 2014). According to the Zarco-Tejada *et al.* (2014) precision agriculture has led to reduced machinery- and input costs and increasing crop yields. Within precision agriculture there are a few different tools available for implementation. Examples are controlled traffic farming (CTF) and variable rate application (VRA) of inputs.

1.2 Precision agriculture

Precision agriculture is a general descriptive term for the technologies designed to support farmers with their crop management. Fountas *et al.* (2006) defines precision agriculture as the management of spatial and temporal variability at a sub-field level to increase economic returns and even reducing the environmental impact of crops.

The concept of precision agriculture is the application of modern technologies and principles to increase the crop performance and reduce the environmental impact. This could be done by managing the spatial and temporal variability associated with production within the agricultural sector (Pierce & Nowak, 1999). The introduction of computers, Global Positioning System (GPS) and agricultural equipment technology has made it possible to use Site-Specific Crop Management (SSM). SSM allows managing fields on a sub-level where it is possible to reference field data to a specific geographical position (Reichardt & Jürgens, 2009; Khanna *et al.*, 1999).

The implementation of SSM was possible because of sensor technology combined with procedures to link mapped variables to general farming activities, for example, seeding, fertilization, and herbicide application. SSM in combination with GPS/ Global Navigation Satellite System (GNSS) has made agricultural methods like Controlled Traffic Farming (CTF) and Variable Rate Application possible (Zarco-Tejada *et al.*, 2014).

A CTF method using GPS/GNSS consists of a traffic scheme where machinery is operated along repeatable tracks. The VRA method is based on a strategy where the application of production inputs and activities are adjusted depending on site-specific conditions within the field, in contrast to using an average level of production inputs and activities all over the field. The goal of such operations is to increase the quality of the products, increase the yield and to have a less impact on the surrounding environment (Zarco-Tejada *et al.*, 2014).

Precision farming is dependent on planning and measurement to determine which measures are to be conducted where and to what extent. The ways of mapping the field can be divided into two different methods, map-based or sensor-based mapping. The map-based approach is a two-step operation where the first step is based on mapping the field with the help of soil analysis. The analysis can be done in different ways, but it intends to map the different soil properties within the field to determine the number of inputs applied in step two of the operation through control files. When using the sensor-based approach sensors are measuring the growing crop when preforming measures in the field such as nitrogen application or herbicide application. The sensors can, for example, measure the color and the biomass of the crop to apply the right amount of input in the different parts of the field (Gustavsson *et al.*, 2015).

According to Aubert *et al.* (2012) precision agriculture creates tools to cope with variation and to manage information efficiently. The authors argue that one problem for PA to overcome is the lack of sector standards. To create a higher integration of PA tools, the different components need to cope with each other. The study also discusses that coordination between different stakeholders within the field of PA would be highly beneficial for the entire sector.

Figure 3 highlights the increased use of precision technology over the past decade. The most significant increase of PA technology is the adoption of GPS guidance with an auto steer function. Increasing use of auto steer and GPS guidance functions increases the possibility of variable rate application of different inputs such as nitrogen, potassium and phosphorus (Zarco-Tejada *et al.*, 2014).

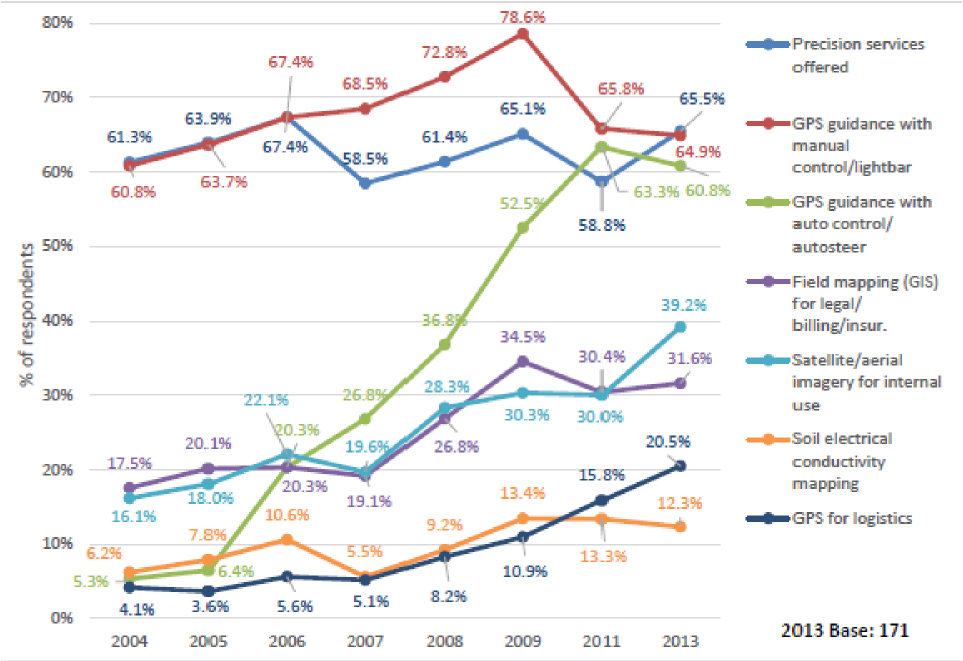

Figure 3: Use of precision agriculture over time (Alexandratos & Bruinsma, 2012).

1.3 Problem

When making comparisons within the European Union (EU), the Swedish agricultural sector is at a lower rate than other comparable countries regarding competitiveness. In a short-term perspective, competitiveness can be defined as an aggregate of price- and cost conditions. The productivity and in a long-term perspective the magnitude of investments play a crucial role. The low rate of competitiveness is an adverse development for Sweden, and according to a yearly report created by LRF Konsult the profitability of Swedish grain farming is low (SJV, 2014; www, LRF, 2017).

A survey of previous research reveals a lack of studies investigating the profitability in the Swedish context when investing in precision agriculture techniques. Previous studies such as Zarco-Tejada *et al.* (2014) argue that precision agriculture can increase the economic result by decreasing costs and improving yield. According to Lambert and Lowenberg-De Boer (2000), who did a review of articles on PA, 73 % of the studies conducted in the field reported positive results from applying PA techniques. Studies conducted by Khurana *et al.* (2008) and Silva *et al.* (2007) displays profitability of adopting precision agriculture techniques in different contexts. These studies indicate the possibility of increasing competitiveness for Swedish farmers by adopting precision agriculture techniques. Earlier research conducted by Elofsson (2003) argues that the use of nitrogen in the agricultural sector has a negative impact on the environment. Precision agriculture technique could provide possibilities to optimize nitrogen allocation in order to lessen the nitrogen use and maintain yield levels (Alexandratos & Bruinsma, 2012).

There are currently no Swedish studies using a optimization model to evaluate the profitability of using variable rate application techniques on a Swedish case farm. In accordance with the arguments listed in Sandberg and Alvesson (2011), the problem localized in this study is a type of gap-spotting. Gap-spotting implies a gap in knowledge. A subject could be overlooked, misunderstood or insufficiently studied. Studies, where precision agriculture is examined on case farms in Sweden, are not well developed. Therefore, the problem is a neglect spotting problem. Research has been conducted regarding profitability of precision agriculture through mathematical optimization and simulation internationally but not in a Swedish context.

1.4 Aim and delimitations

The study aims to examine the profitability of applying precision agriculture in a Swedish context. More specifically the study will investigate how the economic result is affected on a case farm by applying precision agriculture to a rather traditional crop operation for a grain farm.

Research questions:

- What are the economic effects of adopting precision agriculture to the case farm of the study?
- What economic effect do a policy restriction on nitrogen fertilizer have on different scenarios for the case farm of this study?

1.5 Outline

The following section explains the outline and the content of this thesis to give a deeper understanding of the structure. The outline is visualized in figure 4 below.

Chapter two presents the articles relevant for this study in the form of a literature review.

Chapter three presents the theoretical framework consisting of a theory presentation.

In chapter four the methodological approach is presented together with the model developed to reach the aim of this study.

Chapter five presents the empirical findings from developing parameter estimates of collected data. The results from the empirical findings are analyzed and discussed in chapter six. Chapter seven will present the conclusions of the thesis.

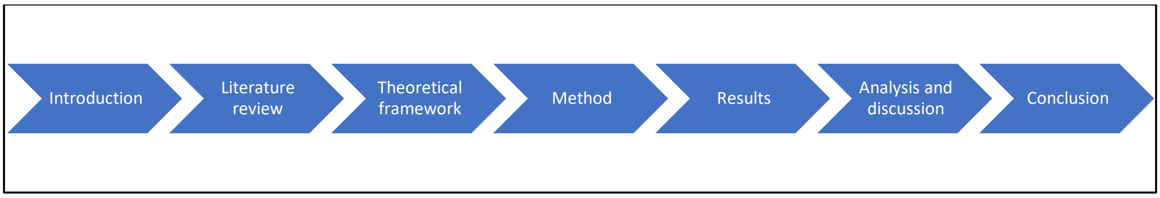

Figure 4: Illustration of the outline of the study (own processing).

1.6 Delimitations

This study focuses on the application of precision agriculture on the case farm Bjertorp and data is obtained from the case farm. The work focuses on the variable rate application sector of precision agriculture. Techniques such as controlled traffic farming will not be considered. The study attempts at first hand to investigate the variable rate application of nitrogen. Potassium and phosphorus will be managed as response function to the applied nitrogen and the yield. The model developed for measuring the profitability requires adjustments to be applicable outside the context of the case-farm Bjertorp. The study evaluated precision agriculture profitability on three different crops, winter wheat, spring barley and oats. According to the statistics wheat, barley and oats are the most common cereals grown in Sweden (www, SJV, 2018). The reason for the choice of these three crops is the commonness and significance of the crops. Organic farming and KRAV-certified production will not be considered in this study.

The study will not consider environmental gains, such as reduction of carbon dioxide emissions, of using precision agriculture. A reduction of nitrogen will be discussed but not investigated in terms of environmental effects, but rather as an economic effect on the case farm. The marginal value of nitrogen is calculated and analysed through a nitrogen restriction policy. Zarco-Tejada *et al.* (2014) suggests there are environmental gains by applying precision agriculture to modern farms. Zhang *et al.* (2002) identified precisions agriculture as an opportunity to meet EU:s goals to reduce agro-chemicals. If Swedish farmers are to adopt precision agriculture techniques, the first step is to examine the profitability (Zarco-Tejada *et al.*, 2014). In a subsequent stage, the environmental gains from using the techniques may be evaluated.

The risk reduction potential of precision agriculture discussed by Lowenberg-DeBoer (1999) will not be considered in this study. The model focuses on economic profitability and will not consider risk reduction or account for changes in expected utility of the technology due to the nature of the aim.

2 Literature review

In this study, a narrative literature review has been applied. The basics of the method is that the researcher reads and interprets literature within a specific field. The aim is to create a deeper understanding of the subject. A narrative literature review may give a rather complete picture of the study area due to the unknown path of the review. By using the narrative form, new literature is generated, and more aspects are taken into consideration. Critique aimed at narrative literature reviews often point out that it is less focused and more extensive than a systematic review (Bryman & Bell, 2015).

The literature search of the study is built around the keywords: Precision agriculture, the profitability of precision agriculture, variable rate technology, variable rate application, optimization and mathematical programming. The databases used in the literature search is Google Scholar, Web of science and SLU:s search service, Primo. The databases contain a broad spectrum of academic material written on SLU and external universities. Material in the literature review is collected from books, academic articles, thesis's and dissertations. By using a narrative literature review, more literature has been generated by having been cited in articles found in the database searches.

2.1 Articles

Table 1: Examples of studies regarding precision agriculture (own processing).

Author	**Subject**	**Region**	**Model**
(Andersson & Wall, 2009)	effects of a restriction in greenhouse gas emissions	Sweden	Optimization
(Aubert *et al.*, 2012)	An empirical analysis of farmers' adoption decision of precision agriculture technology	USA	Qualitative
(Baio *et al.*, 2017)	Financial analysis of the investment in PA techniques on cotton crops.	Brazil	Simulation
(Batte & Arnholt, 2003)	Precision farming adoption and use in Ohio: case studies of six leading-edge adopters.	USA	Qualitative
(Brady, 2003)	Managing agriculture and Water Quality	Sweden	Optimization
(Diederen *et al.*, 2003)	Adoption of innovations in Agriculture.	The Netherlands	Qualitative
(Fountas *et al.*, 2006)	A model of decision making.	Denmark	Qualitative
(Jonasson, 1996)	Mathematical programming for sector application	Sweden	Optimization
(Khanna *et al.*, 1999)	Site-specific crop management	USA	Qualitative
(Khurana *et al.*, 2008)	Agronomic and economic evaluation of site-specific nutrient management.	India	Simulation
(Lawes & Robertson, 2011)	Application of variable rate technology.	Australia	Optimization
(Lowenberg-DeBoer, 1999)	Risk management potential of Precision farming technologies.	USA	Optimization
(Pierce & Nowak, 1999)	Aspects of Precisions Agriculture	USA	Qualitative
(Robertson *et al.*, 2008)	Within-field variability of wheat yield	Australia	Simulation
(Silva *et al.*, 2007)	The economic feasibility of precision agriculture.	Brazil	Simulation
(Zarco-Tejada *et al.*, 2014)	Precision Agriculture: An opportunity for EU farmers.	Europe	Qualitative

Andersson and Wall (2009) conduct a study of the effects of a restriction in greenhouse gas emissions by developing an optimization model to investigate the effects. The conclusions from the study show that effects will vary depending on enterprise structure of the farm. The optimization model in their study will serve as an inspiration for the model formulated to reach the aim of this study.

Aubert *et al.* (2012) analyzes and discusses the adoption of PA technologies and the different reasons behind decisions to invest in various kinds of PA techniques. The study concludes that adoption of PA technology remains relatively low despite positive effects. The article attempt to find an explanation for the low adoption. The authors conclude that many different reasons lie behind the lack of adoption for many farmers, for example, lack of area standards and lack of coordination between stakeholders. Standards are needed to create effective communication between different PA techniques. Integration between sensors, tractors, computers, and GPS is needed to create a working system for PA.

The use of PA techniques reduced the production cost by 6,6 % and increased the operating profit with 7,9 % when compared with conventional agriculture techniques according to Baio *et al.* (2017). In the study, an experiment on a 91-hectare big cotton field was conducted using a simulation method where PA techniques were applied and compared it with a similar field where the conventional farming technique was used. The study also showed a reduction of nitrogen costs with around 41 % when PA techniques where used to vary the application rates. Although the study is applied to cotton, it shows the potential of PA and creates a deeper understanding of the subject for the continued work in this study.

Batte and Arnholt (2003) concluded a study where the objective was to collect information about the adoption and use of PA from early adopters in Ohio. To reach their objective, the authors conducted a case study of six early adoptive farmers in Ohio and then a cross-case summary to visualize the findings. According to the authors, all six farms use of PA has helped them improve their business. The managers of the case farms had split opinions on whether the overall PA system was profitable but all agreed they would continue to adopt new PA techniques as they became available on the market.

Brady (2003) evolves Jonasson (1996) model and uses it to analyze the relative cost of efficiency of arable nitrogen management in Sweden. Brady (2003) model is designed to measure how Sweden scheme of nitrogen abatement instruments affect crop farms in southern Sweden and linked this to coastal nitrogen load. Brady (2003) concluded that increased subsidies to permanently remove land from intensive commodity production could be a cost-efficient supplement to nitrogen control policy in Sweden. In this study, Brady's model is used as inspiration when formulating the precision agriculture optimization problem.

Diederen *et al.* (2003) studied adoptions of innovations in the agricultural sector and the behavior guiding adoption decisions. The authors differs from other studies by not analyzing one single adoption but focusing on a broad range of innovations. According to the authors, the advantage of their chosen method is that the results will be more robust when not linked to a particular innovation. In the study the primary focus is the, search for, handling of and sharing of information concerning innovations, given perfect market conditions (Diederen et al., 2003). The study contribute with knowledge about adopters of PA and the reasons behind using the techniques.

Fountas *et al.* (2006) develop a model to characterize farmer's behavior and decision-making. The model focuses on the decision process when working with information-intensive processes, such as precision agriculture. The author's model contributes with understanding concerning farm managers thought process when making decisions concerning application of PA techniques.

Jonasson (1996) did a thesis where he evaluated mathematical programming as a tool to predict effects of policy changes in the agricultural sector. In the study, two different models were applied, SASM (a Swedish Agricultural Sector Model) and MAP (Model optimizing the use of Acreage and Production). According to Jonasson (1996), both models contribute to interesting aspects of the implication of policy changes. Jonasson (1996) model with production functions will be considered when developing the optimization model in this thesis.

Khanna *et al.* (1999) did a survey of four states in the USA to determine to what extent farmers used site-specific technologies in their farming operation. The conclusions of the study revealed that the rate of adoption was generally low in the four states. A significant portion of the farmers had implemented some PA tool, but many expressed a decision to postpone investing in technology such as variable rate application and yield mapping until further development in the area were completed. The respondents of the survey believed PA techniques would experience a significant increase in the coming five years. The authors of the study argued that young, full-time farmers operating big farms would be the most likely to adopt PA techniques.

The study by Khurana *et al.* (2008) examines and discusses the profitability of using site-specific nutrient management for irrigated wheat in India. The authors focus on managing spatial variations of nitrogen, phosphorus and potassium. Khurana *et al.* (2008) investigate the same management of variations in nutrients as will be conducted in this study. The authors analyze the soil variations, yields and efficiency of applied nitrogen through a simulation model. The authors conclude that the use of site-specific nutrient management scheme could help increasing wheat yields. The conclusions also suggest that site-specific nutrition management could reduce pest incidence associated with excessive nitrogen use and unbalanced plant nutrition.

Lawes and Robertson (2011) use an optimization model to evaluate the effects of using variable rate technology to every cropped field on one farm. The case farm of the study grows wheat on an area of 2800 ha. The results of the study show that VRT technology generate a substantial return in a third of the studied fields. The authors argue the value of VRT will vary between farms depending on the variations in each field. Large variations will lead to an increased value of VRT technology. Lawes and Robertson (2011) also discussed the uncertainty concerning VRT technology among Australian grain growers.

Lowenberg-DeBoer (1999) focuses on the possibility of PA technologies working as a risk management tool. The study uses farm data from six different farmers in Northeastern Indiana, Northwestern Ohio and Southern Michigan. All farms contributed with soil data, information about fertilizers spread and yield data. Conclusions of the study support the hypothesis that precision farming may have risk-reducing effects.

Pierce and Nowak (1999) have similar thoughts about PA as Aubert *et al.* (2012). They identify the possibilities within PA but argue about the need for continuous evolution and integration between all elements. The authors highlight the problem with one type of integrated pest management strategy for entire fields when site-specific needs might be drastically different within fields. By adopting PA site-specific actions can be made within the field and from that it is possible to optimize the production and decrease production costs (Pierce & Nowak, 1999).

Robertson *et al.* (2008) conducted a study on the fields of Australia evaluating the use of zone management of fertilizers. In the study, management zones were created comparing yield data from the fields. The fields were clustered into two to five zones with similar yield. The results of the study suggest that the potential profitability of zone management depends on the soil and yield variations. The authors also conclude that the profit of using zone management increases when the price of grain and fertilizer increases. The work by Robertson *et al.* (2008) is compared with the results of this study.

Silva *et al.* (2007) did a case study researching the profitability difference between conventional agriculture and precision agriculture in Brazil. The study evaluated the effects of both systems on maize and soybean. The researchers aimed to verify the profitability of applying precision agriculture in the region of the case farm in Brazil. The authors concluded that the profitability is higher when using the precision agriculture system, depending on the increased productivity. The authors also found that operating costs were higher in the precision agriculture system.

The report from Zarco-Tejada *et al.* (2014) aims to investigate the potential profitability of precision agriculture. The report investigates all types of PA techniques and concludes that CTF is the most profitable example and that the profitability of VRT depends on several factors (Zarco-Tejada *et al.*, 2014).

2.2 Summary of literature review

The literature review displays that there are some studies in the area of precision agriculture showing the investment to be profitable. Articles found in the literature review also revealed that farmers might be willing to implement the tools in order to improve their business without being sure of the profitability. The gap found in the literature is the lack of investigations of the profitability of PA in a Swedish context. Hence this study aims to contribute to knowledge within the spotted gap. The literature review also displays the different choices of modelling techniques available in order to investigate this phenomena.

3 Theoretical framework

3.1 Applied optimization

Optimization refers to applied mathematics to decide the optimal option in different situations (Lundgren *et al.*, 2001). To create a working optimization model all control variables must be possible to vary. By creating an objective function and adding constraints to the model, it will work to find a feasible solution, a point or area that satisfies all constraints (Griva *et al.*, 2009).

Figure 5 shows the work path when solving an optimization problem according to Lundgren *et al.* (2001). To begin with, the empirical problem has to be identified, which is a complicated process. The problem must then be simplified, and the researcher must make delimitations and decide what's relevant and what to sort out. When the problem is simplified and quantified, a model is developed with an objective function, control variables, and restrictions. To solve the optimization problem programs such as GAMS and Excel solver is suitable (Lundgren *et al.*, 2001).

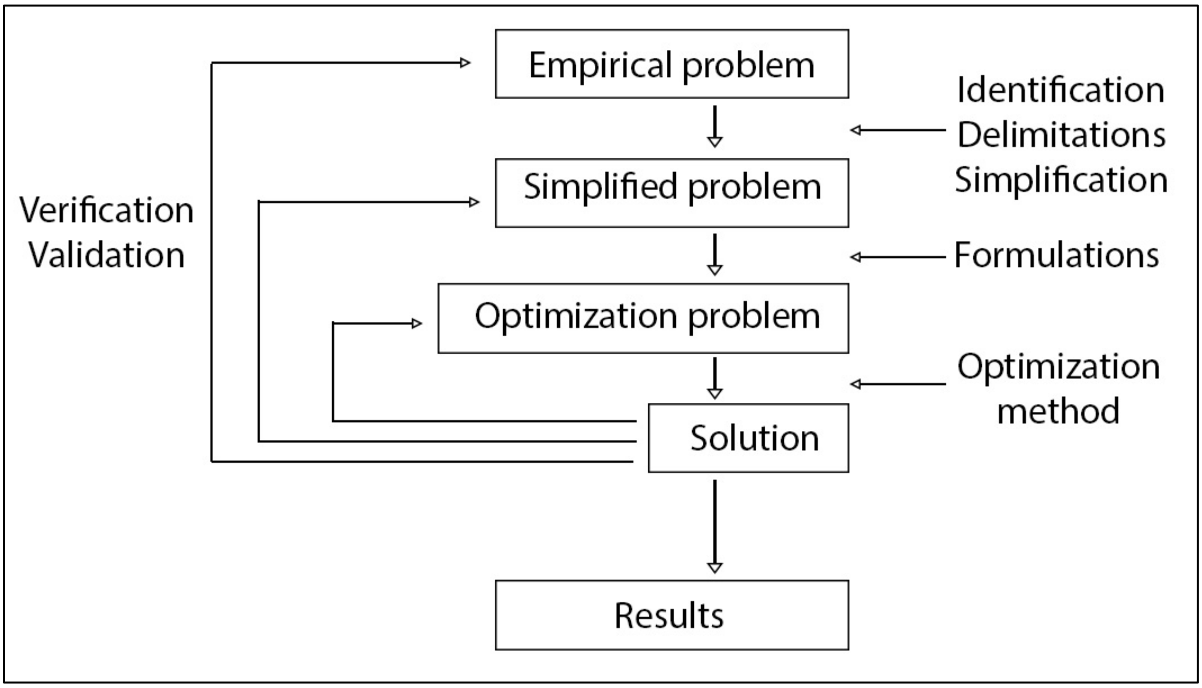

Figure 5: Work path to solving an optimization problem (Lundgren et al., 2001;) (own processing).

Optimization models can be created for both linear and non-linear problem's (Lundgren *et al.*, 2001). A non-linear problem contains at least one nonlinear function. The model used to solve the problem in this study contains nonlinear problems. The objective function is the economic result of the case farm. The economic result is decided from crop yields, crop prices and costs for the farm. The crop yields are dependent on the level of nitrogen application. The problem will be formulated in four different models. Two models with precision agriculture techniques, one with a fixed nutrient ration of 24-4-5 (nitrogen, phosphorus and potassium) and one with the possibility to allocate the nutrients without considering fertilizer formulas where each nutrient can be allocated optimally for each part of a field. These two models with precision agriculture are compared with two models of the same problem but without the precision agriculture possibility and therefore without the costs of using PA. The two models of conventional agriculture are similarly formed like the ones with PA, one with a fixed nutrient ration of 24-4-5 (nitrogen, phosphorus and potassium) and one with the possibility to allocate the nutrients without regard for nutrient formulas.

3.2 Profit maximization

The maximization of profit is divided into two different dimensions, minimization of costs and maximization of revenues. To reach the objective a production level where both the profit maximization and the cost minimization dimensions are satisfied must be found (Debertin, 2012). Equation (1) displays a general form of a maximization problem.

$$\max \pi = P_y * Y - P_x * x_i - FC \qquad s.t. Y \leq f(X_i|U_i) \qquad (1)$$

$$Y \leq 0 \;\; X_i \leq 0 \;\; U_i \leq 0$$

In this case, the profit is denoted (π) and is determined by the total revenues and the total cost. Total revenues are based on the produced quantity (Y) and the commodity price, (P_y). Total cost is dependent on two different factors, one fixed and one variable (Debertin, 2012). The fixed cost is denoted (FC) and is not attached to the level of production. The variable cost is dependent on the input price, (P_x), and the amount of allocated input, (X_i).
According to Debertin (2012), profit maximization through ensuring a maximized output from applied input could be a more comprehensive approach. This approach could be formulated like the display in equation (2).

$$\max \pi = P_y * f x_i - P_x * x_i - FC \qquad (2)$$

3.3 Production function

According to Debertin (2012), a production function is a way to describe a technical relationship where inputs are transformed into output. A general way of writing a production function is displayed in equation 3. Where (Y) represents the output and (X) represent the input. It is valid for every (X) equal to or greater than zero, assigning a value for (Y).

$$Y = f(x) \qquad (3)$$

The production function contains the necessary information to maximize the profit, the inputs contribution to the output product. The input to output relationship and information about the input price and output price provides knowledge of how resources should be allocated to different production activities (Debertin, 2012).

The production functions used to solve the problem in this study is formulated with the help of the general formula referred to in Debertin (2012).

$$Y = f(N) = A + BN - CN^2 \qquad (4)$$

The basis of the function is to calibrate data from different test environments in Sweden and displays average yield when a given amount of nitrogen is applied (Brady, 2003; Jonasson, 1996). Equation 1 is the production function for a given crop at a given site where f(N) is the yield (kg per hectare), (N) is the amount of nitrogen applied, and (A), (B), and (C) are parameters given for each crop and place. The optimal amount of nitrogen applied is dependent on commodity price and input price. The optimal amount of nitrogen applied is calculated from equation (5) where (π) represents the profit per hectare.

$$\Pi = P_y(A + BN - CN^2) - P_nN - TFC \qquad (5)$$

The optimal yield and nitrogen application are given by the relationship in equation (6).

$$\frac{\partial \Pi}{\partial N}: P_y(B - C2N) - P_n = 0 \qquad (6)$$

In this case, the yield improves when more nitrogen is applied until the yield reaches a biological maximum, see figure 6.

$$\frac{\partial f(N)}{\partial N} x\, P_y = 0 \qquad (7)$$

At the optimally biological nitrogen application N(1) is the optimal solution and the revenue is represented by R(1), see equation (4). A line which is the tangent the production function in the economically optimal point, explained by equation (7), represents the relation between product price and nitrogen. If nitrogen would be purchased for free, the economically- and biologically optimal points would be the same.

$$\frac{\partial f(N)}{\partial N} x\, P_y = P_n \qquad (8)$$

Equation (8) gives the optimal nitrogen application N(2) and an economically optimal yield R(2), see figure 6. Figure 6 displays the relationship between yield/revenues and nitrogen application.

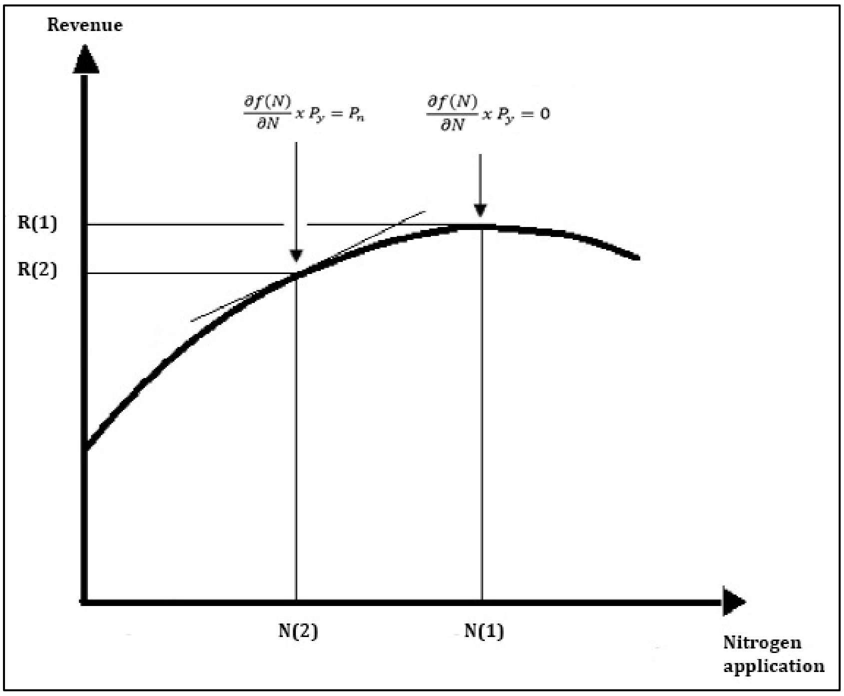

Figure 6: Correlation between nitrogen application and revenues (Debertin 2012; Andersson & Wall. 2009; own processing).

A necessary condition to maximize profits is the fact that $\frac{\partial f(N)}{\partial N} x\ P_y = P_n$, i.e. the slope of the marginal value product is the same as the price, (P_n). The necessary condition does not guarantee that the profit will be maximum, but it represents a circumstance where a maximum profit could be reached. One crucial aspect of the production function is the law of diminishing marginal returns (Pindyck & Rubinfeld, 2014). This law deals with the phenomena that the inputs are characterized by different efficiency at various rates of application. As the input application gradually increases it produces less and less additional output. One way to display diminishing marginal returns is to calculate the marginal physical product (MPP) of an input. MPP refers to the output in relation to a changing input application. MPP shows how much more a unit of input contributes to the production of output. In the case of the study, how much more one unit of nitrogen contributes to yield. Another aspect of diminishing returns and MPP is to use product prices in relation to MPP, the value of the marginal product (VMP). The definition of VMP is the value of one additional unit of input when the output is sold to a market at a constant price. VMP gives the information of how one additional input contributes to the revenues in total (Debertin, 2012).

3.4 Alternative theoretical approach

The theory of applied optimization allows the researcher to examine the normative picture of the problem. The applied optimization theory with support in Jonasson (1996) and Brady (2003) work allows the questions concerning profitability of PA to be answered through a quantitative assessment.

One theoretical approach including management theories and aspects could lead to increased understanding of underlying managerial factors affecting investment in PA. This study could have been carried out in a similar way of Batte and Arnholt (2003) where early adopters of PA in Ohio were researched to discover what factors drove the innovation of PA techniques. A similar study carried out in Sweden would increase the knowledge of the reasons behind investing in PA. If the study aimed to investigate the underlying factors of investing in PA, the study by Batte and Arnholt (2003) would be highly useful.

Studies conducted by Aubert *et al.* (2012) and Pierce and Nowak (1999) examine the reasons behind a slower than expected adoption speed of PA techniques. A similar approach would be interesting in a Swedish context. The study could be conducted with a qualitative approach where farmers where interviewed about their thoughts about precision agriculture and why/why not they used a particular technique.

In order to create a normative model to be able to examine the economic potential of the problem the theoretical choice of applied optimization deems to be the best choice available. The theory allows the researchers to examine the mathematical connections between precision agriculture and increased revenue in the case firm of this study.

An alternative method as opposed to optimization is simulation (Aronson *et al.*, 2005). The use of simulation to the studied problem of this study would indicate the most probable outcome of investing in precision agriculture. The objective of the study would thereby be to investigate the profitability between two alternative crop operations. The optimal solution is needed in order to support decision making. However, this approach does not secure that neither, precision agriculture or conventional systems are managed in an optimal manner.

4 Method

4.1 Research strategy

The study aims to examine the profitability of applying precision agriculture in a Swedish context. The choice of research method is essential to discuss according to Robson and McCartan (2016). The choice of method could lead the study in different directions. To achieve the aim of this study, a quantitative approach is implemented. A quantitative method differs from a qualitative method by mostly using numbers and focusing on theory testing instead of creating theories (Bryman & Bell, 2015). A quantitative method is known to focus on the view of the researcher and not the view of the participants. In figure 7 below a typical quantitative research process is illustrated according to Bryman and Bell (2015).

The ontological standpoint of this study is objectivism. This means that there is an objective reality. Obejctivism refers to phenomena independent of social actors. The profitability of precision agriculture is seen as a technological phenomenon where the role of social actors is somewhat reduced. The authors can examine the profitability of precision agriculture from an external point of view. The authors have used a positivistic epistemological standpoint, where a theory is applied to an empirical problem in order to examine the issue (Bryman, 2015).

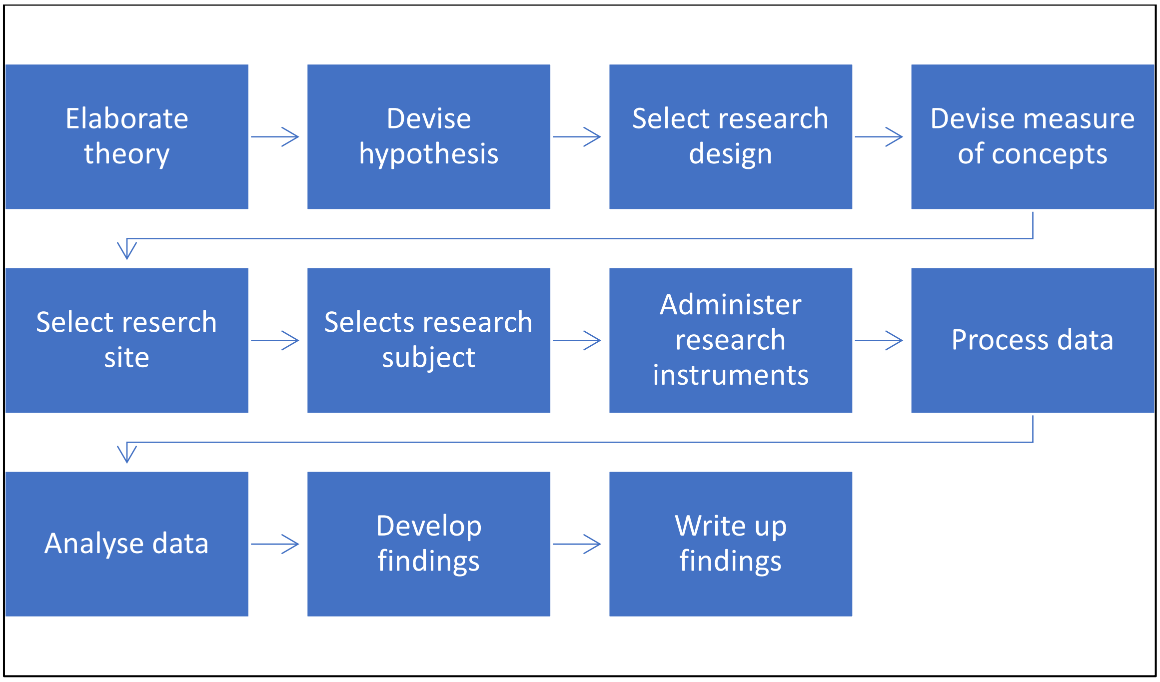

Figure 7: The process of quantitative research (Bryman & Bell, 2015; own processing).

The quantitative method fits the aim of the study considering that no subjective values will be considered. The data will for the most part, consist of numerical quantitative data. The empirical data consists of nitrogen application data, measurement of the soil and harvest yield for different locations in each field.

Although there are differences between qualitative and quantitative research methods, they still display similarities. For example, both quantitative and qualitative research have to work with data reduction to make the data more accessible to analyze. They both strive to answer research questions, and they both have to relate their data analysis with the research(Robson & McCartan, 2016; Bryman & Bell, 2015).

When working with a quantitative method researchers are often concerned with the generalizability of the work outside the studied context. The concerns regarding generalizability will be an important discussion point in this study since data is collected from one single farm to develop the optimization model (Bryman & Bell, 2015).
A deductive approach is applied. In the deductive approach, the theory is applied to the empirical data. In this research, it is essential to conduct a thorough literature and theory review. The central theory applied to the data in this study will be microeconomic theory through applied optimization, which will allow a model to be created to investigate the profitability of PA. The deductive approach allows the researcher to formulate questions and/or hypothesis stemming from existing theory and collect data to test the formulated questions and hypothesis (O'Reilly, 2008). In the case of this study, an inductive approach does not fit the aim. The data is not collected to generate theory, but the theory is used to evaluate data. Without the theory of applied optimization, the data would be difficult to process (Bryman & Bell, 2015).

It exists two different alternatives when coming to the decision of modelling, normative and descriptive. The descriptive model often generates a more comprehensive understanding of the problem. The problem with using a descriptive model is that the result is not equivalent to the best decision alternative. One example of a descriptive model is simulation. The normative model attempt to generate the best decision alternative but might not generate the same level of comprehensive understanding as the descriptive alternative. A normative model is often referred to as an optimization model. This study aims to investigate the best decision out of the alternative to applying precision agriculture or to keep using conventional methods, and therefor will use the normative approach to modelling (Aronson *et al.*, 2005).

Hence, in this study a normative model is applied in order to answer the research questions. If a descriptive model, simulation, where to be used, the answers would refer to the most likely event of investing in precision agriculture. To answer the research questions the most likely event is not sufficient. Therefore a normative model, more precisely an optimization model, is used. The method of optimization is sufficient to answer the research questions because of suppling the optimal solution to the problem of investing in precision agriculture or not.

4.2 Research design

To reach the aim of this thesis, a case study form will be adopted. Case studies allow the researcher to study single or multiple cases to understand a phenomena. Case studies are often connected with qualitative research but can be successfully used in quantitative research as well (Mills *et al.*, 2009). To be able to reach the aim of this study a limitation to one single case is required to develop a working model. In this case, the farm Bjertorp in Västergötland will be used as the unit of analysis.

The reason for choosing Bjertorp is the amount of collected data from the fields. During many years yield, soil mapping and nitrogen application are documented for each field, which allows the researchers to reach their aim without having to collect all primary data from the field (pers. comm., Wetterlind, 2018).

Case studies allow the researcher to study decisions and consequences of those decisions. This study will investigate the consequences of investing in PA for the case farm. The model is developed adhering to relevant objective functions and constraints. The critique of case studies is often concerned with generalizability of the results (Yin, 2003).

The case study will be constructed as an experimentary study (Bryman & Bell, 2015). Since only one case farm is used, two models will be constructed showing different scenarios. One model assumes using precision agriculture tools with unique production functions for every hectare sized sample and one model with general production functions for each crop. This will allow the case to be analyzed as an experimentary case study with different scenarios. The nitrogen levels, profit levels and yield levels will be compared between both models and conclusions will be drawn.

4.3 Quality assurance

4.3.1 Reliability

Reliability is concerned with the consistency in the measure of a concept. There are three key factors to consider when examining the reliability of measurement, stability, internal reliability and inter-rater reliability (Yin, 2003). Stability is concerned with the change of a measurement over time, is the data stable over time or does it vary. Internal reliability handles the possibility of different data combined doesn't focus on the same phenomena and can not successfully be combined. Reliability also focuses on the possibility of lack of consistency in decisions such as sorting, categorizing and coding data. If the researchers are not consistent with the categorizing etc. there is a risk that data is not handled consequently (Bryman & Bell, 2015).

4.3.2 Validity

Validity refers to whether the gathered empirical data answers the question that was initially formulated or not. Validity concerns if conclusions drawn from a completed study is connected to one another (Yin, 2003). When testing the validity, the authors of this study plan to apply face validity. When using face validity, the researcher hands their work to another person for review. The person should have experience in the researched area to be able to assess if the empirical data is in line with the research question and aim (Bryman & Bell, 2015).

External validity is concerned with the possibility to generalize the results of the study outside the studied context (Mathison, 2005). External validity is the main reason for quantitative researchers to are keen to generate representative samples according to Bryman and Bell (2015). Case studies with only one case is problematic to generalize to different cases in contexts outside the studied one (Yin, 2003).

4.4 Data collection

Data needed to complete the study is collected from different sources. The data on soil analysis and harvest measurements is supplied by SLU (pers. comm., Wetterlind, 2018). The data needed on the nitrogen application levels from each part of the field is supplied by Yara (pers. comm., Nissen, 2018). Data concerning the price of different input variables, such as nitrogen, phosphorus, and potassium is gathered from Agriwise for the years analyzed in the model (www, Agriwise, 2018). The cost of buying precision agriculture services is provided by advice from an anonymous source in the industry.

All data used in this study is secondary data. Bryman and Bell (2015) list many advantages of using secondary data. The data allows the researcher to use quality data without spending time and money on collecting it first-hand. In the case of this study, the data used is collected by researchers at SLU and allows more time spent on creating a working optimization model instead of collecting data. Soil samples were collected from the fields of Bjertorp creating nutrient maps used in this study. The yield data of the different crops are collected from the combine when harvesting at Bjertorp. The nitrogen application levels are gathered from N-sensor spreading files. Due to the time limit of this study secondary data is preferable to increase time spent on the analysis of results. Some limitations with using secondary data according to Salkind (2007) such as the lack of familiarity and the complexity of the data. To receive an understanding of collected data in this study the authors were invited to work with the data processing together with SLU researcher Johanna Wetterlind.

The sampling is a type of non-probability sampling. Each field in the study is divided into hectare sized squares. The soil analysis data used in this study was conducted with one test per hectare, and that is the reason for the use of hectare sized samples in this study. The yield- and nitrogen application data are represented by more than one point per hectare. This problem is solved by using a mean of all points within each hectare sized square. The use of probability sampling could give a highly misguiding result in this study due to the risk of only using high or low yield points in one field and miss the variations within the field (Salkind, 2010).

4.5 Data processing

To prepare the collected data for the optimization model it is processed within the program ArcMap. The received data considering soil and harvest yields were supplied by Wetterlind in the form of text files. The text files needed processing in a geospatial processing program to give the type of data needed in this study (Salkind, 2010).

ArcMap is used to create a grid and select research points in each field of the case farm. In the selected fields of the case farms the research points consist of data concerning soil, harvest yields, and nitrogen application levels.

The cost of precision agriculture is based on a number of factors, costs of machinery, navigation techniques (GPS) and services allowing the farmer to map the fields, such as soil mapping. The machinery cost is calculated using values from Agriwise on buying a new fertilizer spreader, costs from Yara on buying a nitrogen sensor and data from a machinery salesperson on navigation equipment (Agriwise, 2018). The fertilizer spreader needs to be compatible with control files or an N-sensor to be able to use variable rate application. One crucial aspect for the investment of precision agriculture is the amount of tillable land the farm operates. In this study a farm of 300 hectare is used, because of the size of the investment, it is assumed that the most likely farmers to adopt the variable rate technology are farmers who are able to operate the farm as a full-time occupation. Therefore, it is suitable with a farm of 300 hectares. Given the size of the farm, the capital cost amounts to 254 SEK per hectare and year (see appendix 1).

4.5.1 Production functions

The production functions are formulated as response functions to nitrogen in the same manner as Brady (2003). The reason for not considering potassium and phosphorus in the functions is the lack of general knowledge concerning relationships between them and crop yield (Bäckman *et al.*, 1997; Sinclair & Park, 1993; Frank *et al.*, 1990; Paris & Knapp, 1989). The crop yields are based on the production functions developed by Jonasson (1996). The production functions from Jonasson (1996) cannot be directly applied to the case farm but will be calibrated with empirical data collected from the farm Bjertorp.

To calibrate the production functions to fit the regional variations a factor called LQF is used to fit the function into the harvest area where Bjertorp is located. The LQF factor is multiplied by the production function for each crop. The new production functions do not equal to the actual yields of the case farm, to solve this issue a method developed by Jonasson (1996) and applied by Brady (2003) is used to calibrate the functions. Brady and Jonasson assume farmers always act rationally and use the optimal amount of nitrogen in relation to factor- and product prices. By calculating the adjustment factors feta (θ) and delta (δ) the intercept and inclination are configured. The data used in the calibration stems from the empirical data collected from the case farm and data collected from region-specific capital budgeting sheets in Agriwise (www, Agriwise, 2018), the average price of nitrogen ($\overline{P_N}$), average nitrogen application level ($\overline{N}$), average yield ($\overline{Y}$) and the average price for the products. The adjusted production functions are determined according to equation 9.

$$Y = \theta(a + \delta bN - cN^2) \qquad (9)$$

Economically optimal nitrogen application rate is then calculated applying equation (9) to equation (10).

$$\frac{P_N}{P_Y} = \theta(\delta b - 2c\overline{N}) \qquad \overline{N} = \frac{\theta\delta P_y - P_N}{\theta_{2cPy}} \qquad (10)$$

By solving $\theta$and $\delta$from equation, (9) and (10) Equation (11) and (12) are developed. By first solving $\delta$from equation (11) θ can be solved from equation (12).

$$\delta = \frac{\overline{P}_N a - \overline{P}_N c\overline{N}^2 + 2c\overline{N P_y}\overline{Y}}{b\overline{P}_y\overline{Y} - \overline{P}_N b\overline{N}} \qquad (11)$$

$$\theta = \frac{\overline{P}_N}{\overline{P}_y \delta b - 2c\overline{N P_y}} \qquad (12)$$

The calibration factors for the crops are used to calculate the new constants $\hat{a}, \hat{b}$ and $\hat{c}$.

$\hat{a} = \theta_a$
$\hat{b} = \theta\delta_b$
$\hat{c} = \theta_c$

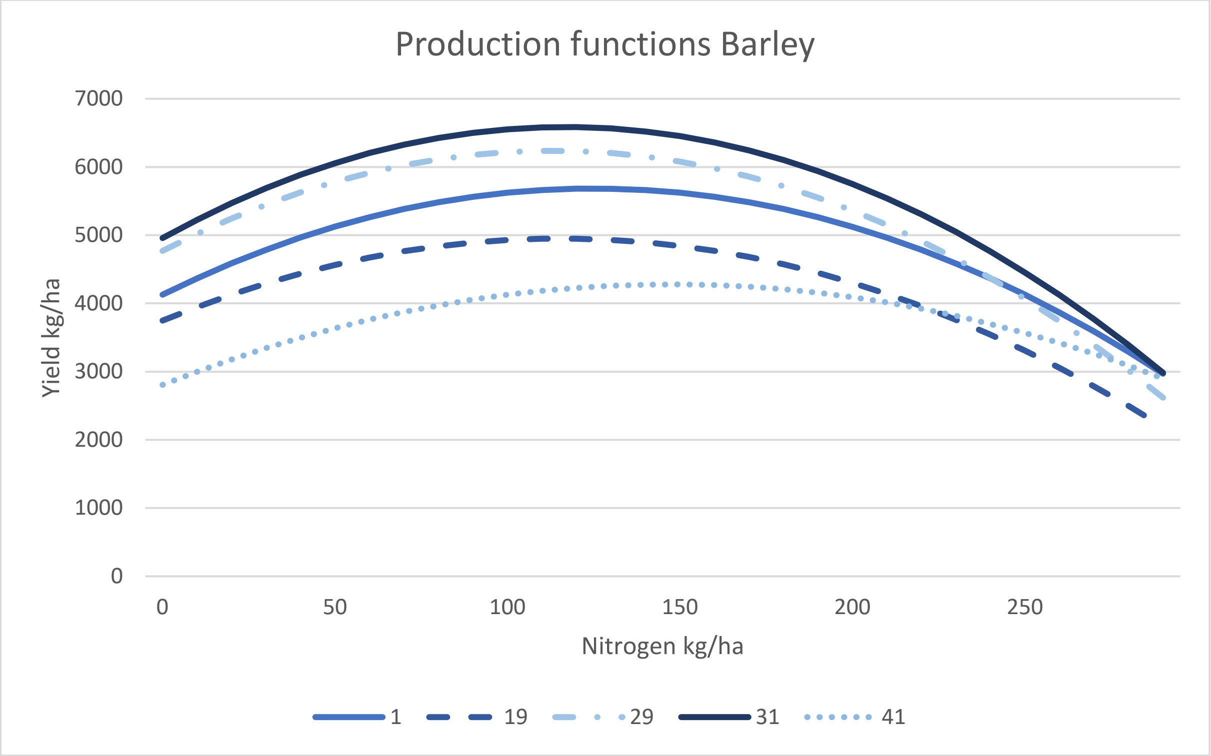

Figure 8: Site-specific production functions for barley (own processing).

Figure 8 shows the site-specific production functions for Barley adjusted according to the methods explained in equation (9)-(12). The visualization of the different production functions shows how the growing conditions for spring barley varies within one field. The production functions do not consider the price of nitrogen, and the curves show the optimal biological application of nitrogen where the gradient is equal to zero. The values for all production functions are available in appendix 2.

4.6 Applied modeling

The model of the case farm is built on production functions based in material from Jonasson (1996) and altered by the method used by Brady (2003) and Jonasson (1996). This allows modifications to the production functions where they are fitted to the local attributes of the case farm. This procedure provides a more accurate output data from the production functions to correlate with the biological data from the case farm, including yield- and nitrogen application as well as data from three different crops: winter wheat, barley and oats.

The field is divided into management zones depending on productivity levels and is fitted to the width of a fertilizer spreader to recreate a realistic working path for the management of the field. The historical data from the case farm are both used to divide the fields into management zones and to allocate an adjusted production function fitted to each of the zones and allocate soil properties to each zone. This provides the possibility of calculating the differences between a scenario where the farm does not have the possibility of using precision agriculture as opposed to conventional technique, where the field is managed the same way all over the field. When the farm has the possibility of using precision agriculture, it will be possible to use the management zones and therefore to apply the right amount of input to each zone instead of using a mean application all over the field. This procedure allows the model to take nitrogen-, phosphorus- and potassium application into account. There are two different scenarios regarding the phosphorous and potassium application, one scenario where the application is dependent on the nitrogen application. The other scenario provides the possibility of applying the optimal amount of each nutrient in relation to the yield and variable cost of each hectare of grown crop.

In addition to the variable costs of nitrogen, phosphorus and potassium, a fixed cost is allocated to each hectare of grown crop. This cost covers the capital cost for precision agriculture equipment.

In the case of phosphorous and potassium, this study uses two methods of handling the crop requirement of these nutrients. The first method uses a nutrient formula of 24% nitrogen, 4% phosphorous and 5% potassium as can be found in conventional fertilizers on the market in Sweden (www, Yara, 2018). The second method handles these requirements as a response function to yield. When using this model the amount of every nutrient is unrelated to each other which gives the model the opportunity to optimize the use of these nutrients. This method also uses the soil data to from the fields to balance the nutrient application in relation to the amount of nutrients in the soil. The methods are compared to each other to analyze which model is the optimal to use.

To visualize the optimization problem, it is shown in the algebraic form below.

$$Max\ L\ (x_{sj}N_{sj}F_{sj}K_{sj}){:}\ \sum_{j=1}^{J}\sum_{s=1}^{S}(x_{sj}P_{yj}f_s(N_{sj})) - \sum_{j=1}^{J}\sum_{s=1}^{S}\left((P_nN_j + P_fF_j(N_{sj}) + P_kK_j(N_{sj}) + c_jx_{sj})\right) - \sum_{j=1}^{J}x_jinv \quad (13)$$

Under constraints;

$$\sum_{j=1}^{J}\sum_{s=1}^{S}x_{sj} \leq \bar{A} \quad (14)$$

$$\sum_{j=1}^{J}\sum_{s=1}^{S}N_{sj}x_{sj} \leq \bar{N} \quad (15)$$

Where;

x_{sj}	Crop j of site s
P_{yj}	Income for one kg of crop j
$f(N_{sj})$	Yield per hectare of crop j at site s
N_{sj}	Nitrogen requirement for crop j at site s
c_{xj}	Variable cost per hectare of crop j excluding nutrients
P_n	Price of nitrogen
P_f	Price of phosphorous
F_j	Phosphorous requirement for crop j as related to crop yield
P_k	Price of potassium
K_j	Potassium requirement for crop j as related to crop yield
inv	Capital cost per hectare of precision agriculture equipment
$\bar{A}$	Areal constraint
$\bar{N}$	Nitrogen constraint

In order to solve the maximization problem both of the constraints has to be fulfilled (Lundgren *et al.*, 2001). The total area of tillable land is limited and can reach to the maximum of $\bar{A}$, see equation 14. The required nitrogen (N_{sj}) is dependent on the choice of crop, the number of hectares where the crop is grown and the nitrogen requirement of the specific crop, which is dependent on the production functions. By summing up the nitrogen requirement per hectare and the acreage to an aggregated nitrogen requirement, the total nitrogen requirement $(\bar{N})$ is assessed. The functions for calculating the requirement of phosphorous and potassium are response functions of the nitrogen application, i.e. the expected yield, for each grown crop and, in the scenarios where precision agriculture techniques are available, the soil properties at the different sites are taken into consideration. The objective function is composed into two different parts, the first where the revenues and the fixed cost per hectare of a grown crop are collected. In the second part, where the variable costs of nitrogen, phosphorous and potassium are collected.

The maximization problem with three different crops as modelled empirically is formulated in equation 16.

$$\begin{aligned} Max\ L(\ x_{s1}x_{s2}x_{s3}N_{s1}N_{s2}N_{s3}\lambda_1\lambda_2\ ) : & \textstyle\sum_{s=1}^{S}(x_{s1}P_{y1}f(N_{s1}) + x_{s2}P_{y2}f(N_{s2}) + x_{s3}P_{y3}f(N_{s3})) - \\ & \textstyle\sum_{s=1}^{S}(c_{x1}x_{s1} + c_{x2}x_{s2} + c_{x3}x_{s3}) - \sum_{s=1}^{S}(P_nN_{s1}x_{s1} + P_nN_{s2}x_{s2} + \\ & P_nN_{s3}\,x_{s3}) - \textstyle\sum_{s=1}^{S}(P_fF_1f(N_{s1})x_{s1} + P_fF_2f(N_{s2})x_{s2} + \\ & P_fF_3f(N_{s3})x_{s3}) - \textstyle\sum_{s=1}^{S}(P_kK_1f(N_{s1})x_{s1} + P_kK_2f(N_{s2})x_{s2} + \\ & P_kK_3f(N_{s3})x_{s3}) - \textstyle\sum_{s=1}^{S}\sum_{j=1}^{3}(invx_{s1} + invx_{s2} + invx_{s3}) \end{aligned}$$

$$+\lambda_1(\bar{A} - (x_1 + x_2 + x_3))$$

$$+\lambda_2(\bar{N} - (\textstyle\sum_{j=1}^{J}\sum_{s=1}^{S}N_{sj}x_{sj})) \qquad (16)$$

The first derivative of $x_1, x_2, x_3, N_{s1}, N_{s2}, N_{s3}, \lambda_1, \lambda_2$ represent the first order necessary conditions to maximize profit of equation 16 with regard to the restrictions in the model (Debertin, 2012). When the maximization problem is solved with regard to all the control variables and set equal to zero, the marginal values can be defined. The marginal value of one more unit of land is calculated through equation 17.

$$\frac{\partial L()}{\partial x_{s1}} : P_{y1}f(N_{s1}) - c_{x1} - P_nN_{s1} - P_fF_1f(N_{s1}) - P_kK_1f(N_{s1}) - \lambda_1 - \lambda_2N_{s1} - inv = 0$$

$$\lambda_1 = P_{y1}f(N_{s1}) - c_{x1} - P_nN_{s1} - P_fF_1f(N_{s1}) - P_kK_1f(N_{s1}) - \lambda_2N_{s1} \qquad (17)$$

The marginal value of nitrogen is after some simplification calculated through equation 18.

$$\frac{\partial L()}{\partial N_{s1}} : P_{y1}\frac{\partial f(N_{s1})}{\partial N_{s1}} - P_n - P_f\frac{F_1\partial(N_{s1})}{\partial N_{s1}} - P_k\frac{K_1\partial(N_{s1})}{\partial N_{s1}} + \lambda_2 = 0$$

$$\lambda_2 = P_{y1}\frac{\partial f(N_{s1})}{\partial N_{s1}} - P_n - P_f\frac{F_1\partial(N_{s1})}{\partial N_{s1}} - P_k\frac{K_1\partial(N_{s1})}{\partial N_{s1}} \qquad (18)$$

From the equations 17 and 18, the marginal value of nitrogen and land are obtained. The values give information regarding how the farmers profit would change when the restriction i.e. the b_i-value, is increased with one unit. The λ_1-value from equation 17 shows how much profits would increase if the available land would increase with one unit. The λ_2-value from equation 18 gives information regarding how the profit increases from being allowed to use one more unit of nitrogen. If λ_2 is equal to zero, i.e. the nitrogen constraint is not binding, equation 18 has to be equal to zero. This implies that the optimality condition for nitrogen is site specific for each crop. In addition to the traditional optimality condition $P_{y1}\frac{\partial f(N_{s1})}{\partial N_{s1}} - P_n = 0$ for nitrogen application, the phosphorous and potassium application also affect the optimality condition.

4.7 Motivation of choosen method

The point of the study is to measure the profitability of precision agriculture in a Swedish context and to reach the aim a quantitative method is used. The choice of a normative approach is justified by the need to examine the best possible alternative of investing in precision agriculture. The main critique of the chosen method according to Bryman and Bell (2015) is the problem with generalizing the results and the model. The profitability might be correct in the context of the case farm but might not be the same on different Swedish farms. The production functions developed in the study might be site specific to a degree where it could be hard to generalize to other cases and geographical areas. Generalization outside the context of the case farm would be based on the reader's opinion and judgment (Yin, 2003).

4.8 Ethical issues

Ethics is important in research according to Robson and McCartan (2016). Oliver (2010) states that all information must be authentic to the originally collected data. If the data is altered in any way it does not only affect the reliability of the study but jeopardizes the relation between researcher and informant. To avoid misunderstanding between informant and researcher the researcher has been open about the objective of the study, which other stakeholders who will contribute with data and which way the data will be used.

One question associated with the ethical issues of the study is to consider if the informant has incentives to contribute with inaccurate information. The data on yields and soil originates from SLU. The goal of this thesis is to present the model, data and findings in a fair way and to highlight the possibility of different interpretations and conclusions of the results (Oliver, 2010).

5 Results

In the following chapter, the results of the optimization model is presented.

5.1 Empirical data

The collected data in the study consists of crop yields, data from soil analysis, price levels of fertilizer, crops and general costs for the growing of different crops during the years 2010-2015. Data is collected for the crops winter wheat, barley and oats. Fertilizer costs, market price of the crops and the general cost for each crop is collected from Agriwise and is a mean of the years used in the study. Soil analysis data is provided by Johanna Wetterlind, SLU, from field measurement on the specific fields of the case farm used in this study.

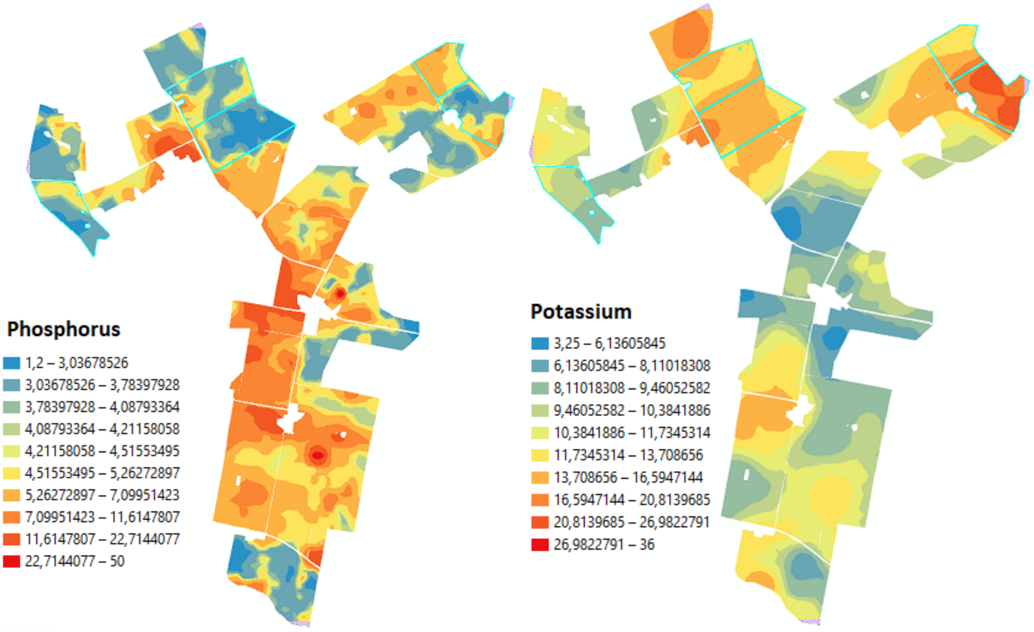

Figure 9: Map of soil nutrients on Bjertorp (Own processing).

5.1.1 Marginal values

The marginal values (λ_1 *and* λ_2) are derived from the model and used when comparing and interpreting the different models. The marginal value gives information regarding how much one extra unit of the restricted asset would contribute to the objective function (Debertin, 2012).

5.2 Model with conventional agriculture

The conventional model is formulated with mean functions of the production functions from the precision agriculture model. The conventional model therefore does not have the possibility to vary fertilizer application levels. It will only be allowed to use one level per crop. As described in the method chapter the conventional model is solved under two different assumptions, one with a fixed fertilizer formula between nitrogen, Phosphorus and potassium of 24-4-5, and one with the assumption that the ratio between the different fertilizers is variable and can be allocated optimally. The figures show profitability levels during different limitations on nitrogen. The numbers on the x-axis show the amount of nitrogen used in relation to the optimal amount.

5.2.1 Conventional agriculture with fixed nutrient ratio

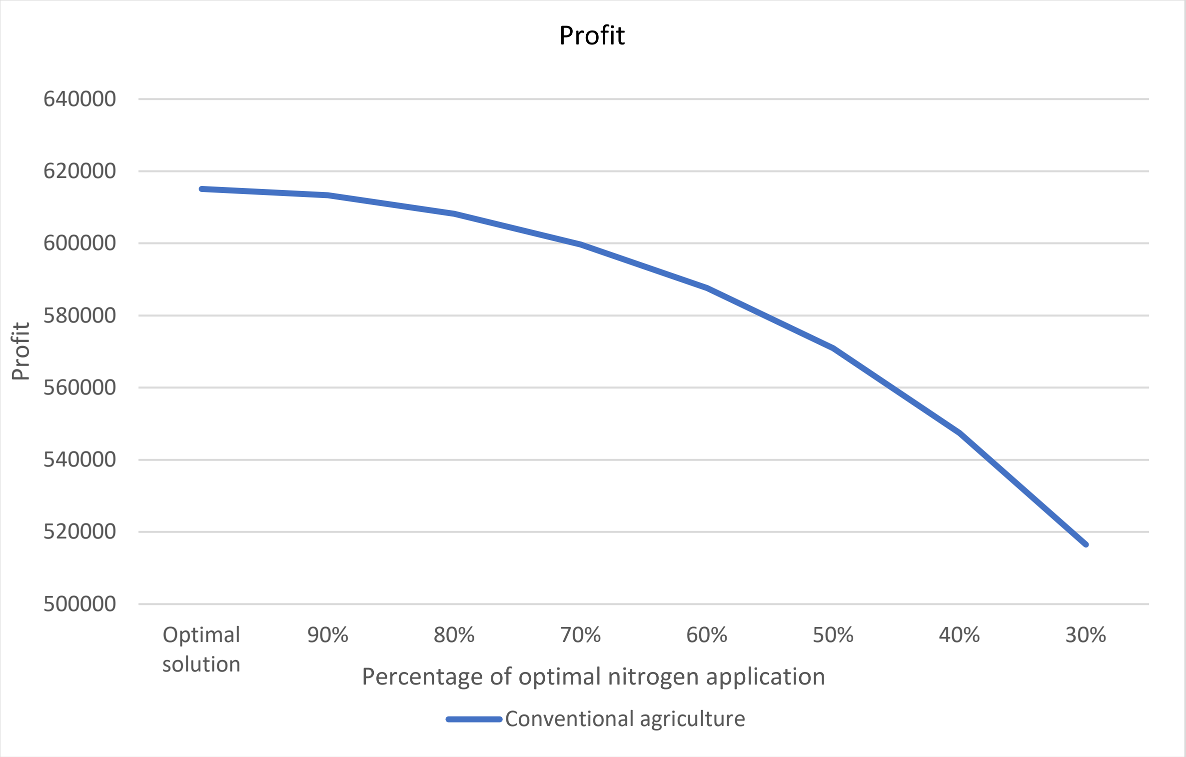

Figure 10: Profitability of a conventional model under different nitrogen restrictions (own processing).

Figure 10 displays the profitability level of the conventional model during different nitrogen restriction levels with a fixed nutrient formula. The results stem from solving the optimization problem with different restrictions of nitrogen. The nitrogen is restricted on a total basis, which means that the model could use all allowed nitrogen on one crop if that solution generates the highest profit. Figure 10 displays that the profit of the case farm decreases when implementing a nitrogen restriction policy. The profit is declining gradually when the allowed nitrogen application is decreased.

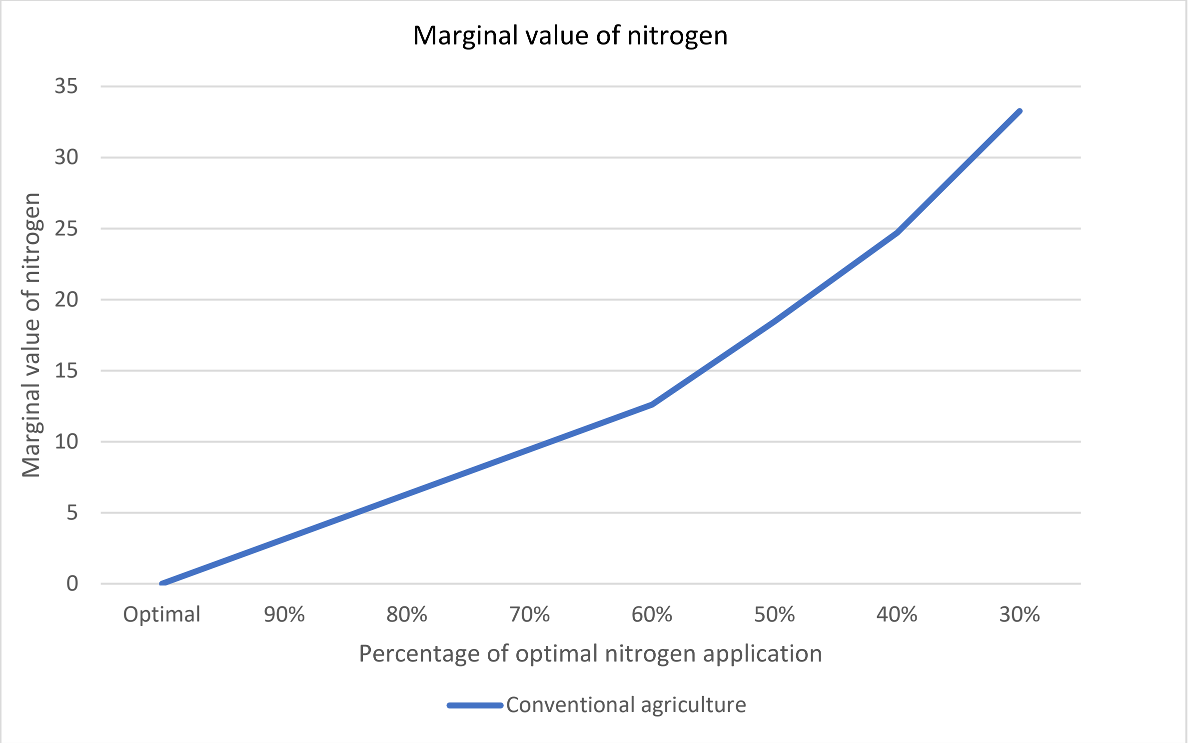

Figure 11: The Marginal value of nitrogen for the conventional model under different nitrogen restrictions (own processing).

Figure 11 displays the marginal value of nitrogen during the same restriction levels as in figure 10. The model shows how much extra profit each added kilogram of nitrogen generates at different restriction levels. The value of one extra kilo nitrogen increases when restricting the optimization model with decreasing nitrogen allowance. Figure 10 and 11 together highlight the value of nitrogen when growing crops and how much restriction in the nitrogen use will decrease the case farms operational profit from crops.

5.2.2 Conventional agriculture with variable fertilizer ratio

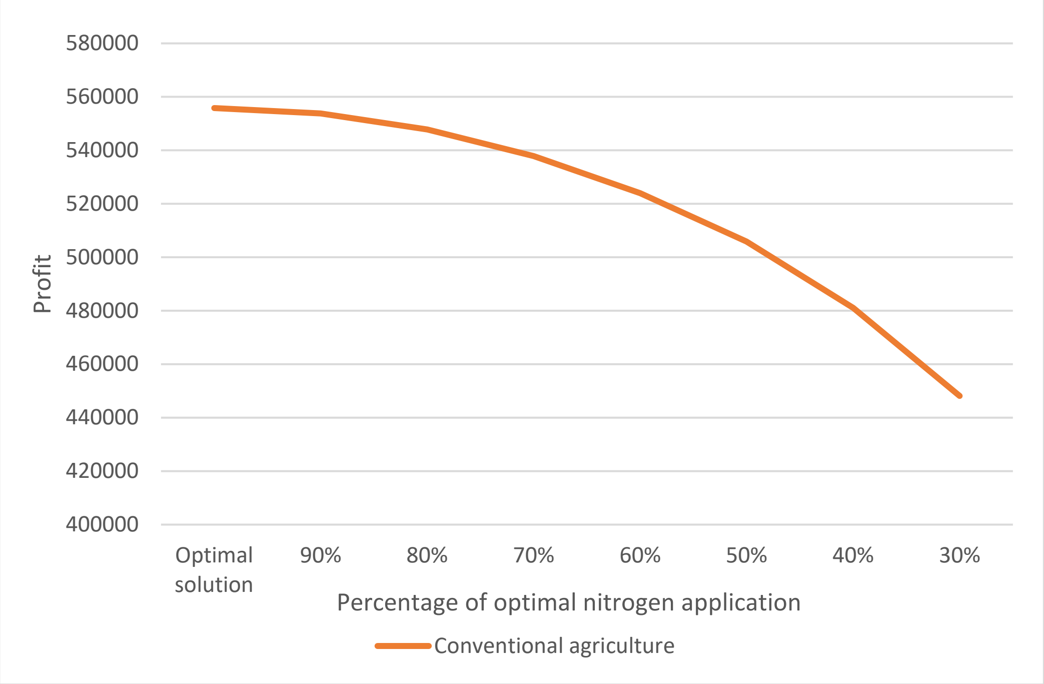

Figure 12: Profitability of conventional model under different nitrogen restrictions (own processing).

Figure 12 displays the profitability levels of the conventional model during different nitrogen restriction levels with the possibility to allocate the nutrient ratio to fulfill the need of the crop optimally. When the model can allocate the exact need of phosphorus and potassium without regard of the amount of added nitrogen, the exact amount removed from the ground when harvesting is added in the form of fertilizer. In the conventional farming model with a fixed fertilizer formula, the levels of added phosphorus are lower than the amount removed through the crop. When restricting the amount of allowable nitrogen application the profit of the case farm declines gradually.

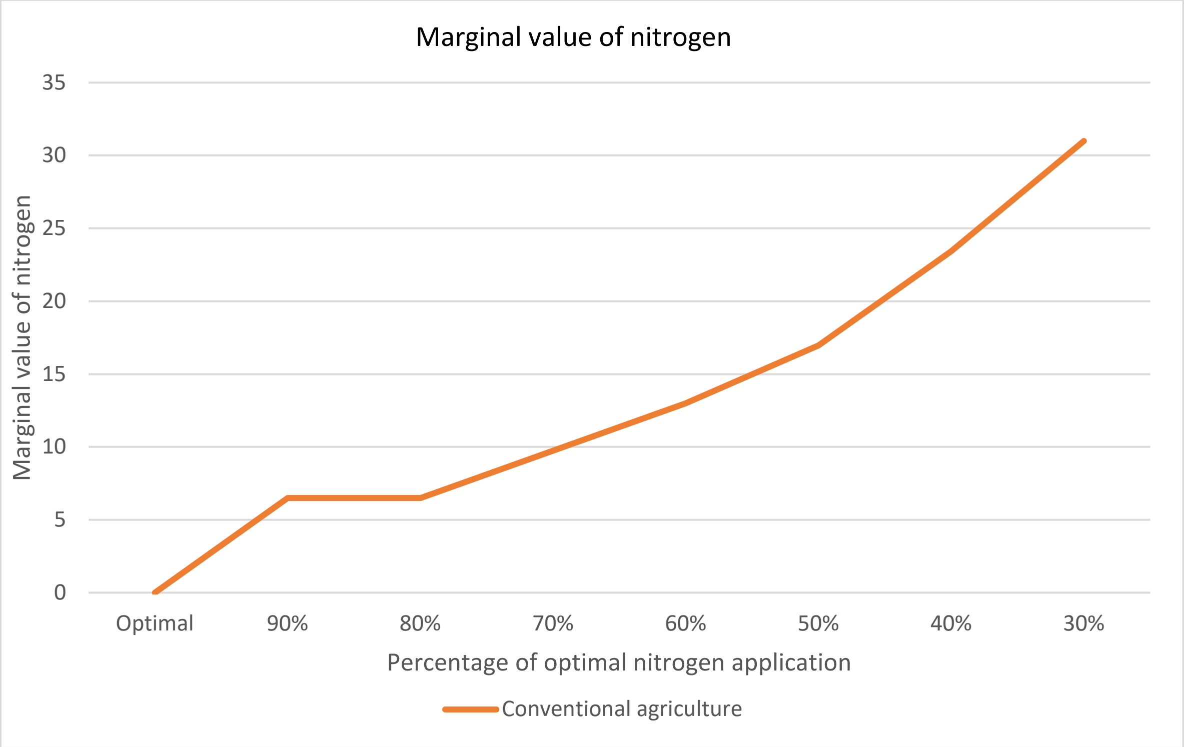

Figure 13: The marginal value of nitrogen of conventional model with variable fertilizer ratio (own processing).

The marginal value of nitrogen when allocating the fertilizer without considering a fixed ratio is similar to one where a ration is needed. At 30 % of optimal nitrogen application, the profit is slightly higher in the model with a ratio between nitrogen, phosphorus and potassium of 24-4-5.

5.3 Effects of precision agriculture

The models using precision agriculture are based on production functions for each hectare of grown crop. One model uses fertilizers with a fixed ratio of nitrogen, phosphorus and potassium and the other model has the opportunity to determine the optimal nutrient ratio for each hectare of grown crop.

The cost of precision agriculture is based on a number of factors, costs of machinery, navigation technique and services allowing the farmer to map the fields. The machinery cost is calculated using information from Agriwise on buying a new fertilizer spreader, data from Yara on buying a nitrogen sensor and data from a machinery salesperson on buying navigation equipment. The fertilizer spreader used in this study **was** the most expensive one Agriwise had listed in order to make sure the technology would allow the use of precision agriculture techniques. The costs of PA is dependent on the size of the farm, in this case, the cost was allocated to a mid-scale 300-hectare farm. The cost of PA sums up to 254 SEK per hectare.

5.3.1 Precision agriculture with decided fertilizer ratio

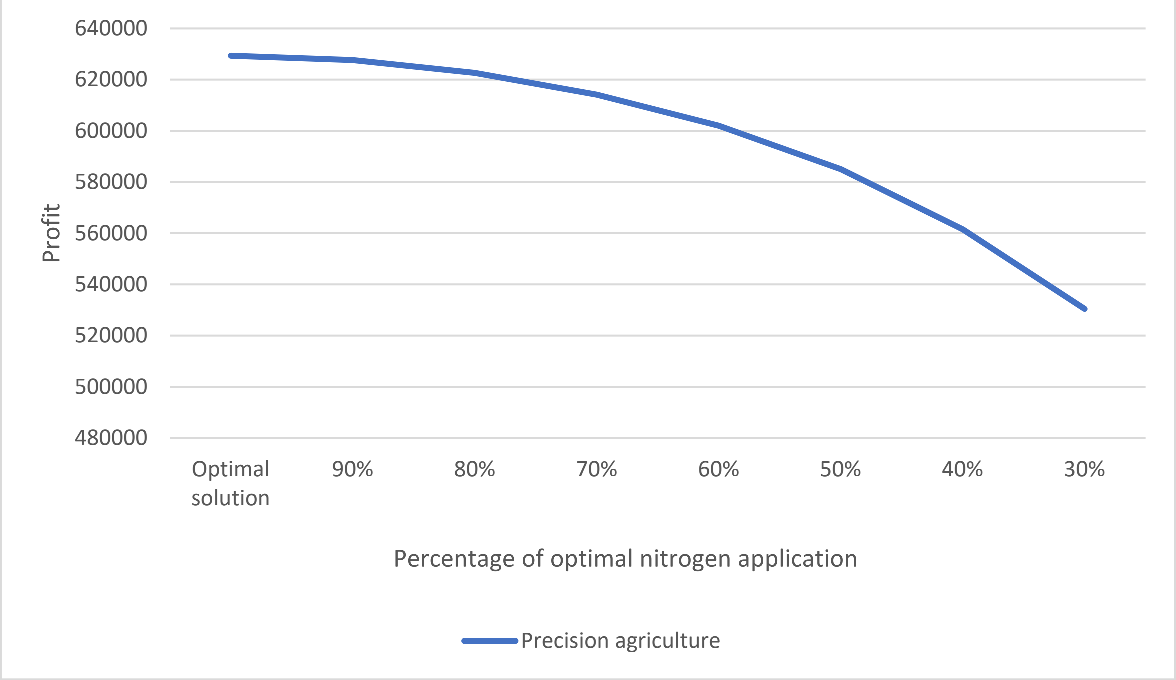

Figure 14: Profitability of precision agriculture with a fixed nutrient ratio (own processing).

Figure 14 shows the profitability of the case farm at different levels of nitrogen restriction. The model optimizes every hectare by changing the levels of nitrogen supplied. When restricting the possibility of using the optimal amount of nitrogen the model can allocate the nitrogen amount in any way optimal under the restriction in question. This implies that the model could decide to use nitrogen on only one crop if that would be the most profitable solution.

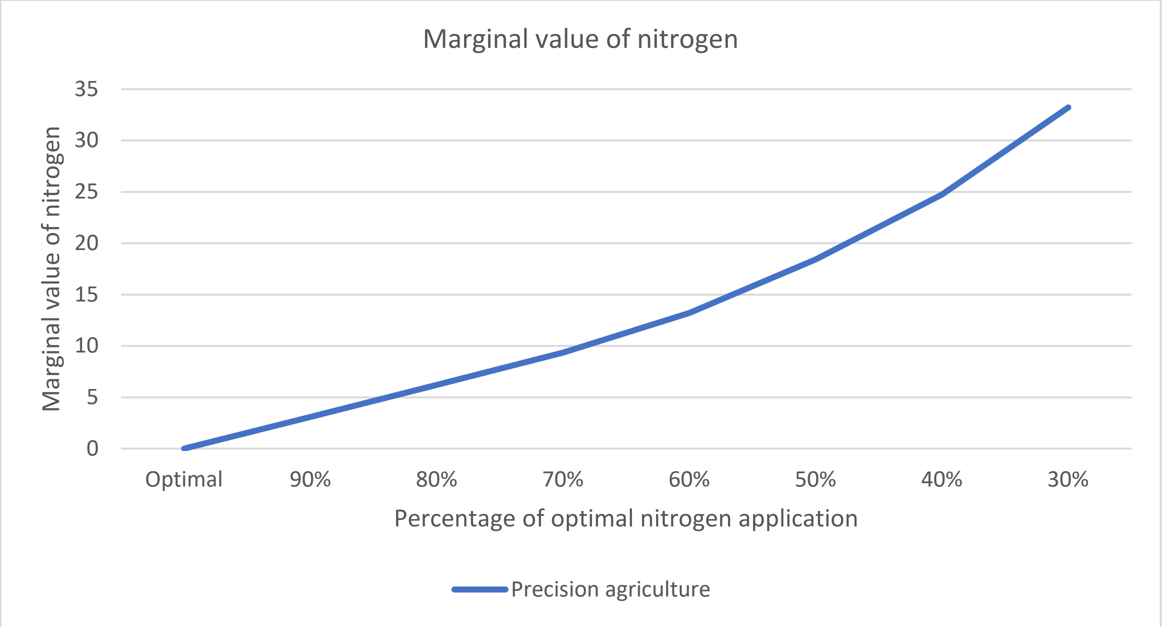

Figure 15: The marginal value of nitrogen for precision agriculture with a fixed nutrient ratio (own processing).

The marginal value of nitrogen in precision agriculture is similar to the value of extra nitrogen in the conventional model. The nitrogen is essential for the output of the crop, and therefore it is quite valuable. When restricting the amount of nitrogen allowable to use, the marginal value increases, see figure 15.

5.3.2 Precision agriculture with variable fertilizer ratio

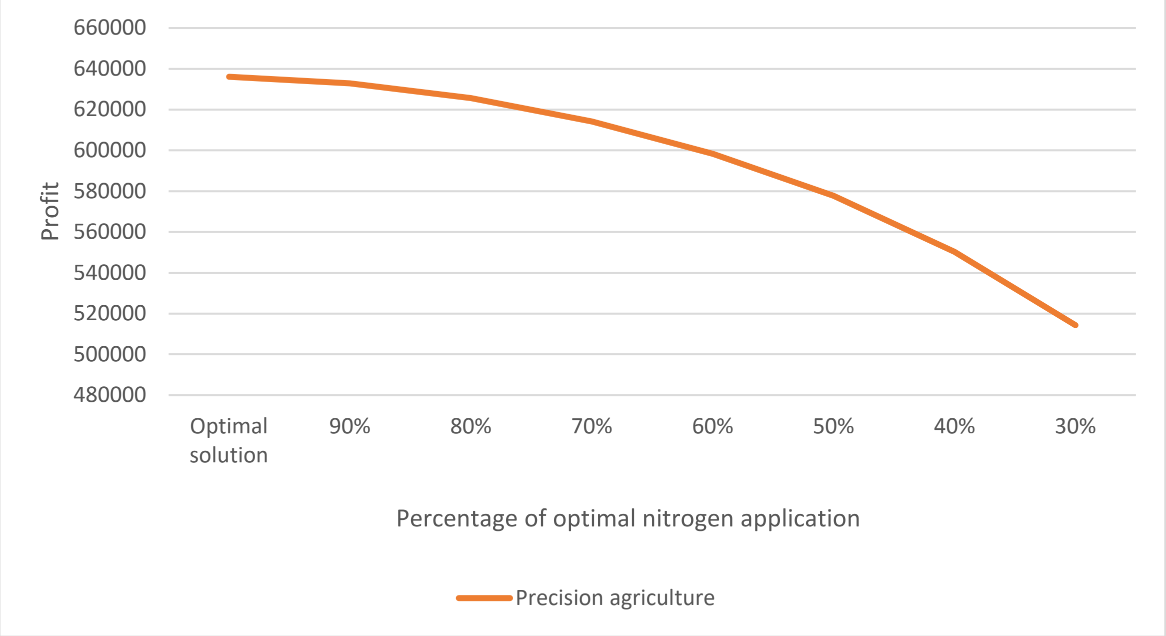

Figure 16: Profitability of precision agriculture with a variable nutrient ratio (own processing).

In the optimization model where the model is free to allocate the nutrients optimally, the profit levels are similar to the model with a fixed nutrient ratio. The difference between the models is mainly the application of the exact amount phosphorus and potassium required.

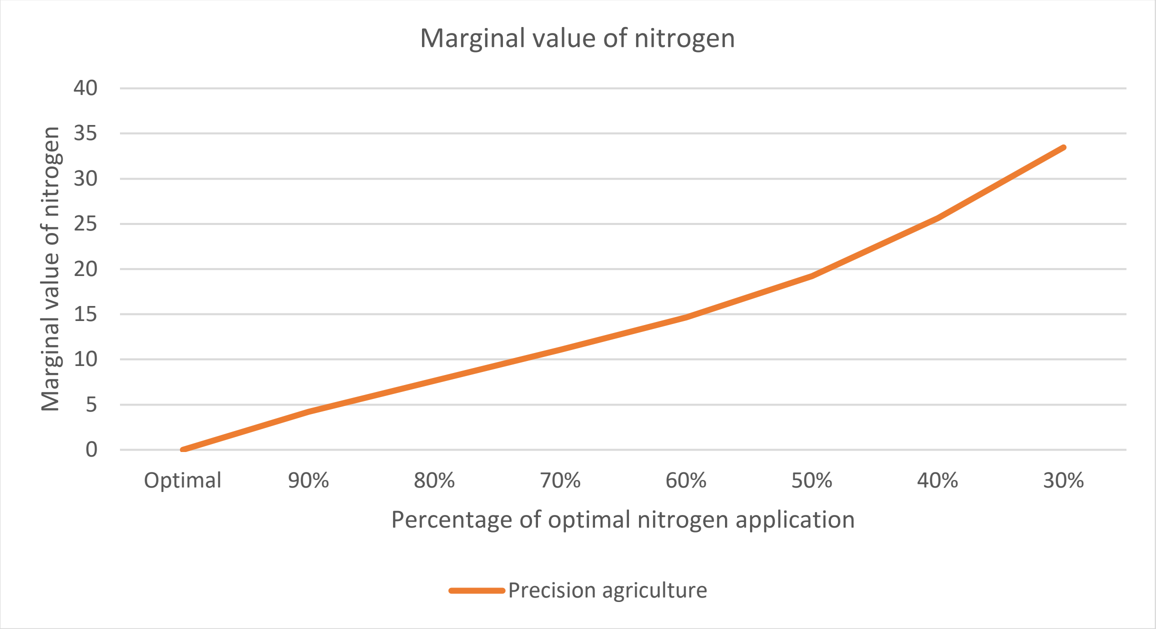

Figure 17: The marginal value of nitrogen for precision agriculture with a variable nutrient ratio (own processing).

Figure 17 shows the marginal value of obtaining one extra kilo of nitrogen during different restriction levels. If the amount of nitrogen was restricted to 30 % of the optimal level the gain of one extra kilo of nitrogen would represent a value of 34 SEK. The marginal value of nitrogen increases with stricter restrictions on the amount allowed.

6 Analysis and discussion

6.1 Fixed nutrient formula

In the following chapter, an analysis of the results from the optimization model is presented where the ratio of nitrogen, phosphorus and potassium is decided to a nutrient ratio of 24-4-5.

In the model using precision agriculture a mathematical optimization is carried out for each hectare of the farm, in the conventional one optimization is made for each crop. This means that the model with PA can optimize the added amount of fertilizer with regard to the production ability of the soil for each hectare. Compared to the study by Baio *et al.* (2017) carried out in Brazil where the use of precision agriculture was analyzed on cotton fields, this study does not reveal the same drop in the use of fertilizer. Baio *et al.* (2017) found the use of fertilizer costs was reduced by around 40 %, in the case of this study the amount of fertilizer used is almost at the same level. The results of this study instead show that the allocation of nitrogen optimally for each hectare increases the yield and therefore increases output with the same amount of fertilizer used.

6.1.1 Profit

Table 2: Profitability of conventional and precision agriculture with fixed nutrient formula (own processing).

Percentage of optimal nitrogen application	Conventional agriculture (SEK)	Precision agriculture (SEK)	Profit increase (%)
Optimal solution	615090	629354	2,3%
90%	613376	627697	2,3%
80%	608233	622654	2,3%
70%	599662	614216	2,4%
60%	587662	602036	2,4%
50%	570955	585009	2,4%
40%	547475	561594	2,5%
30%	516506	530486	2,6%

Table 2 display the profitability levels when using and not using precision agriculture at different levels of nitrogen restrictions. The profit of using precision agriculture is around 15 000 SEK, resulting in an additional profit of approximately 150 SEK per hectares, independent of which level of nitrogen restriction is used. These results show that as the allowable nitrogen use is reduced, the additional profit of using precision agriculture is increasing in relation to conventional agriculture. One explanation to this could be that the precision agriculture model is able to allocate the nitrogen more precisely within the field than what is possible in the conventional agriculture model.

The results in terms of the profitability are similar to the conclusion of Silva *et al.* (2007) were they found precision agriculture to be the more profitable method compared to conventional agriculture.

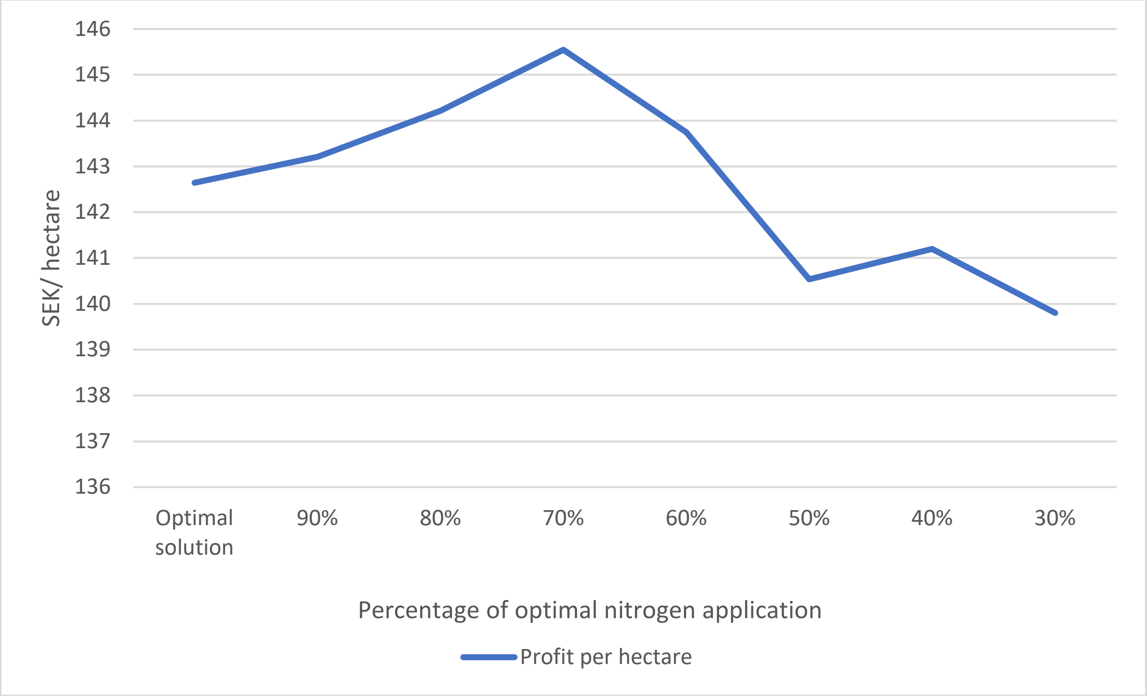

Figure 18: Additional profit of using precision agriculture with fixed nutrient formula (own processing).

Figure 18 shows the additional profit per hectare of using PA. The results of this study show higher potential of PA than suggested by Lawes and Robertson (2011). Both Lawes and Robertson (2011) and Robertson *et al.* (2008) suggest that the profitability of PA varies between farms and depends on the levels of soil- and yield variations in the fields. Table 3 displays the variations in yield at Bjertorp for the different crops used in this study. The standard deviation of phosphorus levels in the soil of Bjertorp is 1,39 and 4,32 for potassium. These numbers display a more substantial variation of potassium at Bjertorp. This indicates that variable application technology might be more profitable on potassium compared to phosphorus.

Table 2 shows that the profitability of PA increases slightly until 70 % of the optimal amount of nitrogen is used. When restricting the model to use 70% or less of the optimal nitrogen the profitability drops slightly. One of the reasons for the decline is that the amount of nitrogen is not sufficient and the optimal allocation focus nitrogen use on winter wheat, and thereby losing some of the PA advantages on oats and barley.

Table 3: Yield variations at Bjertorp before precision agriculture (own processing).

Yield (tonne/ha)	Winter wheat	Barley	Oats
Max	14,400	8,643	13,880
Min	6,330	1,974	2,300
St.dev	1,156	1,206	1,457

Table 3 displays the yield variations at Bjertorp before using precision agriculture. The yield variations are significant and the standard deviation is between 1.1 – 1.5 tonnes per hectare, depending crop. When using precision agriculture the yield variations are decreased to 0.2 – 0.6 tonnes per hectare, see table 4. The results show that precision agriculture are decreasing the yield variations within the fields at Bjertorp. This due to the possibility of applying the optimal amount of nutrients to each hectare within the field. The yield variations displayed in table 4 is asses from the use of the fixed nutrient formula of 24-4-5.

Table 4: Yield variation at Bjertorp after precision agriculture (own processing).

Yield (tonne/ha)	Winter wheat	Barley	Oats
Max	12,214	6,209	9,378
Min	11,340	3,612	6,757
St.dev	0,213	0,702	0,593

6.1.2 Marginal values

The marginal value of land is visualized in figure 19. Application of PA increases the economic value of gaining access to an additional hectare of land. During no restriction of the amount used nitrogen the use of PA would increase, the additional value, in terms of profit, of one additional hectare land with 600 SEK compared to the conventional model.

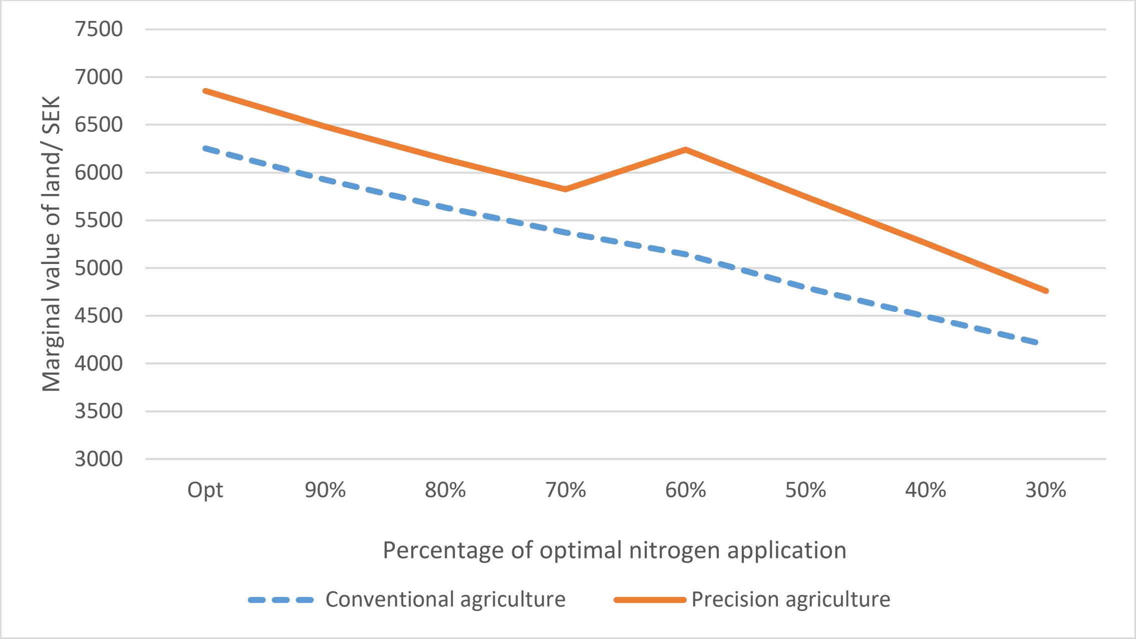

Figure 19: The marginal value of land for conventional and precision agriculture (own processing).

6.2 Variable nutrient formula

In the following section, an analysis of the results is presented for the case where the ratio between nitrogen, phosphorus and potassium is variable. The variable nutrient ratio allows the model to optimize the amount of added nutrient to, each crop in the model for conventional agriculture, and to each hectare in the scenario where precision agriculture is used. This due to the fact that PA allows the model to consider every unique site when adding nutrients. When PA is not adopted the nutrients will be allocated only to consider yields for each crop.

In the scenario when precision agriculture is applied, the model takes the existing nutrients from the soil as well as the yield level at the site into consideration when deciding the rates of phosphorus and potassium. In the conventional agriculture, only yield decides how much potassium and phosphorus must be added to the soil. Therefor the need for nutrient application is decreased when using PA and considering existing soil properties.

6.2.1 Profit

Table 4 shows the level of profitability when using conventional agriculture and precision agriculture at different levels of a nitrogen restriction.

Table 5: Profitability of conventional and precision agriculture with variable nutrient formula (own processing).

Percentage of optimal nitrogen application	Conventional agriculture (SEK)	Precision agriculture (SEK)	Profit increase (%)
Optimal solution	555804	636099	12,6%
90%	553811	632909	12,5%
80%	547829	625625	12,4%
70%	537861	614136	12,4%
60%	523904	598406	12,5%
50%	505857	577742	12,4%
40%	481047	550319	12,6%
30%	448130	514323	12,9%

Table 4 displays the total profit for the case farm with 100 hectares of land allocated to three different fields. As seen in the table, the use of precision agriculture is highly profitable when nutrients are allowed to be allocated in a variable manner. The profit increases with more than 80 000 SEK in the optimal solution when using variable rate application techniques. Hence, resulting in an additional 800 SEK profit per hectare when using precision agriculture.

In figure 20, the additional profit of using precision agriculture per hectare is visualized. Compared to the study by Lawes and Robertson (2011) the return of using precision agriculture is substantially higher in the case of this study. The study of Lawes and Robertson (2011) revealed substantial returns of using PA on a third of their studied area and argued that the result was highly dependent on the variations within the fields (see yield variations of Bjertorp in table 3.

Pierce and Nowak (1999) argued that signs of profitability when applying precision agriculture was generated mostly from soils with moderate to high variability in yield and nutrients. The results of this study show that variability within the fields is an important aspect, but it is not the only factor. In the case of Bjertorp, simply having access to soil data, and not having to overuse fertilizers such as potassium and phosphorus may increase profitability.

Comparing the results of the study when using variable ratio of nutrients makes the results comparable with the results found by Silva *et al.* (2007). Silva *et al.* (2007) studied precision agricultures effect on the profitability when growing corn and soybean in Brazil. The results of the study indicate a profit increase with around 60 US dollars (approximately 520 SEK) per hectare. Results of this study suggest that the profit of using precision agriculture is around 800 SEK per hectare. This study, and the one conducted by Silva *et al.* (2007), is conducted in different parts of the world and for different crops but the fact that precision agriculture is profitable in the context of both case farms makes the idea of precision agriculture more interesting to further evaluate.

Comparing results from Silva *et al.* (2007) with for example Khurana *et al.* (2008) visualizes the fact that precision agriculture can increase profits depending on different factors. In the case of Khurana *et al.* (2008) the profit was increased by somewhat higher yields but mostly from lower nitrogen and fertilizer costs. This is not true in the case of Silva *et al.* (2007) from Brazil where an increase in the yield was the only explanation to increasing profits. The operating cost were higher in the case of precision agriculture compared with conventional agriculture. When matching the two different studies with this study conducted on Bjertorp in Sweden, the results of Silva *et al.* (2007) has more resemblance with the results of this study. Figure 20 visualizes the increase in profit at different restriction levels by applying precision agriculture compared to operating the farm with conventional techniques. The additional profit is decreasing when the allowable use of nitrogen is reduced but the increased profit of PA is still substantial, at around 660 SEK per hectare at 30 % of optimal nitrogen allowed.

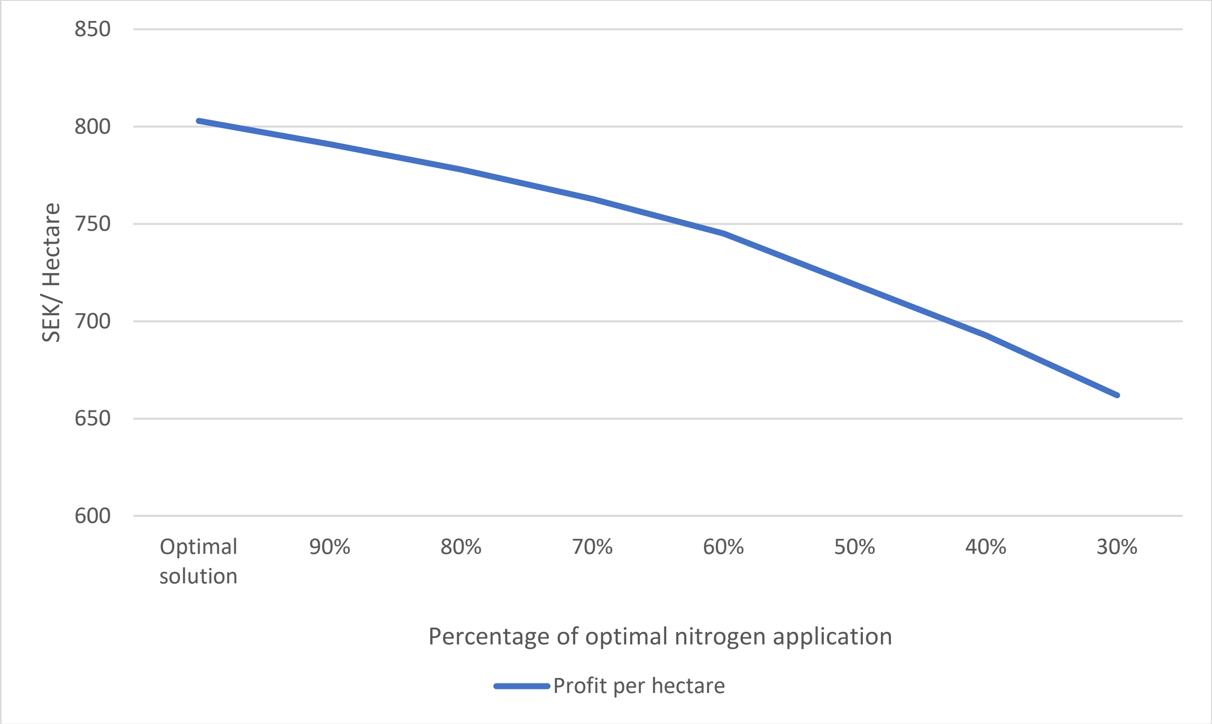

Figure 20: Additional profit of conventional and precision agriculture with an variable nutrient formula (own processing).

Although the case farm of this study would benefit from using precision agriculture when working with a variable fertilizer ratio, the same thing does not have to be true in other cases. Lawes and Robertson (2011) argue that benefits from using precision agriculture are likely to vary from farm to farm.

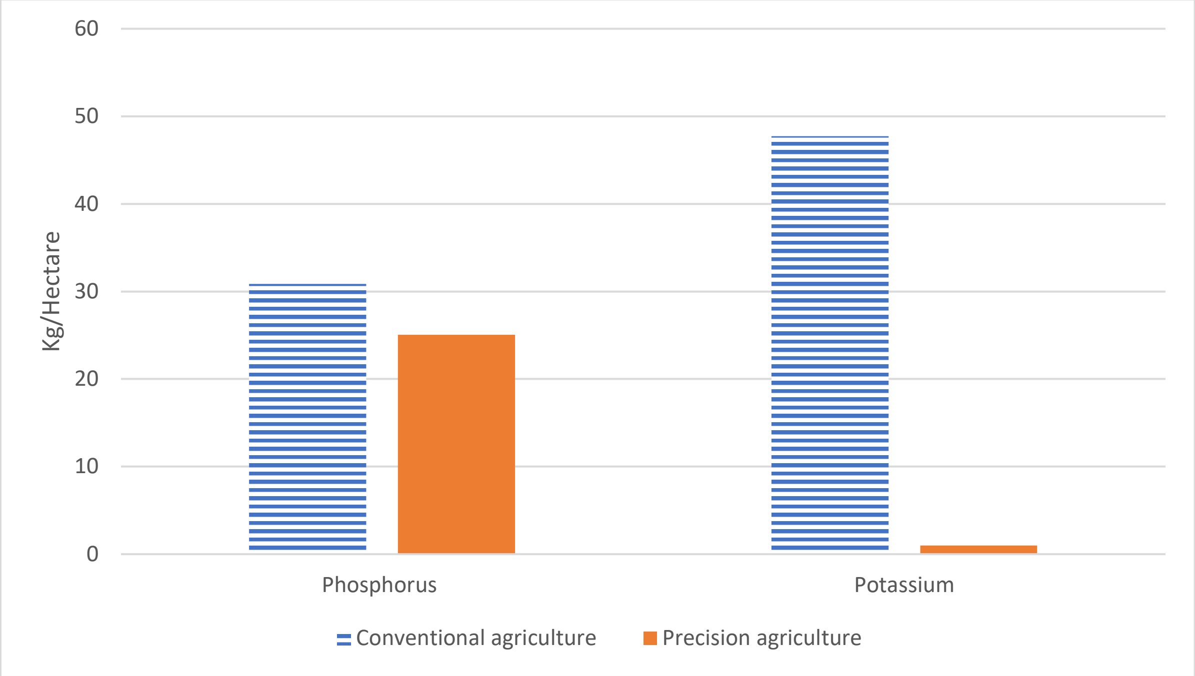

Figure 21: Phosphorous and potassium requirement (own processing).

One of the reasons behind the big difference in profit levels is the reduced use of potassium and phosphorus, visualized in figure 21. When using precision agriculture, the existing soil nutrients are considered and taken into consideration when deciding the need for phosphorus and potassium. In the case of Bjertorp, the level of potassium in the fields are high, which means that the need for added potassium when using PA is low. In conventional agriculture, the model adds the amount of potassium in the form of fertilizer dependent on only the yield of the harvest, not considering the levels already existing in the soil. Robertson *et al.* (2008) highlights that the level of nutrients in different zones of the fields are an important factor when evaluating the profitability of PA. Hence, the results of this study corresponds well with the factors for a profitable implication of PA concluded by Robertson *et al.* (2008).

Pierce and Nowak (1999) also discuss the fact that PA has the potential to reduce variations of the soil and on long-term make the spatial variations easier to handle. This could decrease the profitability of PA according to the authors. Since PA allows farm operators to allocate nutrients in an optimal way, variations due to soil properties and suboptimal nutrient application could decrease over time. A decrease in soil variation would lessen the added benefit of applying precision agriculture techniques.

6.2.2 Marginal values

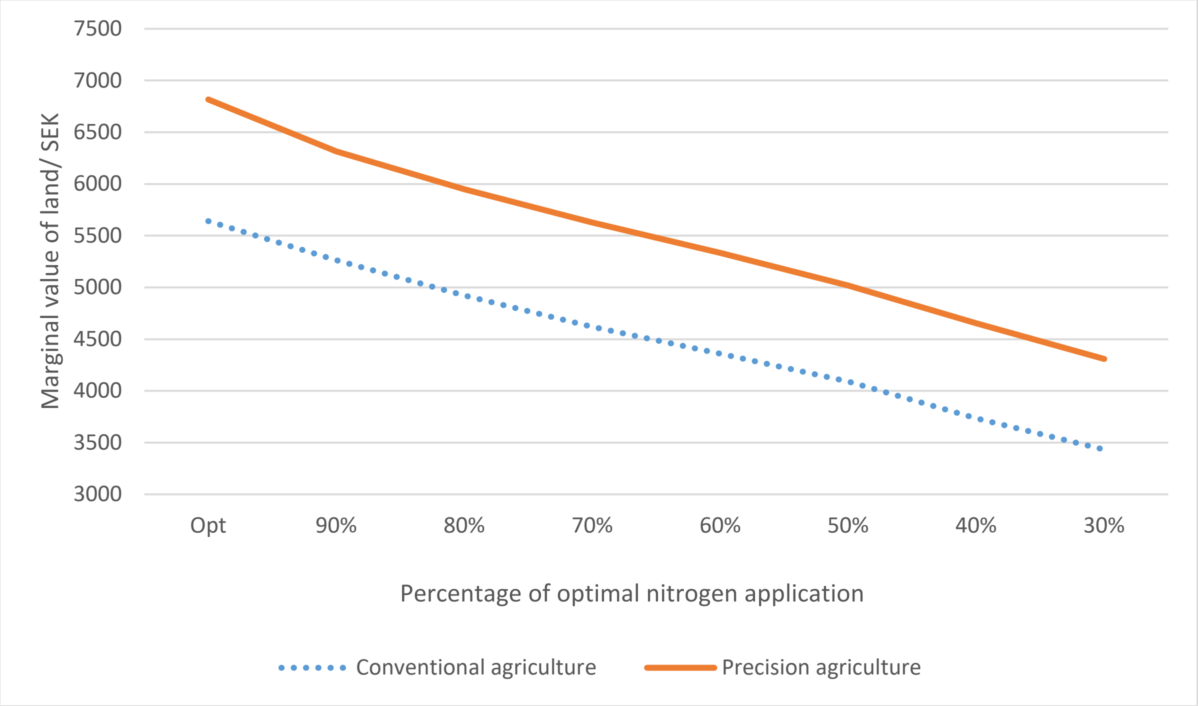

Figure 22: The marginal value of land for conventional and precision agriculture (own processing).

Figure 22 shows how the marginal value of land differs from using precision agriculture. In this model where nutrients are freely allocated without consideration of fixed ratios between the nutrients. The difference in the marginal value of land between conventional and precision farming are slightly decreasing when the nitrogen restriction is increased. The additional marginal value of land is 1175 SEK when using PA compared to conventional agriculture. The additional 1175 SEK in marginal value of land allows the case farm to pay 1175 SEK extra in rent per hectare and year and still reach the same profit. This means that the case farm will increase their competitiveness in the tenancy market compared to a traditional grain farm without precision agriculture.

The marginal value of nitrogen is another interesting aspect to measure. Results show that given a model with variable nutrient ratios the precision agriculture technique increase the value of one additional kilogram of nitrogen. The value of one additional accessible kilogram of nitrogen increases as the nitrogen is restricted to lower amounts compared to the optimal use.

As the nitrogen restriction is increased the difference between the marginal value of nitrogen for conventional and precision agriculture is increasing. This difference shows that precision agriculture gives the opportunity of allocating the nitrogen more optimally within the field to obtain a higher yield, leading to higher revenues and more effective resource use. As the restriction of nitrogen use is reduced, the marginal value of nitrogen is increasing for both conventional and precision agriculture. At 90% nitrogen use the marginal value of nitrogen for conventional agriculture is larger than the marginal value for precision agriculture. As the nitrogen use is lowered the marginal value for precision agriculture is higher the marginal value for conventional agriculture, as seen in figure 23.

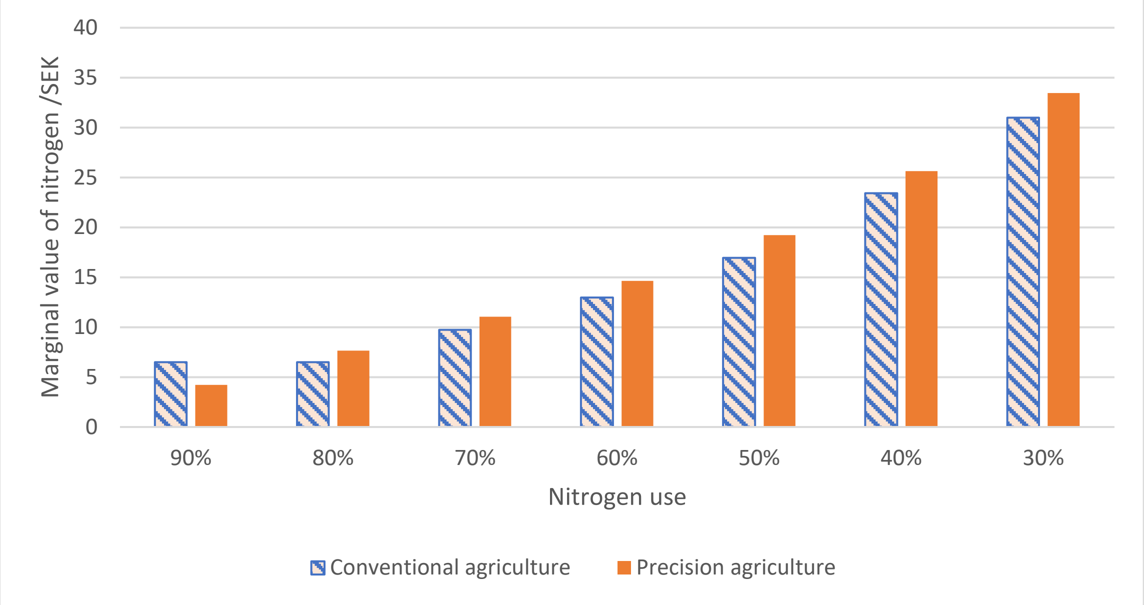

Figure 23: The marginal value of nitrogen for conventional and precision agriculture (own processing).

Another aspect regarding the nitrogen use for the different methods is that the marginal value for precision agriculture is getting relatively higher than the marginal value of the conventional agriculture. This implies that when using precision agriculture techniques, there is a possibility to allocate the nitrogen to the part of the field where it is possible to obtain a higher yield and therefore improvement in profit. When having the possibility to allocate the nitrogen in an optimal manner the yield per kg added nitrogen increases. This could according to Alexandratos and Bruinsma (2012) decrease the environmental impact of agriculture. As displayed in table 5, the precision agriculture techniques enables the case farm to increase the yield per kilogram of applied nitrogen in comparison with conventional agriculture. The difference between the methods increases as the maximum allowable use of nitrogen is decreased. These results show that the case farm would lose less yield give a nitrogen policy restriction when using precision agriculture techniques.

Table 6: Yield per kilogram of applied nitrogen (own processing)

Percentage of optimal nitrogen application	Precision agriculture (kg/ha)	Conventional agriculture (kg/ha)	Difference
90%	74,77	72,40	2,37
60%	103,83	100,21	3,62
30%	181,32	174,21	7,11

6.3 General discussion

Among Australian grain producers, there is considerable uncertainty about the relative advantages of using variable rate application (Lawes & Robertson, 2011). This study will provide knowledge about the effects of adopting PA for the case farm and thereby contribute with knowledge for farmers of how a farm can be affected by using PA. Since this study is carried out on only one case farm, the results are not generalizable, but they still give an idea of a possible outcome of using precision agriculture.

Another study discussing adoption of PA is presented by Aubert *et al.* (2012). The study lists reasons behind the lack of adoption of PA from farmers. One of the significant conclusions is the lack of standards in the field of PA, and the different techniques do not yet work together optimally. This study has worked with parts of precision agriculture that are possible to use without having to worry about the lack of standards. Still, the study cannot conclude in general terms that other farmers than the case farm may utilize the same techniques as in this study and obtain the same results. Pierce and Nowak (1999) conclude similar findings as Aubert *et al.* (2012) if precision agriculture is to be successful the system must evolve into an integrated management system.

Batte and Arnholt (2003) study suggest that research concerning the profitability of precision agriculture techniques is needed in order support decisions of adopting PA. Although the study is made in an American spatial context, the results could be similar in Sweden. This study has focused on contributing with how profitability can be increased on a case farm by adopting variable rate technology.

Studies conducted on adoption of precision agriculture often boil down to the willingness to adopt new technologies by farmers. Khanna *et al.* (1999) suggest that young farmers, operating big farms are more likely to adopt new precision agriculture techniques despite some doubt about profitability. The results of this study hope to simplify the decision to adopt precision agriculture. When increased income is contrasted against the costs of the technology it clearly reveals that there is a possibility of increasing the operational profit of the farm. The lack of generalizability of this study may decrease the use, but knowledge about the possibility of profitability might be enough for some Swedish farmers to decide to adopt the technology.

Results from Batte and Arnholt (2003) indicate that farm-managers in America had decided to adopt PA without being sure it led to an increase in profit. The decision to adopt the techniques was taken to simplify the farming operation and increase control of inputs in relation to yields. The farmers of the study were confident that their decision to adopt PA would increase future profits. If connecting the thought of the managers from Batte and Arnholt (2003) to this study a similar approach could be suggested. If using PA and variable rate application of nutrients this could allow the soil to remain productive for a long period of time. If the removal of nutrients, from harvesting, is continuously higher than the input, of commercial fertilizers, the nutrient levels of the soil will decrease. This could affect the crop-growing operation negatively.

Khurana *et al.* (2008) concluded in their study that site-specific nutrient management could be profitable for India wheat farmers. In comparison to this study they focused on making statistical analysis studying nutrient levels, yields and the effects of applied nitrogen. This study used the same parameters but developed an optimization model to evaluate similar issues as Khurana *et al.* (2008). Khurana *et al.* (2008) showed that according to their calculations average net return increased by 13 % from applying site-specific nutrition management. Results of their study also show that wheat yields could improve with at lower use of nitrogen. In this study, the average application of nitrogen was almost identical between the models using precision agriculture and the models using conventional agricultural methods. Although the use of nitrogen in this study is not reduced by applying precision agriculture, the crop yields increased by using a variable rate application of fertilizer. This means that applying precision agriculture to the case farm will increase the exchange of nitrogen compared to yield. If the yield is increased without increasing amount added nitrogen, the output will be more effective and have less impact on the environment per kilogram produced grain.

Silva *et al.* (2007) conclude that precision agriculture is a profitable investment for farmers growing soybean and maize in Brazil. They also bring up some other interesting aspects in the conclusion that could turn out to be interesting aspects to consider in this study. One example of this is the increased need for investment capital. Precision agriculture, even though profitable, requires increase in invested capital in equipment and machinery. The requirement of skilled labor also increases when applying precision agriculture. The farmer needs to make sure everyone operating the machinery has the competence needed to handle the different equipment. If there is a lack of availability of skilled labor the advantages of precision agriculture could decrease. This due the fact that staff might not be able to handle the equipment properly.

Table 7: Yield per hectare/ crop and management system (own processing).

Crop	Precision agriculture (kg/ha)	Conventional agriculture (kg/ha)	Yield increase
Winter Wheat	12 046,0	11 317,0	6,4%
Barley	5 360,0	5 320,4	0,7%
Oats	8 372,9	8 336,3	0,4%
Total	25 778,9	24 973,8	3,2%

Table 6 shows the difference in yield of the different crops when using precision agriculture compared to using conventional agriculture. The most notable difference is observed in Winter Wheat where precision agriculture increases the yield with 6,4 %. In total, the use of precision agriculture increases the yield with 3,22 %. Silva *et al.* (2007) gained a 16 % yield of maize when implementing precision agriculture compared to this study where only a 6 % yield increase of wheat is accomplished.

The conventional model in this study uses mean production functions of each crop determined by all site-specific production functions created in the model with precision agriculture. In the case of Bjertorp, they have been working over the past years to even out the site-specific differences in soil properties across the fields. If the fields do not contain sufficient variation, precision agriculture will become less profitable. This could be one explanation, apart from the fact this study uses different crops, to why the results of this study differ from the results presented by Silva *et al.* (2007). These results show that the variations, regarding nutrients and other soil properties, in the winter wheat field where more significant than the variations in the fields where barley and oats are grown. This shows that the within field variation is one crucial factor when investigating the profitability of a precision agriculture investment but difference may also be crop specific.

7 Conclusions

In this chapter, the conclusions from the study are presented.

The aim of the study was to examine the profitability of applying precision agriculture in a Swedish context.

Research questions:

- What are the economic effects of adopting precision agriculture to the case farm of the study?
- What economic effect do a policy restriction on nitrogen fertilizer have on different scenarios for the case farm of this study?

The study concludes that precision agriculture is a profitable investment for the case farm of this study. The case farm shows profitability from applying precision agriculture both in the model with a fixed nutrient ratio and in the one where the nutrients can be allocated without regard for the existing fertilizers products.

A comparison of the model with a fixed nutrient ratio and the one without fixed ratio shows that the profitability of applying precision agriculture is substantially higher when allowed to allocate nutrients independent of existing fertilizer formulas. The results of the study also visualize the importance of variations in the soil when evaluating the profitability of applying precision agriculture to the farm operation. The economic gain from using variable rate application increases when in-field variations are substantial.

The conclusions of this study show restriction in the amount of used nitrogen affect the profitability of the crop operation quite drastically. If the allowable use of the optimal amount of nitrogen is reduced to 30 % than profitability decreases with 19,1 % in the model with precision agriculture and 19,3 % in the conventional agriculture model give a variable nutrient ratio. This shows that the profitability difference does not differ much in the models with precision- and conventional agricultural models when restricting the allowable use of nitrogen. The restriction of nitrogen decreases the profit almost equally in both models.

Results of the study show that the case farm would lose less yield under a nitrogen policy implication when using precision agriculture compared to conventional agriculture techniques.

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Personal messages

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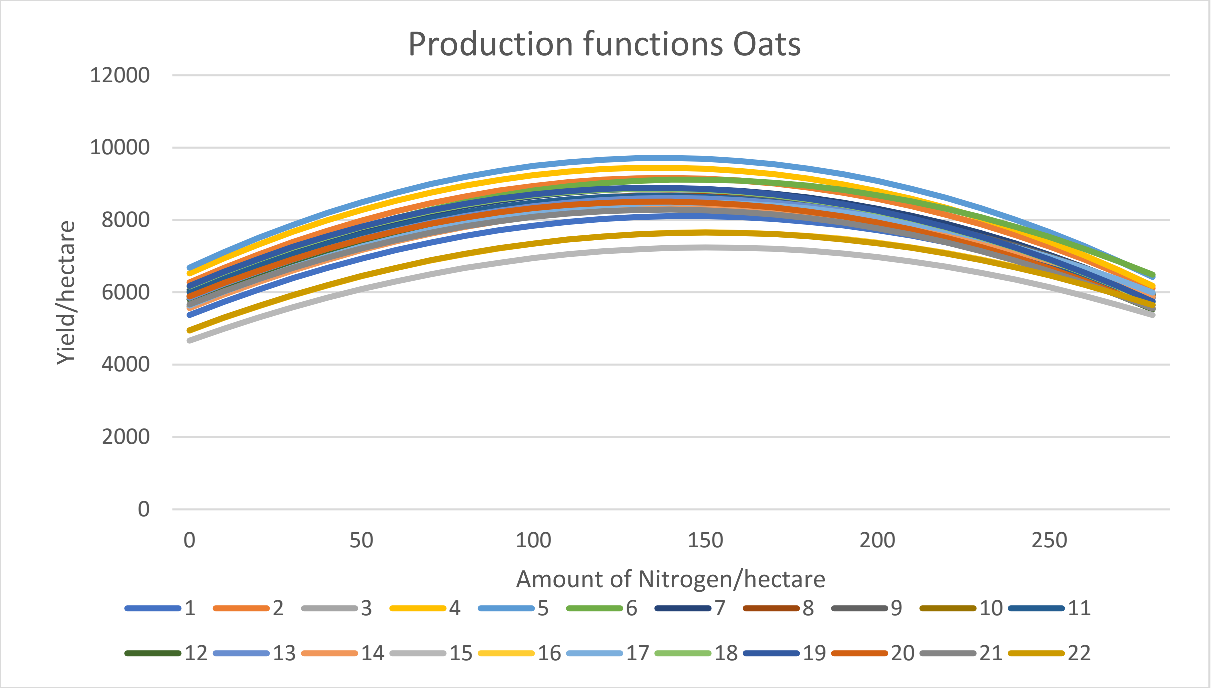
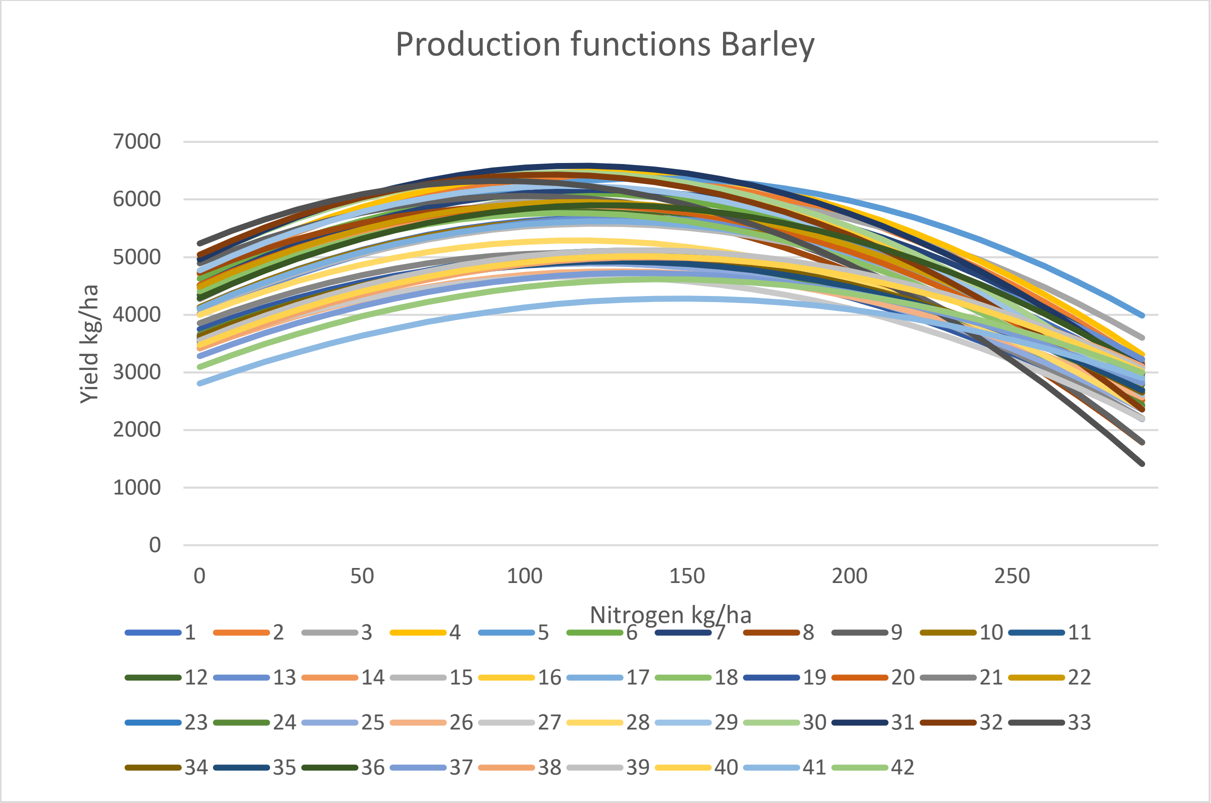
Appendix

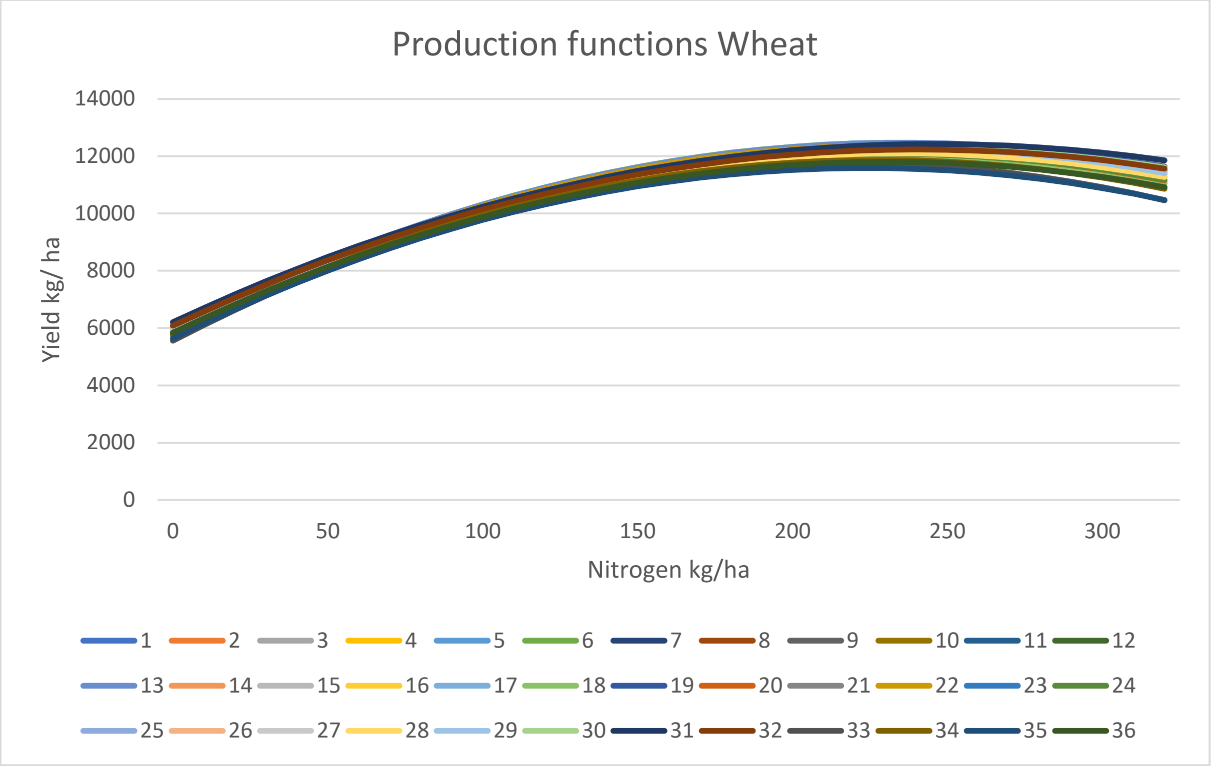
Appendix 1- Calculation of annual capital cost of PA investment

Investment in precision agriculture						
Hectares	300			Years	10	
Soil mapping service	330	SEK/ha				
Equipment						
Fertilizer spreader and GPS	340000					
Sensor	176000					
Soil mapping		99000		Total cost		516000
Soil mapping/year		24750		Yearly cost equipment		51600
Cost per Ha/year		254	SEK			
Cost per year		76350	SEK			

Appendix 2- Production Functions for each crop






Production functions Wheat
Yield kg/ ha
14000
12000
10000
8000
6000
4000
2000
0
0
50
100
150
200
250
300
Nitrogen kg/ha
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
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