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Sustainability effects of introducing legumes in traditional cropping systems
- an experimental case study in Swedish context

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Sustainability effects of introducing legumes in traditional cropping systems -an experimental case study in Swedish context

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Abstract

The agricultural sector of the world faces a growing food demand because of a growing world population. To support this growing demand, it could be necessary that agricultural production increases, this increase in production must be achieved sustainably. One way to achieve more sustainable production in agricultural could be to diversify the production systems. Legumes are a crop group that holds properties that could be of importance when trying to achieve more diverse and sustainable agriculture.

This study aims to examine how a diversification with legumes would affect typical Swedish cereal dominated cropping systems in terms of sustainability. More specifically, the three dimensions of the triple bottom line are investigated separately. Indicators of sustainability in each dimension are identified, and these show the effects of legumes in the cropping systems. To examine the effects legumes attributable to the sustainability in the cropping systems, two case farms are developed. Five different indicators are applied; these are profitability, nitrogen usage, phosphorus usage, energy production, and protein production. The study considers three different legumes, feed peas, yellow peas, and broad beans. From the two case farms, a mathematical optimization model is developed from which the indicators are calculated. The approach of the study is quantitative and uses secondary data from several sources.

Results from the study indicate that legumes could increase the profitability of both case farms. The results show an increase in the profitability of between 0-4 %. The study indicates that nitrogen and phosphorus usage on the farm decreases. The results on phosphorus differ from previous studies, where it is found that legumes would increase the usage of phosphorus in a cropping system. The results on the indicators of energy and protein are similar to previous research and point towards an increase in protein production and a decrease in energy production. The major conclusion is that diversification with legumes could have an impact on the sustainability of the two case farms. Only one out of five indicators point towards reduced sustainability compared to a state with no legumes; this is the indicator of energy production. However, in the discussion, the implication of lower energy production is discussed, and it is found that a lower energy production might not be bad for the single farmer.

Sammanfattning

Jordbrukssektorn i världen står inför en växande efterfråga på livsmedel på grund av en växande världsbefolkning. För att möta denna växande efterfråga är det nödvändigt att jordbruksproduktionen ökar, denna produktionsökning måste uppnås på ett hållbart sätt. Ett sätt att uppnå en mer hållbar jordbruksproduktion kan vara att diversifiera produktionssystemen. Baljväxter är en gröda som kan vara betydande vid försök att uppnå ett mer diversifierat och hållbart jordbruk.

Denna studie syftar till att undersöka hur en diversifiering med baljväxter skulle påverka traditionella svenska spannmålsdominerade växtodlingssystem med avseende på hållbarhet. Mer specifikt undersöks de tre dimensionerna; ekonomisk hållbarhet, miljömässig hållbarhet och social hållbarhet separat. Indikatorer identifieras i varje dimension för hållbarhet, och dessa visar effekterna baljväxter har i växtodlingssystem. För att undersöka hållbarhetseffekterna av baljväxter i växtodlingssystem utvecklas två fiktiva fallgårdar. Fem olika indikatorer tillämpas och dessa är lönsamhet, kväveanvändning, fosforanvändning, energiproduktion och proteinproduktion. Studien undersöker tre olika baljväxter, foderärt, gulärt och åkerbönor. Utifrån fallgårdarna utvecklas en matematisk optimeringsmodell där indikatorerna beräknas. Studiens tillvägagångssätt är kvantitativt och använder sekundärdata från olika källor.

Resultaten från studien tyder på att baljväxter kan öka lönsamheten på Svenska växtodlingsgårdar. Lönsamheten ökar enligt resultaten mellan 0-4 % på fallgårdarna. Resultaten indikerar att gårdarnas kväve- och fosforanvändning minskar. Resultaten på fosforanvändningen skiljer sig från tidigare studier, där det konstateras att behovet av fosfor ökar i växtodlingssystem där baljväxter ingår. Resultaten på indikatorerna för energi- och proteinproduktion överensstämmer med tidigare forskning och pekar på en ökning av proteinproduktion och en minskning av energiproduktion. Slutsatsen är att en diversifiering med baljväxter kan öka hållbarheten hos de två fallgårdarna. Endast en av fem indikatorer pekar på lägre hållbarhet med baljväxter inkluderat i växtodlingssystemen jämfört med växtodlingssystem utan baljväxter.

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1 Introduction

The introduction presents a brief background of the agricultural sector in the world. This is followed by an introduction of cropping systems, and the possible contribution legumes could provide in a more sustainable agricultural system. The problem is stated, and the aim and research question is introduced.

1.1 Background

Since the latter half of the 19th century, global food production and world population have increased (Yang *et al.*, 2018). As the world population increases the demand for food increases as well, and Yang *et al.* (2018) argue that market demand will keep on growing until 2050. To support the increasing demand for food, agricultural production in the world needs to increase, and this growth in production needs to be achieved without harming the environment (Diaz-Bonilla *et al.*, 2014). The agrarian sector in the world accounts for a substantial environmental impact (Bockstaller *et al.*, 2008). These impacts could be greenhouse gas emissions, eutrophication, and loss in biodiversity.

The United Nations (UN) has defined sustainable development goals that aim for a sustainable future (United Nations, 2018). It consists of 17 goals that relate to different areas of sustainable development. Number 2 of the sustainable development goals is the goal Zero Hunger that addresses aspects of sustainable development in connection with agricultural production. One sub-target of the Zero Hunger goal is to reach a more diversified agricultural production with more diverse farming systems. Since the 1900s, 75 % of crop diversity has disappeared from the fields, and the UN aims for a more diversified agricultural production. In order to develop a more sustainable agricultural production, it could be of importance that farming systems become more diversified (Imadi *et al.*, 2016). According to Imadi *et al.* (2016), more sustainable farming systems could enhance biodiversity and increase food security.

A common way to define sustainability is by triple bottom line with three dimensions of sustainability; economic sustainability, social sustainability, and environmental sustainability (Elkington, 1998). Environmental factors in agriculture can be, greenhouse gas emissions from the production of crops, social factors can be, contribution to food security and economic factors may be, the profitability of a company (Zhen & Routray, 2003). A concept that has a close link to sustainability is the concept of Sustainable development (Székely & Knirsch, 2005). Sustainable development was defined in the book Our Common Future as: “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987, p. 43). These two concepts have set the pace for the sustainability work in today’s enterprises (Székely & Knirsch, 2005)

In research regarding sustainable agriculture, the farm is viewed as a system that produces outputs in terms of, e.g., cereals, livestock or milk (Craheix *et al.*, 2016; Imadi *et al.*, 2016). A cropping system is described as a sequence of crops grown and the practices used for producing them (Blanco-Canqui & Lal, 2008). The concept includes the consideration of all techniques used for producing a crop and all possible cropping sequences over time. Within a cropping system, farmers form decisions on which crops and inputs to use (Dury *et al.*, 2012). Essential factors to consider within a cropping system are resources such as arable land, fertilizer input, and which crop to grow at each field. The management of these resources influences the profitability of the farm (Debertin, 2012). According to Blanco-Canqui and Lal (2008), it is common to concentrate on high yield and high-value crops in a cropping system without considering the effects one crop can have on another crop. These effects could be the pre-crop effect, enhanced soil structure, and a decrease in fertilizer usage. Depending on how the cropping system is managed, it can affect the sustainability of a farm (Lehtonen *et al.*, 2005; Pannell & Glenn, 2000). The focus on high-value crops is also a trend in Swedish agriculture. Statistics of Swedish crop allocation shows that a large acreage of Sweden is covered with cereal crops (Fogelfors, 2015).

The Swedish crop producing farms tend to focus on a few crops, and figure 1 shows the distribution (Jordbruksverket, 2018b). The year 2017, cereal, legumes, oilseed, and special crops covered 50 % of the total acreage in Sweden, ley covered 44 % of the total acreage, and 6 % was fallow land. Without consideration of ley and fallow, 80 % of the acreage consists of cereals, and 20 % consists of oilseed, legumes, and special crops such as sugar beets and potatoes. Generally, crop-producing farms do not grow ley, and the smaller circle represents how a crop-producing farm in Sweden would allocate its resources (Fogelfors, 2015).

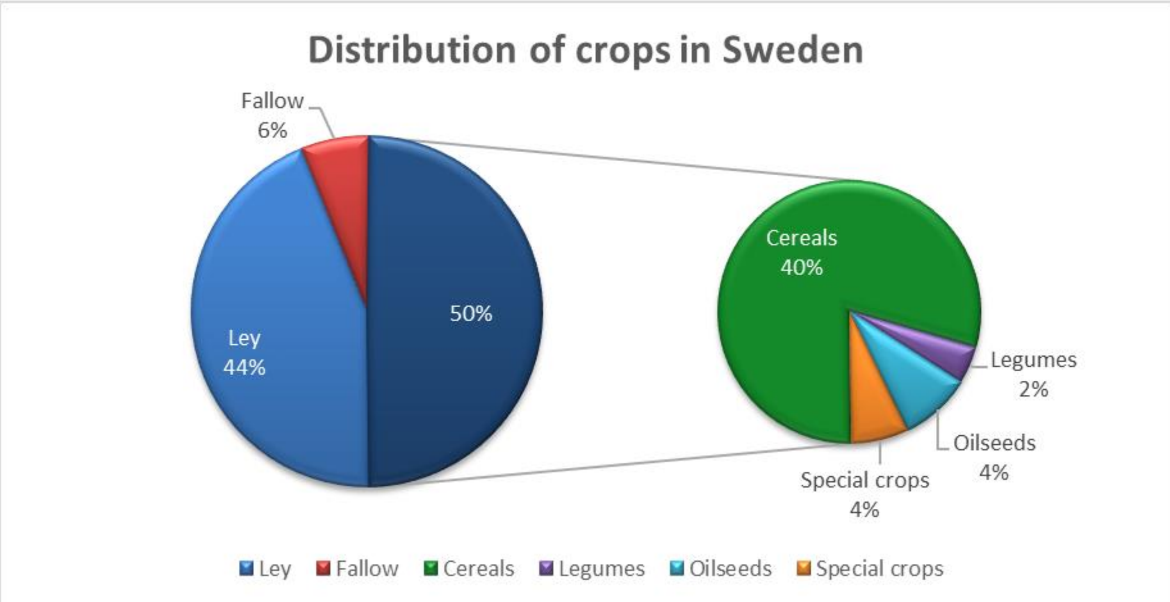

Figure 1. Distribution of crops in Sweden 2017 (Jordbruksverket, 2018b) (own rendering)

More sustainable cropping systems could be systems that include other crops than today's agriculture (Liu *et al.*, 2016). Cropping systems that include more types of plants can contribute to a reduction of the use of fertilizer and chemicals, which both reduce the climate impact and the eutrophication (Stagnari *et al.*, 2017). According to Liu *et al.* (2016), it could be necessary to diversify the crop rotation to tackle future problems with diseases connected to crops that might arise due to climate change. One way to diversify the cropping systems could be to increase the acreage of legumes in cereal dominated cropping systems (Ebert, 2014). The legumes could contribute both by the possibility to fixate nitrogen in the ground and its economic pre-crop values (Preissel *et al.*, 2015). Examples of legume crops are soybeans, peas, and broad beans.

Figure 2 shows the acreage of legumes in Sweden between the years 2005 and 2018. During the years 2005-2015, the acreage of legumes in Sweden has been at an average level of 1.4 % of the total acreage (Jordbruksverket, 2018b). In 2015 the European Union launched a policy known as the ecological focus area (EFA) where the farmer needs to grow a particular crop such as legumes or fallow on 5 % of cultivated land (Söderberg, 2016). As a result, the legume production acreage increased from 1.4 % to 2.3 % of the total acreage in Sweden.

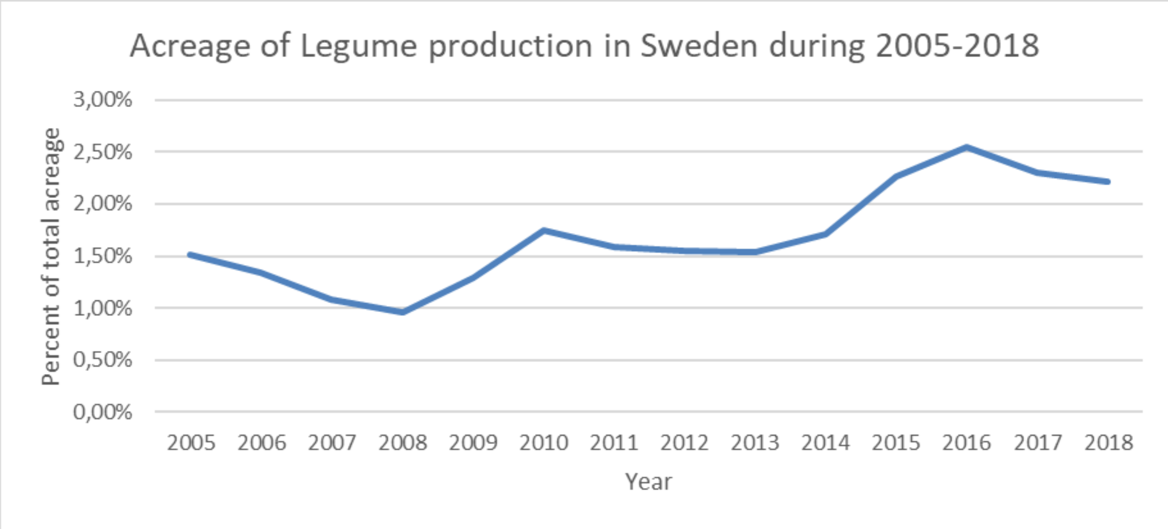

Figure 2. Total legume acreage in Sweden as a percentage of the total acreage for agricultural production (Jordbruksverket, 2018b) (own rendering)

1.2 Problem statement

In 2018, the European Union launched the protein plan; this plan intends to increase vegetable protein production in the European Union (European Comission, 2018). One goal is to diversify the cropping systems by increasing the acreage of protein crops in the union, e.g., legumes. The protein plan also proposes that the European Union should increase its self-sufficiency on plant-based protein for human consumption. Within the European Union, there is a trend towards more awareness of what people eat. People tend to consume more vegetable protein to benefit the environment (Naylor, 2016). The demand for plant-based protein for human consumption has increased by 11 % annually in the years 2013-2017 (European Comission, 2018). This green trend opens the possibility for producers to market products that might have been uneconomic to produce before due to low demand and low prices (Naylor, 2016). From the increasing demand, legumes could become more competitive in an economic perspective compared to other crops. This trend, combined with the protein plan, might increase the acreage of legumes in the European Union (European Comission, 2018).

It is widely agreed that legumes are a possible way to increase the environmental sustainability in today's cropping systems (Röös *et al.*, 2018; Reckling *et al.*, 2016a; Ebert, 2014). By diversifying the cropping system, legumes can contribute to more robust and less vulnerable systems, concerning diseases, which could reduce the dependency on pesticides and increase profits (Zander *et al.*, 2016). Previous research in an international context tend to focus on methods to evaluate the sustainability of a farm, and not predict how a farm would perform with new crops (Liu *et al.*, 2016; Robert *et al.*, 2016; Sadok *et al.*, 2009). Tidåker *et al.* (2018) presented different methods to evaluate sustainability on-farm level and found that no universal system exists. Examples of systems for assessing sustainability are the RISE and MASC systems (Sadok *et al.*, 2009; Hani *et al.*, 2003). These focus on collecting a large amount of data regarding a specific farm, and from this data, develop several indicators that contribute to assessing the sustainability of the farm.

Reckling *et al.* (2016b) performed a study of legumes and the effects it would have on cropping systems in the Swedish region Västra Götaland. Reckling *et al.* (2016b) found that the legumes had a positive impact based on the indicators, nitrogen efficiency, nitrogen leakage, and gross margin. The study that Reckling *et al.* (2016b) performed focuses mainly on the benefits of the nitrogen fixation and does not focus on the three dimensions of the triple bottom line. International studies of sustainability in agriculture tend to use other sets of indicators than Reckling *et al.* (2016b) applied, such as energy efficiency and profitability (Tidåker *et al.*, 2018; Hayati *et al.*, 2011; Yli-Viikari, 1999). The United States Environmental Protection Agency argues that it could be of importance to monitor the phosphorus usage in agriculture since it causes eutrophication (Environmental Protection Agency, n.d.). When studying crop effects and sustainability in an international context, the study apply optimization models to capture what happens in the cropping system (Liu *et al.*, 2016). From these optimization models, it is possible to identify indicators of sustainability, and these contribute to show whether the systems are more, or less sustainable (Meul *et al.*, 2008).

Within Sweden, no optimization study regarding the sustainability aspects, in terms of the triple bottom line, of legumes in a cropping system exists. This creates a gap in the literature and leads to the aim of this study (Sandberg & Alvesson, 2011). A study of the triple bottom line aspects could act as both decision support for farmers and politicians (Magrini *et al.*, 2016). For farmers, a deeper understanding of the effect legumes hold in a cropping system could be helpful in the planning of their business (Zimmer *et al.*, 2016). For politicians, information concerning the triple bottom line aspects of the legumes could be helpful when forming future policies (Meynard *et al.*, 2018).

1.3 Aim

This study aims to examine how a diversification with legumes would affect typical Swedish cereal dominated cropping systems in terms of sustainability. More specifically, the three dimensions of the triple bottom line will be investigated separately. Indicators of sustainability in each dimension are identified, and these show the effect legumes hold in the cropping system. To reach the aim, the following three research questions are developed.

- How is profitability affected when more legumes are introduced in typical Swedish cereal dominated cropping systems?
- How is nitrogen use and phosphorus use affected when more legumes are introduced in typical Swedish cereal dominated cropping systems?
- How are energy production and protein production affected, in terms of edible energy and protein for livestock and human, when more legumes are introduced in typical Swedish cereal dominated cropping systems?

To answer the questions, an optimization model is constructed of the cropping system to explore what happens when legumes are introduced. Two case farms are developed and used in the optimization model to examine how the indicators change.

1.4 Delimitations

The study is geographically limited to consider two crop-producing areas in Sweden. The crop producing areas that are considered and investigated separately are Götalands Södra Slättbygder (GSS) and Svealands Slättbygder (SS). Figure 3 shows where these crop-producing areas are located. These two regions are chosen due to the regional differences in terms of crops grown.

In SS 85 % of the cultivated cropping area is grown with only cereals (excluding ley and fallow), while in GSS 67 % of the area is grown with only cereals (excluding ley and fallow). The other percentages consist of other crops such as rapeseed and sugar beets. The exclusion of ley is motivated since crop farms rarely include ley in their cropping system (Fogelfors, 2015). In SS 1,9 % of the acreage is covered with legumes and in GSS 1,6 % of the acreage is covered with legumes, which is close to the average amount of legumes in Sweden (Jordbruksverket, 2018b).

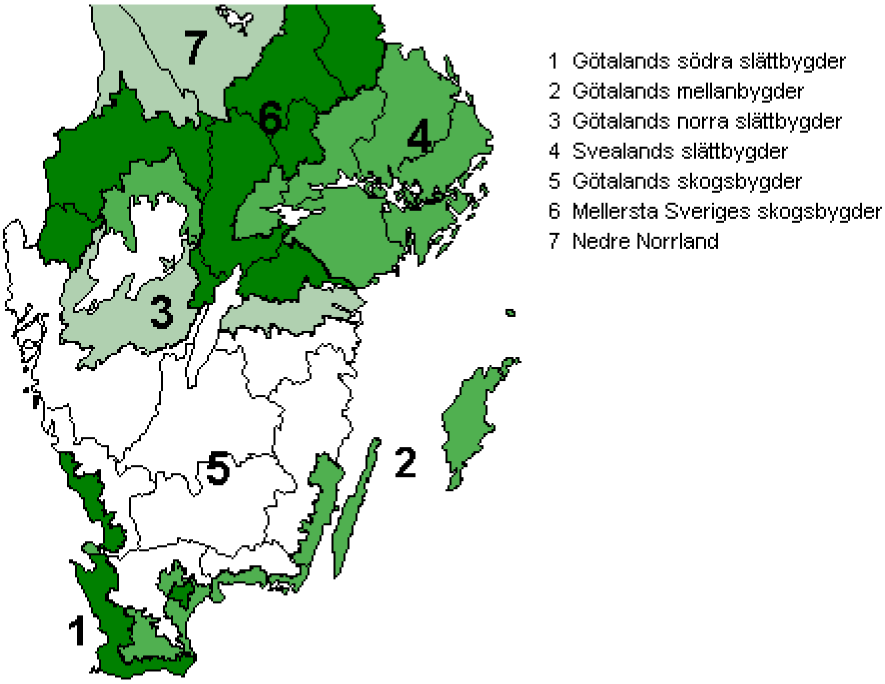

Figure 3. Production areas in southern Sweden (Jordbruksverket, 2018c) (own rendering)

Three legumes are considered in this study, broad bean, yellow peas, and feed peas. These crops are already grown in Sweden and are possible to grow in the two considered regions (Fogelfors, 2015). These three crops can be used for both feed consumption and human consumption, and this is the reason for focusing on these three crops. Other legumes are excluded due to a lack of data on harvest levels and Pre-Crop effects. The study only considers conventional production.

This study is delimited to consider cropping systems and the effects that occur within a cropping system. The effects that livestock could have in a farming system are therefore not considered. All harvested crop is expected to be sold in the market, and it is assumed that the possibility to sell the produced goods exist. The study does not consider whether market channels exist to market the products. This study is delimited to analyze the effects of diversification with legumes from a triple bottom line perspective of sustainability. This study evaluates what happens with a cropping system without legumes and with legumes, based on several indicators of sustainability. These indicators could be of help for decision makers.

The study does not consider the risk attitude of farmers and the risk that is connected to growing legumes. Reckling *et al.* (2018) argue that the risk is higher in legume crops than cereal crops. The risk is higher since the variation in legume harvest level is greater, and the farmer takes a higher risk when growing this crop. However, there is research which indicates the opposite, Döring (2015) states that yield variation of legumes is often overestimated and in some cases, it is lower than cereal yield variation. Risk is not considered in this study since focus lies on the sustainability effects of introducing legumes.

The nutritional contents of the crops can be challenging to determine (Nemecek *et al.*, 2008). This study is limited to investigate the actual energy and protein produced by the crops and not the energy that humans or animals can process. No valuation of the quality of energy and protein produced is done; instead, the differences between the two cases, no legumes and with legumes are discussed. This approach is similar to the way Nemecek *et al.* (2008) designed the study on how legumes affect cropping systems in Europe.

1.5 Structure of the report

In this section, the structure of the report is presented and is illustrated in figure 4. Chapter two presents a literature review of articles relevant for this study to obtain a deeper understanding of the research field. Chapter three presents the theoretical framework that is used in this study, and the central theories are explained. Chapter four presents the methodology applied in this paper. The fifth chapter presents the data and empirical results. The sixth chapter discusses the implications of the results, and the seventh chapter presents the conclusion.

Figure 4. Illustration of the structure of the report

2 Literature review

A literature review is a thorough and critical evaluation of previous research on a topic of interest to the author. A useful literature review will define key terminology and identify a theoretical framework for the topic being addressed (Allen, 2017). The literature review will also help to describe previous research in the field that is relevant for the aim and research question (Bryman & Bell, 2015). In this study, a narrative literature review is applied. The narrative literature review provides the potential for individual insights and opportunities for speculation compared to, for example, a systematic review (Allen, 2017).

The literature review of this paper is built around the keywords: Sustainability of legumes, sustainability indicators, cropping systems, crop rotation effects, diversification of cropping systems, optimization, and profit maximization. The databases that are used are Google Scholar, Food Science and Technology Abstracts, Web of Science, and SLUs search engine PRIMO. The material in the literature review is collected from academic journals, theses, books, and dissertations.

There are numerous scientific articles and books regarding the properties of legumes, both international and Swedish. Previous research focuses on the properties of the legumes plants and the possible contribution it could have to the sustainability of the cropping systems. The following literature review presents previous research within the field of legumes. It also presents previous research on economic models of farms and cropping systems. Lastly, it gives a brief introduction to the previous research of sustainability indicators.

2.1 Previous studies of legumes

Several articles on the properties of legumes were found in the literature review. The most relevant articles are presented in the following chapter.

2.1.1 Economic effects of legumes

Within the research field of legumes and the effects legumes can have within a cropping system a number of articles have been published (Zander *et al.*, 2016; Zimmer *et al.*, 2016; Döring, 2015; Plaza-Bonilla *et al.*, 2015; Preissel *et al.*, 2015). Preissel *et al.* (2015) performed a literature review of previous articles published on pre-crop effects and benefits of legumes. Preissel *et al.* (2015) find that the pre-crop properties affect the economic and environmental sustainability within a cropping system positively. Ebert (2014) presented similar results in his review on food security in a changing world. In the study, Ebert (2014) found that a legume supported cropping system could increase the income of the farmers because of the pre-crop effects. Ebert (2014) also found that a legume supported cropping system could increase the food security of the system. Meynard *et al.* (2018) propose that more research should be done on the economic and environmental values of legumes in cropping systems to advance the state of knowledge in the field. Research on such effects should be done in the specific regions where the crops are grown (Preissel *et al.*, 2015). Reckling *et al.* (2016b) performed a study in the Swedish region Västra Götaland to examine the effects of legumes on cropping systems in the region. Through quantitative data collected from the board of agriculture, Reckling *et al.* (2016b) simulated possible crop rotations in the region and then modeled gross margins for the crops and how the legumes affected the nitrogen usage. The findings pointed towards an environmental gain in terms of less nitrogen usage but only a small effect on the gross margin.

Most research that examines the effect crops have in a cropping system tends to be of the modeling nature (Smith *et al.*, 2017; Stagnari *et al.*, 2017; Reckling *et al.*, 2016b; Zander *et al.*, 2016). Pre-crop effects are introduced as an attribute on the subsequent crop to create an image of how the pre-crop properties affect the entire system. The effects legumes on the subsequent crop are usually an increase in yield of 500-1500 kg. This yield increase is not always considered as an attribute of the legume but rather an attribute of a subsequent plant rotation (Magrini *et al.*, 2016).

Magrini *et al.* (2016) investigated the rare presence of legumes in French agriculture from an evolutionary economics perspective. Evolutionary economics takes into account the disequilibrium of a specific event, taking place on the market. It could be a disequilibrium in terms of knowledge, technological expertise, or how the market has developed during the years investigated. According to Magrini *et al.* (2016), the profitability of legumes is too low because farmers do not calculate margins and yields at the scale of rotation. Magrini *et al.* (2016) also argue that the low presence of legumes is due to how the markets in Europe have developed. The market favors cereal crops since these are crops where expertise and knowledge exist. The market is in a lock-in that favors cereal crops. Magrini *et al.* (2016) propose that more research needs to be performed on the subject of cost-accounting methods and nitrogen management in agriculture, to get out of this lock-in. Zimmer *et al.* (2016) did a study on the attitude that Luxemburgish farmers have towards legumes. The study built on a survey-based method that tried to find an answer to the question of why farmers choose not to grow legumes. The findings pointed towards a gap in the knowledge between farmers and researchers. The main conclusion of the study was that there is a wide gap between the farmers' perception of the value of legumes and the economic fact of their relative competitiveness. Meynard *et al.* (2018) performed 55 semi-structured interviews with French farmers to find the reasons for lack of diversification in French agriculture. The authors highlight that the value-chain needs to be further developed to diversify the cropping systems in France.

Preissel *et al.* (2015) argue that the profitability within a cropping system is a way to measure economic sustainability. The argument that profitability can measure economic sustainability is supported by Hayati *et al.* (2011). Smith *et al.* (2017) conducted a study on the performance of cropping systems in Canada. In the study, different sets of crop-rotations were analyzed to check for its economic performance with and without legumes. Smith *et al.* (2017) found that the legumes had the potential to improve the gross margin of the cropping system to 194 dollars per hectare compared to the 62 dollars for the traditional crop rotation. The model Smith *et al.* (2017) designed was quantitative, and they used data from a long-term crop rotation experiment to develop the model. The traditional crop rotation in this region of Canada was considered as Wheat – Wheat – Fallow. According to Preissel *et al.* (2015), studies of the profitability of legumes in cropping systems are useful as decision support for both farmers and politicians.

2.1.2 Environmental effects of legumes

The research on the environmental effects of legumes tends to focus on the nitrogen fixating properties of the plant (Zander *et al.*, 2016; Preissel *et al.*, 2015; Therond *et al.*, 2011). The ability to fixate nitrogen is a biological property of the plant. Legumes can fixate around 130 kg of nitrogen and of that nitrogen 20-30 kg is left in plant residue for the subsequent crop (Zander *et al.*, 2016). The production of fertilizer (Nitrogen, Phosphorus, and Potassium) is energy intensive, and approximately 40 % of the greenhouse gas emissions from crop farms originate from the production of chemical fertilizer (Berglund *et al.*, 2009). In most research regarding the sustainability of legumes, nitrogen usage in the cropping system is used as an indicator of the sustainability of the system (Zander *et al.*, 2016; Preissel *et al.*, 2015; Therond *et al.*, 2011). Hayati *et al.* (2011) highlight that it could be necessary to focus on more indicators when assessing the environmental sustainability of cropping systems, and presents dependency on Phosphorus as another important indicator to account.

Phosphorus is a finite resource, and according to Cordell *et al.* (2009), an essential component in today's agriculture. Cordell *et al.* (2009) believe that it is necessary to monitor the use of phosphorus to get a good view of how the finite resource could be optimally used in the future. Since phosphorus is a scarce resource, it is likely that prices would rise in the future. Price rise on a resource could influence both the economic and environmental sustainability of a cropping system (Preissel *et al.*, 2015; Debertin, 2012). A price increase could also have a socioeconomic effect since a rise in prices would affect poor farmers first (Ebert, 2014; Cordell *et al.*, 2009). In a study of the world production on cereal and legumes, it was found that cropping systems that included legumes, used more phosphorus than the cropping systems without legumes (Lott *et al.*, 2011). The study was performed in a world content, and six continents, Asia, Europe, South America, Oceania, North America, and Africa were investigated. Lott *et al.* (2011) argue that it is essential to monitor phosphorus usage in agriculture since it holds a possibility to influence the sustainability of today's agriculture. In the study, they investigated phosphorus use in systems with and without legumes to see how the phosphorus usage was affected. The method was quantitative, and they found that the cropping system including legumes, used around 18% more phosphorus than the ones excluding legumes. According to Mitran *et al. (2018)*, legumes need more phosphorus to keep the plants growing because the phosphorus is needed in the nitrogen-fixation process.

2.1.3 Social effects of legumes

Ebert (2014) argues that legumes could be important in future cropping systems to support the growing population of the world and contribute to social sustainability. According to Ebert (2014), a legume supported cropping system could increase both the energy production of the system and protein production. Nemecek *et al.* (2008) support the arguments proposed by Ebert (2014) that protein production could increase in the system. However, Nemecek *et al.* (2008) find that energy production in cropping systems including legumes produces 1-19 percent less gross energy compared to cropping systems without legumes. If energy production and protein production is affected negatively when legumes are introduced into a cropping system, it is possible that social sustainability decreases (Ebert, 2014).

According to Stagnari *et al.* (2017), it could be of importance to perform further research on the topic of the socioeconomic effects that legumes hold. Examples of socioeconomic benefits proposed are that legumes could decrease the use of external inputs such as fertilizers and agrochemicals. This could also increase the health of the farmers growing legumes, and in the end hold a social benefit in the society as a whole (Ebert, 2014)

2.2 Economic models of farms and cropping systems

It is possible to develop empirical models of farms that economically mirror the farms (Liu *et al.*, 2016; Debertin, 2012; Andersson & Wall, 2009; Larsén, 2008; Blad, 2004). These models can be in the form of a profit maximization problem where the optimal allocation of resources within a farm is identified. These models are similar to the profit maximization models that Preissel *et al.* (2015) presented. By creating an empirical model in terms of an optimization model of the cropping systems, it is possible to change parameters within the system. These parameters could be fertilizer usage or which crop to grow. Liu *et al.* (2016) treats the subject of crop production systems and develops a dynamic model of the crop production systems. In the research, a dynamic optimization model is applied to collected data. The optimization framework is developed to account for long-term effects that crops could have in-between years factors, and data collected from several sources are used to determine the effects crops can have in the system.

Castellazzi *et al.* (2008) present a detailed economic model of crop rotations. In the paper, Castellazzi *et al.* (2008) discuss that crop rotations do not necessarily have to be fixed in terms of what crops are grown every year. Crop rotation is said to be fixed, cyclical or flexible. In flexible crop rotation, the farmer changes its decision depending on price levels and the yearly properties. The paper presents a good illustration of the decisions the farmer faces when designing crop rotations. Larsén (2008) modeled crop rotations by using crop rotational constraints in the dissertation on how collaboration affects farms in Sweden. The crop rotational constraints are designed from the biological properties of the plants, the technology available on the farm, and the area in which the crop is grown. Within the modeling of a cropping system, the information provided by Castellazzi *et al.* (2008) and Larsén (2008) is useful to mirror the decisions a farmer faces when deciding what crops to grow.

2.3 Sustainability assessment methods

Pannell and Glenn (2000) discuss the problem of the many sustainability indicators proposed by scientists. Most of the sustainability indicators today are inspired by the triple bottom line. According to Pannell and Glenn (2000), there is no guidance to which of the indicators provided in the literature that provide sufficient information about the complex issue of sustainability. A fundamental criterion for choosing to monitor an indicator is that the benefit of doing it must exceed the costs. They see no meaning to include indicators who already are widely monitored, for example, yield, weed problems, market prices, bank balance, equity, and interest rates. It should not do any different to include these indicators into a sustainability indicator framework because the farmers already consider it.

Singh *et al.* (2012) presented an overview of sustainability assessment methods and concluded that there are several existing methods to assess sustainability. Within these methods, the authors conclude that most existing approaches to measure sustainability tend to focus on environmental sustainability, and not the three dimensions of the triple bottom line. The authors argue that it could be of importance to think of the interlinkages between indicators and between different properties within a system. Tidåker *et al.* (2018) did a review on the many sustainability indicators that exist today; in the review, it is concluded that no universal system exists. However, it can be noted in the review that when assessing the sustainability of a cropping system, most assessment methods try to assess the sustainability of the three dimensions of sustainability. According to Hayati *et al.* (2011), it is essential that sustainability indicators capture the three dimensions of sustainability. No single indicator can do this; instead, a set of indicators can be used to assess sustainability.

2.4 Summary of literature review

Table 1. Earlier studies within the research field regarding legumes, cropping systems and sustainability indicators presented in alphabetical order

Author	Subject	Region	Method
Andersson and Wall (2009)	Emissions from Swedish farms	Sweden	Quantitative modeling
Berglund *et al.* (2009)	Emissions from Swedish agriculture	Sweden	Quantitative
Blad (2004)	Modeling of farms	Sweden	Quantitative modeling
Castellazzi *et al.* (2008)	How to model crop-rotations	UK	Quantitative
Cordell *et al.* (2009)	Food security and phosphorus	Global	Review
Debertin (2012)	Agricultural production economics	Global	Book
Döring (2015)	Discusses legumes in cropping systems	Europe	Quantitative
Ebert (2014)	Food security and cropping systems	Taiwan	Qualitative
Hayati *et al.* (2011)	Ways to measure agricultural sustainability	Global	Review
Larsén (2008)	Presents methods to model cropping systems	Sweden	Quantitative
Liu *et al.* (2016)	Economic model of crop rotations	Not clear	Quantitative
Lott *et al.* (2011)	Role of phosphorus in legume and cereal production	Global	Quantitative
Magrini *et al.* (2016)	Presence of legumes in French agriculture	France	Qualitative/quantitative
Meynard *et al.* (2018)	Diversification in French agriculture	France	Qualitative
Mitran *et al.* (2018)	Phosphorus role in legume production	Global	Review
Nemecek *et al.* (2008)	Protein and Energy production in agriculture	Europe	Modeling
Pannell and Glenn (2000)	Sustainability indicators in agriculture	Australia	Quantitative
Plaza-Bonilla *et al.* (2015)	Discusses the benefits of legume plants	France	Field study and simulation
Smith *et al.* (2017)	Diversification of crop rotations	Canada	Quantitative
Zander *et al.* (2016)	Increase legumes in the EU	EU	Review
Preissel *et al.* (2015)	Benefits of legumes in cropping systems	Europe	Modeling/quantitative
Reckling *et al.* (2016b)	Assessment of legumes in cropping systems	Germany, Sweden	Quantitative
Singh *et al.* (2012)	Overview of sustainability assessment methods	Global	Review
Smith *et al.* (2017)	Diversification of crop rotations	Canada	Quantitative
Stagnari *et al.* (2017)	Benefits of legumes	Not clear	Quantitative/review
Therond *et al.* (2011)	Modeling of cropping systems	EU	Quantitative simulation
Tidåker *et al.* (2018)	Ways to measure sustainability	Sweden	Review
Zander *et al.* (2016)	Decline in legume production	EU	Review
Zimmer *et al.* (2016)	The gap of knowledge on legume production amongst farmers	Luxembourg	Qualitative

Research exists both on indicators of sustainability, cropping systems, and the effects of introducing legumes in cropping systems. Table 1 shows the articles which are identified as the most important ones in the literature review. Most studies identified in the literature review have been performed in other countries than Sweden. Within Sweden, only one study that examines the effects of legumes in cropping systems has been identified (Reckling *et al.*, 2016b). The study performed by Reckling *et al.* (2016b) focuses on nitrogen use and efficiency within the cropping system and does not capture all the dimensions of the triple bottom line.

According to Hayati *et al.* (2011), it is of importance to capture all three dimensions of the triple bottom line when assessing sustainability. The theoretical gap that is identified is that no previous study has focused on the three dimensions of the triple bottom line within legume production in Sweden. It is also identified that a common way to measure how diversification affects a cropping system is by performing simulations with different types of crop combinations and collect indicators of how the system performs (Smith *et al.*, 2017). This study aims to fill this gap and to provide relevant decision support for farmers when forming decisions regarding the cultivation of legumes.

3 Theoretical framework

This chapter presents the central theories applied in this paper. Firstly applied microeconomics is introduced and the theories of profit maximization. Secondly, the theories regarding sustainability and sustainability indicators are introduced. Finally, alternative theoretical approaches are presented, and arguments are presented on the suitability of the theoretical framework applied in this paper.

3.1 Applied microeconomics and production economics

A central part of this study has microeconomics as a theoretical ground. The foundation of microeconomics is about the economic behavior of individual entities (Pindyck, 2018). Production economics is an area within the microeconomic theory, which is mainly applied in this study combined with theory regarding sustainability. Production economics describes, based on the preferences of a producer, for example, the complex relationship between economy, technology, and biology and how limited resources are optimally utilized (Olhager, 2013).

Producers are often assumed to maximize the profits of their businesses, but they could have other individual goals (Debertin, 2012). In the case of agriculture, farm managers design their farm to maximize profits based on resource restrictions such as land, labor and climate conditions, but they could also organize their farm to maximize farm size or minimize climate impact. One thing that suggests that farmers choose to maximize profits is that they can use the profits to meet other goals.

3.1.1 Profit maximization

Profit maximization aims to produce the products and the number of products that yield the highest profit (Debertin, 2012). Equation (1) generally describes the simplest maximization problem with one output product and one input resource.

$$\Pi = P_y * Y - P_x * X \qquad s.t.\ Y \geq 0,\ \ X \geq 0 \qquad (1)$$

Where the profit (Π) is obtained through the difference between total revenue and total cost (Debertin, 2012). Total revenue is obtained by output price (P_y) and quantity produced (Y), and the total cost is obtained by input price (P_x) and the quantity of used resources (X).

The quantity (Y) depends on the number of inputs and is explained like a function of the input ($f(X)$) (Debertin, 2012). The quantity (Y) can also be fixed, and the number of inputs (X) depends on the quantity (Y) and is explained like a function of output($X(Y)$). The functions describe the biological and technical relationship between input and output, and it is called the production function. In the short term, there are often costs that are not affected by the quantity produced (Y), and these are fixed costs (FC). A general form of this relationship is presented in equation (2) and (3).

$$\Pi = P_y * f(X) - P_x * X - FC \qquad s.t.\ X \geq 0 \qquad (2)$$

$$\Pi = P_y * Y - P_x * X(Y) - FC \qquad s.t.\ Y \geq 0 \qquad (3)$$

Maximal profit is given by the relationship in equation (4) an (5) where marginal revenue is equal to marginal cost (Debertin, 2012).

$$\frac{\partial \Pi}{\partial X} = 0 \implies P_y * \frac{\partial f(X)}{\partial X} - P_x = 0 \implies \frac{\partial f(X)}{\partial X} = \frac{P_x}{P_y} \quad (4)$$

$$\frac{\partial \Pi}{\partial Y} = 0 \implies P_y - P_x * \frac{\partial X(Y)}{\partial Y} = 0 \implies \frac{\partial X(Y)}{\partial Y} = \frac{P_y}{P_x} \quad (5)$$

Producers often act in situations where many different inputs are required to produce many different outputs (Debertin, 2012). Equation (6) describes a general profit maximization problem with many outputs and many inputs.

$$\Pi = P_{Y1} * Y_1 + \ldots + P_{Ym} * Y_m - P_{X1} * X_1 - \ldots - P_{Xn} * X_n - FC \quad (6)$$

Where:
$Y_1 = f_1(X_1, \ldots, X_n)$
$Y_m = f_m(X_1, \ldots, X_n)$
Or:
$X_1 = X_1(Y_1, \ldots, Y_m)$
$X_n = X_n(Y_1, \ldots, Y_m)$

In the agricultural sector, farm managers face a situation such as described in equation 6. The farm manager must determine which crops/products ($Y_1, \ldots, Y_m$) to grow, such as wheat, barley, rapeseed and legumes, and how much inputs ($X_1, \ldots, X_n$) such as fertilizer, seed, chemical and, labor to be used for each crop. The price levels of the inputs and outputs could influence the economic sustainability of a farm (Preissel *et al.*, 2015). Depending on the price levels of the inputs, the profit can either raise or fall (Debertin, 2012). A rise in prices of outputs could affect how much a specific input is used, and if the input price of a resource increases, it could affect the optimal allocation within the analyzed system. In the case of this study, a high price on the resource nitrogen might contribute towards a profit maximization solution with more legumes. This because of the pre-crop properties, and the fact that it contributes to 20-30 kg of nitrogen to the preceding crop (Zander *et al.*, 2016).

3.2 Indicators of sustainability

Today, a lot of the frameworks that exist to measure sustainability account for the three aspects of economic, social and environmental sustainability (Tidåker *et al.*, 2018; Singh *et al.*, 2012; Labuschagne *et al.*, 2005). Within these frameworks, it is common to design indicators that can measure distinct parts of the sustainability dimensions, as is shown in figure 5. These indicators are designed to capture the effects in separate parts of the system where sustainability is measured (Labuschagne *et al.*, 2005).

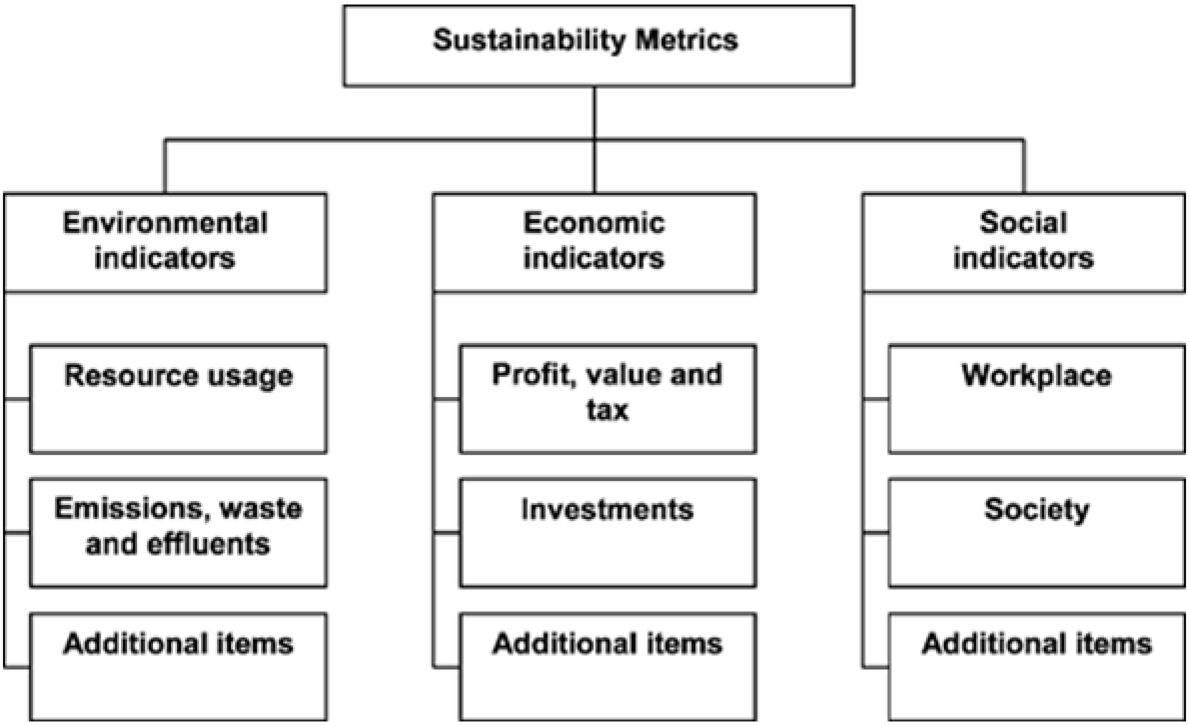

Figure 5. Example of an indicator framework and what indicators can measure (Labuschagne et al., 2005)

The indicators can be designed to measure the effects that take place within the system if a change is made to the system. According to Pannell and Glenn (2000), it is essential that the benefits of evaluating a system with an indicator exceed the costs of doing it. Sustainability is a complex issue, and no single indicator can measure all three dimensions of sustainability. According to Nijkamp and Lancker (2000), a major scientific challenge in any analysis of sustainability is to offer an empirical test to whether a given system is more sustainable than another case. Further on, Nijkamp and Lancker (2000) argue that it is necessary to specify a set of sustainability indicators that can be measured in either a qualitative or quantitative way. It is not necessary to determine whether one state is more or less sustainable, but rather, the indicators should be seen as pointers that help in development planning and decision-making. Within the field of sustainability, there are specific frameworks that are designed to assess the sustainability of agricultural systems. These indicators could, therefore, serve as useful information for farmers in the planning of their business, or decision makers when forming policies.

3.2.1 Indicators of sustainability within agriculture

As explained in the previous section, sustainability indicators deal with the complex issue of measuring sustainability, and no single indicator can measure all dimensions of sustainability (Pannell & Glenn, 2000). Within the field of agriculture, there are some developed frameworks to measure sustainability at the farm level (Tidåker *et al.*, 2018). According to Hayati *et al.* (2011), most of the frameworks and indicators designed to measure the sustainability of agriculture are suitable to evaluate the sustainability of agriculture at an aggregate level. However, Hayati *et al.* (2011) argue that there are indicators that can capture sustainability effects within a farm system, and to capture the effects it is necessary to define a boundary of the system that is analyzed. The distinct systems can be cropping systems, farming systems, or landscape district levels. In this paper, the limit of the system is the cropping system.

The indicators for sustainability within the field of agriculture are designed to capture specific issues that a farmer can face (Tidåker *et al.*, 2018). Indicators of sustainability within the field of agriculture could be indicators such as crop yield, nitrogen usage, and energy production. The literature regarding indicators of sustainability within farming systems presents a diversity of distinct frameworks to evaluate sustainability performance (Keys, 2017; Singh *et al.*, 2012). Examples of such frameworks are the MOTIFS, RISE, and MASC framework (Craheix *et al.*, 2016; Sadok *et al.*, 2009; Meul *et al.*, 2008; Hani *et al.*, 2003).

Nambiar *et al.* (2001) present six considerable criteria when designing and constructing indicators for sustainability in agriculture. The six criteria are: (i) Social and policy relevance (economic viability, social structure, etc.); (ii) Analytical soundness and measurability; (iii) Suitable for different scales (e.g., farm, district, country, etc.); (iv) Encompass ecosystem processes and relate to process-oriented modeling; (v) Sensitive to variations in management and climate; (vi) Accessible to many users (e.g., acceptability). In the research by Nambiar *et al.* (2001), a number of different indicators are presented that can help assess the sustainability of a farm, e.g., crop yield, soil quality, and agricultural management practices.

3.2.2 Indicators applied in this study

The indicators applied in this paper are indicators of profitability, nitrogen usage, phosphorus usage, energy production, protein production within the cropping system, see table 2. These indicators are based on what is found relevant in the literature review and are also proposed in the paper by Hayati *et al.* (2011) as indicators that can measure the sustainability of agriculture. These all fit in on the criteria proposed by Nambiar *et al.* (2001). According to Hayati *et al.* (2011), dependency on fertilizer, such as Phosphorus and Nitrogen, shows the dependency on natural resources. Energy production and protein production show how the system manages to provide food for the growing population of the world, and profit will act as an indicator of economic sustainability. By combining these indicators, it is possible to measure the three dimensions of the triple bottom line. By assessing the farm with these indicators, it is possible that some other important aspect of sustainability is omitted. This could, for example, be the dependency on herbicides or pesticides. The indicators proposed by Hayati *et al.* (2011) are applied to assess the sustainability of the cropping systems.

Table 2. The indicators applied in this study based on the research by Hayati et al. (2011) and Nambiar et al. (2001)(own rendering)

Economic sustainability	**Environmental sustainability**	**Social sustainability**
Profitability	Nitrogen usage	Energy production
	Phosphorus usage	Protein production

In table 2, it is shown what dimension of the triple bottom line the indicators are expected to measure. Profitability is proposed to be the indicator that measures economic sustainability. This indicator was proposed as an important economic indicator by Zhen and Routray (2003) and Hayati *et al.* (2011). The measurement of environmental sustainability is nitrogen usage and phosphorus usage. These indicators can act as important measurements of environmental sustainability because they hold the ability to capture both effects on eutrophication and decrease in emissions (Hayati *et al.*, 2011; Lott *et al.*, 2011). Social sustainability is measured through energy production and protein production, which both act as indicators of food security (Ebert, 2014). The energy production is measured in the unit megajoule (MJ).

3.3 Motivation of theories and alternative theoretical approach

The profit maximization theory, combined with indicators of sustainability that are inserted in the empirical model introduced in chapter 4, will help answer the research questions of this study. Creating an experimental profit maximization model to examine the effects of diversification with legumes in a Swedish cropping system is considered the best possible theoretical choice. By creating a profit maximization problem and using applied optimization, the possibility to identify how the cropping system acts under different circumstances is possible. The result may be useful both for farmers in decision making on production systems and for policymakers. The theory allows the researchers to identify how the cropping system performs with and without legumes. By introducing indicators, profitability, nitrogen usage, phosphorus usage, energy production, and protein production, in the model, it is possible to indicate how the three dimensions of sustainability of the systems change under different circumstances. The profit maximization model in this paper is inspired by the previous work of Jonasson (1996), Brady (2003), Blad (2004), Larsén (2008) and Andersson and Wall (2009).

Evolutionary economics perspective is another theoretical approach, which would be a possible way to understand why there is a lack of diversification within the cropping systems of Sweden. This study could be carried out similarly as the study by Magrini *et al.* (2016), where semi-structured interviews were carried out with stakeholders in the agricultural sector of France to identify why there has been a decrease of legume production in France. If a similar study is done in Sweden, it would create a possibility to increase the knowledge of why farmers choose not to grow legumes. The paper by Magrini *et al.* (2016) would be useful if this study aimed to find the reasons behind the relatively low production of legumes in Sweden and possible ways to solve this. This type of study would create a possibility to identify necessary policy changes or necessary technological changes.

The study conducted by Zimmer *et al.* (2016) is also an inspiration for another theoretical approach. The study investigated the value-chains of linseed, peas, and hemp in France. A similar approach within this study would create a possibility to identify whether there are lock-ins in the value-chain that favor the dominant cereal crops. If this study aimed to investigate why there is a lack of diversification within the Swedish cropping system, a similar approach would be suitable. An approach similar to the approach by Zimmer *et al.* (2016) would be of help to identify the socio-technical factors that cause farmers to make the decisions to grow the most dominating cereal crops. This type of study could be carried out with a qualitative approach with interviews of stakeholders in the agricultural industry of Sweden, similar to the approach by Zimmer *et al.* (2016).

4 Method

This chapter presents the chosen research strategy and the research design of this study. How the data is collected, and the sources of data are presented. It also presents the empirical model and how the model is designed. Lastly, reliability, validity, and ethical considerations of the research are presented.

4.1 Research strategy

When designing a study and choosing a research strategy, the researcher is generally faced with two different options, the qualitative and quantitative research strategy (Saunders, 2007). Depending on the choice of research strategy, the study may reach different results. This occure since there are differences in the way data is collected and how the analysis is performed. This study aims to examine how a diversification with legumes would affect typical Swedish cereal dominated cropping systems in terms of sustainability. To reach the aim, a quantitative method is applied with a deductive approach and an experimental design. The deductive approach is applied since the purpose of this study is to answer questions and not to generate a new theory (Bryman & Bell, 2015). A quantitative researcher is generally faced with two types of modeling designs, experimental and descriptive. An experimental study determines the causality between variables, and the descriptive determines the relationship (Bryman & Bell, 2015). When applying the theory of profit maximization to numerical data, the causality between the variables is determined and not only the relationship (Debertin, 2012).

According to Bryman and Bell (2015), it is important to mention the ontological and epistemological standpoint when performing research. In this research, the ontological standpoint is objectivism and refers to the philosophical standpoint that there is an objective reality and that events take place independently of social actors. The sustainability effects of legumes in a cropping system are connected to the biological properties of the plant that is introduced in the system (Lott *et al.*, 2011). Therefore, our standpoint is that the role of the social actor is somewhat reduced. The social actor influences the cropping system by choosing what crops to grow and input to use. Once the decision has been made, the social actor does not influence the sustainability of the system. The epistemological standpoint in this paper is positivistic, which means that it is believed that knowledge is based on natural phenomena (Saunders, 2007). The study is based on empirical data where theory is used to examine the issue, and the positivistic standpoint fits the study. In the positivistic view, the influence of the researcher on the data is marginal (Saunders, 2007). As an example, the researcher cannot change the properties of the plants; this is a fact and not something that the researcher influence (Bryman & Bell, 2015; Fogelfors, 2015). It could be argued that the researcher influences the collection of data and the choice of research method (Saunders, 2007). By using a structured methodology in this paper, the aim is to make the study replicable, and another researcher should achieve similar results (Gill & Johnson, 2002).

4.2 Research design

The research design of a study provides the framework for the collection of data and analysis of the data (Bryman & Bell, 2015). The research design of this study is inspired by previous research in the field (Liu *et al.*, 2016; Reckling *et al.*, 2016b; Lehtonen *et al.*, 2005). In general, researchers tend to use similar frameworks as previous research (Yin, 2009). Yin (2009) argues that this is a good way to make the results comparable to previous studies. The previous studies mentioned above have all created experimental models of cropping systems to solve the research problem in question.

According to Yin (2009), the choice of research design can affect the generalizability of the results. In this study, a case study research design is used to collect the data for the study. Two fictitious case farms are examined; this can affect the generalizability of the study since the investigation will provide results from two different farms. Since these farms are located in two regions of Sweden with different production conditions, it is possible that the results are difficult to generalize. However, by using two case farms, the generalizability could raise compared to a study with only one case (Yin, 2009). In a multiple case study with more than two cases, the results can become more generalizable than in a study with two cases. By using two cases from different regions of Sweden, it is possible to create a picture of the situation in different parts of Sweden. Since the case farms are designed to mirror a crop-producing farm in each region, it is possible that another farm with similar production conditions would show similar results.

The use of fictitious case farms is inspired by previous research of Reckling *et al.* (2016b) and Andersson (2018). The fictitious case farms mirror cereal-producing farms in the two regions SS and GSS. A statistical comparison of how cereal-producing farms are organized is made through aggregate data from the Swedish Board of Agriculture. This statistical analysis consists of an analysis of how the farms allocated their cropping land and are used to develop a fictional crop rotation. This crop rotation is presented as the current state in the methods chapter 4.3 and is used to calculate the indicators for the current state. A more extensive background to the case farms are presented in chapter 4.3. Agronomic expertise through crop advisors is used to discuss if the case farms correctly mirror a cereal-producing farm in the distinct region (pers, comm., Eriksson, 2019; pers comm., Lagerholm, 2019).

The case study is constructed as an experimental study since the intention is to find out what happens to the case farms if legumes are introduced into the cropping system (Stake, 1995). An experimental model in terms of an optimization model is then developed to reach the aim of this study. The two case farms are used to evaluate different scenarios. These scenarios are the two case farms with and without legumes. The experimental design intends to find out what happens with the indicators proposed in table 2, chapter 3.2.1, profitability, nitrogen use, phosphorus use, energy production, and protein production. These indicators are calculated for a scenario with legumes and one scenario without legumes. The indicators will then consist of what happens within the system, depending on the level of legumes within the system.

There is some critique against case studies. Yin (2009) highlights that researchers performing case studies could allow a biased view in their collection and report of data which could influence the results. To try and not influence the results is necessary to consider while performing case study research (Bryman & Bell, 2015). To somewhat eliminate the risk of biasedness in the report of data, it is important that the researcher is careful to report data and findings fairly and correctly (Yin, 2009).

4.3 Case farms

This study develops two fictional case farms, one for the region GSS and one for the region SS. The two farms are located in regions GSS and SS, the allocation of the farms to these regions is made due to their differences in production today (Jordbruksverket, 2018b). In SS, 90 % of the cultivated area is covered with cereals, excluding ley, and in GSS, 70 % is covered with cereals, excluding ley. According to Fogelfors (2015), crop farms rarely include ley in their cropping systems; therefore, ley is not included in this research. The mathematical model, which is presented in chapter 4.4.2, is based on the fictional case farms.

The case farms are developed from aggregated data from the Swedish Board of Agriculture and expertise supplied by Växtråd and HIR Skåne (Jordbruksverket, 2018b; pers. comm., Eriksson, 2019; pers. comm., Lagerholm, 2019). The case farms are parameterized to mirror large crop-producing farms in the two examined regions. In Agriwise, where part of the data is collected, the possibility exists to choose either a 150-hectare farm or a 500-hectare farm (Agriwise, 2018b). The choice is made to create a 500-hectare farm since this might more correctly mirror how farms would be organized in the future due to the ongoing structural change (Wästfelt & Eriksson, 2017). It is thought that the structural rationalization in Sweden will lead to larger farm units in the future, therefore the larger farm size of 500 hectares is chosen.

The fictitious case farms are developed through a statistical analysis of data concerning crop-production during the years 2008-2017. The analysis consisted of acreage distribution for each year concerning every single crop that was grown in the region (Jordbruksverket, 2018a). All crops that were grown on less than 5 % of the acreage are excluded since these crops are expected to be marginal. This, since they are not expected to be grown on the average farm if it is grown with such low acreage. The crops that are found to be the most common in GSS are oats, barley, winter wheat, rapeseed, and sugar beets. In SS, the most commons crops are oats, barley, winter wheat, rapeseed, and spring wheat. The allocation of the crops in the two distinct regions is shown in figure 6.

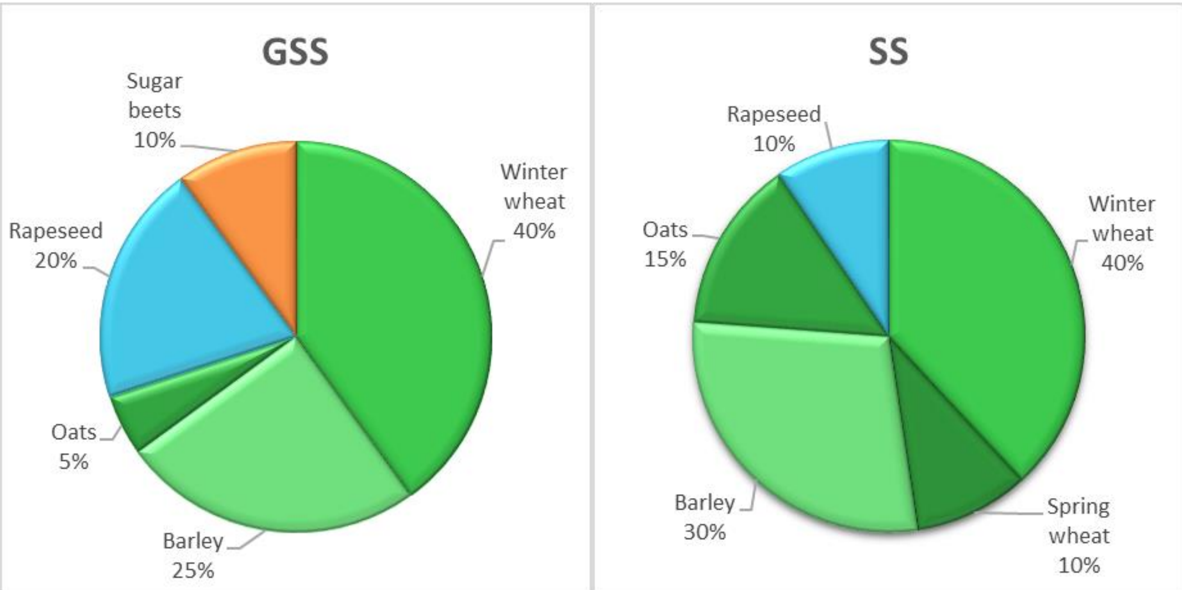

Figure 6. The crop allocation at the two case farms (Jordbruksverket, 2018b)(own rendering)

From the data, the most profitable crop rotation for the current state is developed by inserting the acreage in the optimization model. The crop rotation included all crops found in the statistical analysis and is shown in figure 7 for region GSS and figure 8 for region SS. This is the state the case farms are expected to use today. The crop rotation mainly builds on the statistical data that is analyzed but has also been compared to the crop-rotation schemes presented by Fogelfors (2015). The rotation is a flexible cyclical crop rotation. Thus the rotation is not linear but mainly depends on crop rotational constraints (Castellazzi *et al.*, 2008). According to Castellazzi *et al.* (2008), such a crop rotation better represents the decision-making process behind a crop rotation. This since prices and yearly differences, could force a farmer to change his/her decision on what crops to grow (Fogelfors, 2015). The rotation is fixed in length and returns to the starting point every fifth year due to crop rotational constraints (Castellazzi *et al.*, 2008).

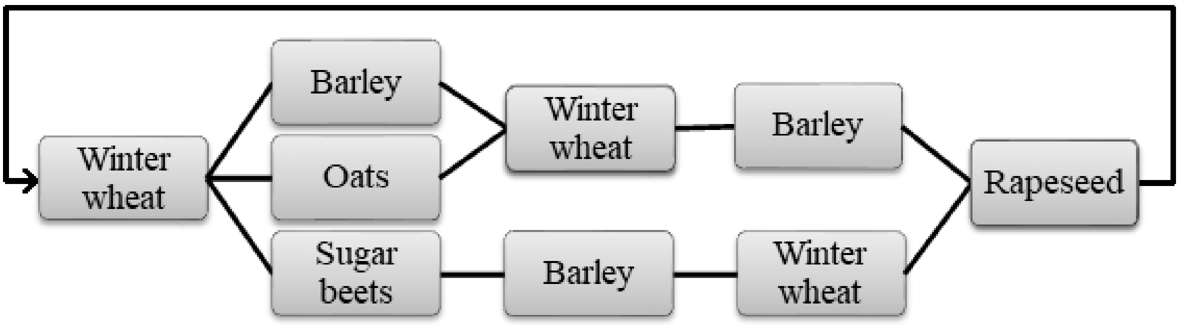

Figure 7. The current state in region GSS, this is what is grown on the case farm

In figure 7, the current crop rotation in GSS is presented. The crop rotation is a flexible cyclical rotation that allows the farmer to choose within the crop portfolio. However, the rotation always starts with winter wheat and ends with rapeseed. This mirrors how the case farms work today. By introducing legumes into the system, it is possible to identify how it would affect the indicators presented in table 2 chapter 3.2.1. With this current state, it is possible to use the indicators to measure the values in the current state and compare these with the state where legumes are introduced as a diversifying crop. In figure 8, the current crop rotation in SS is presented. This one differs from the one in GSS since it starts with winter wheat and ends with barley. The farm in SS is expected to grow less rapeseed each year, because of the shorter period to seed rapeseed in SS (Fogelfors, 2015).

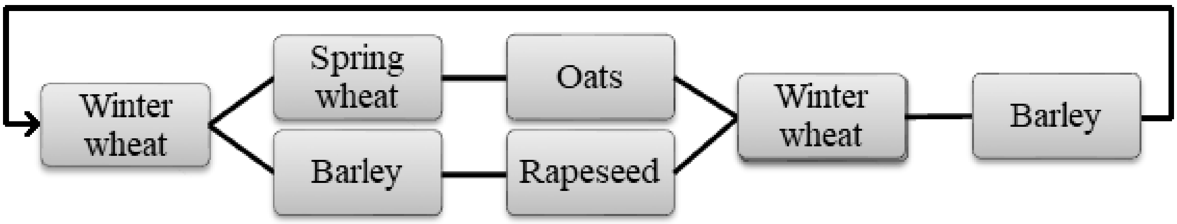

Figure 8. The current state in region SS, this is what is grown on the case farms

4.4 Data collection

Data is collected from several sources. The case farms introduced in the previous chapter are used as instruments to collect suitable data to reach the aim of this study. Crop data are collected for winter wheat, spring wheat, barley, oats, rapeseed, sugar beets, yellow peas, feed peas, and broad bean. All data is processed in Excel to fit into the linear optimization model, which is introduced in chapter 4.4.2.

All the data that is used to answer the research questions and reach the aim are secondary data. An advantage of using secondary data is that less time is spent collecting the data, and more time can be spent on conducting the analysis and designing the optimization model. According to Bryman and Bell (2015), this recommendable since it allows the researcher to focus on answering the research question without having to go through the time-consuming process of collecting primary data. One limitation of using secondary data is the lack of control of data quality. Since the data might have been collected for commercial purposes, it could be necessary to evaluate and discuss the quality of the collected data (Saunders, 2007). By mainly using data from governmental agencies, this problem is somewhat reduced (Bryman & Bell, 2015). An overview of the collected data is presented in appendix 1.

The data on yield levels of the selected crops are collected from the statistical database of the Swedish Board of Agriculture (Jordbruksverket, 2018b). The data regarding yield levels are collected for the years 2008-2017. This data is aggregated data from the regions SS and GSS. The statistical database of the Swedish Board of Agriculture contains harvest levels of all the chosen crops except yellow peas. The yield levels of the yellow peas are supplied from Kalmar Ölands Trädgårdsprodukter (KÖTP) and are the measured harvest levels of the years 2010-2017 (Pers., comm. Zedig, 2019). The organization KÖTP is located on the island Öland in southeast Sweden, and it is an area in Sweden that grows a lot of legumes. In the region where KÖTP is located the harvest level of yellow peas is 5 % lower than the harvest level of feed peas (Jordbruksverket, 2018b; Pers., comm. Zedig, 2019). The harvest level for yellow peas that are used in the empirical model is assumed to be 95 % of the average harvest level of feed peas in the respective region, GSS, and SS.

All data concerning input variables such as nitrogen and phosphorus are gathered and calculated through Agriwise (Agriwise, 2018b; Agriwise, 2018a). All the input variables are average values for the years 2008-2017. Corresponding price levels for all products are gathered from the statistical database of the Swedish Board of Agriculture (Jordbruksverket, 2018b). The database used for collecting the energy and protein levels is USDA (United States Department of Agriculture, 2018). This database contains nutrient information regarding all crops except sugar beet and rapeseed. The energy and protein levels of sugar beet are collected from the company Magnihill, which is a food processing company in southern Sweden (Magnihill, 2018). Data regarding the energy contents of rapeseed is collected from a previous study by Grau *et al.* (2013), the protein level of rapeseed is collected from a seminar performed by Lantmännen at KSLA in 2011 (Lantmännen SW seed, 2011) The data on pre-crop properties are collected from the Swedish Board of Agriculture (Jordbruksverket, 2018c). They present pre-crop properties for several crops, including legumes. This data is compared to other findings to check the quality of data (Bryman & Bell, 2015). The pre-crop properties presented by the Swedish Board of Agriculture match the data in previous studies (Reckling *et al.*, 2016b; Fogelfors, 2015).

4.5 Empirical model

In this chapter, the method of optimization is explained and is followed by an introduction of the empirical model.

4.5.1 Applied optimization

In optimization, the aim is to use applied mathematics to find the best decision alternative in different decision situations (Lundgren, 2008). By using the theory of profit maximization and applying a linear optimization model, it is possible to examine how a farmer can allocate resources most optimally in a given situation. By creating an objective function, which is subject to a number of constraints, it is possible to find the best possible solution under the given circumstances. From the optimization model, the indicators described in chapter 3.2.1 can be determined.

To analyze a problem through linear optimization, it is necessary to follow a number of steps that are presented in figure 9. The first step is to identify the real problem; in this step, the problem is identified (Lundgren, 2008). The real problem is characterized by complexity and many factors that influence it. Therefore it is necessary to delimitate the problem and simplify it. In this case, it could be the delimitation, not to account for risk attitudes of farmers towards legumes. Once the problem has been simplified, the optimization model is developed as a mathematical problem (Lundgren, 2008). When the mathematical problem is developed, considerations have to be made of what data is available. From the mathematical problem, the optimization model is developed. This optimization model includes an objective function and the relevant constraints connected to the problem. In the case of this research, these constraints are crop rotational constraints and acreage constraints. The objective function is the profit maximization function. Once the optimization model is developed, Excel is used to solve the optimization problem. From this solution, the results are derived. It is necessary that these results are validated and verified before using them as information in a decision-making process.

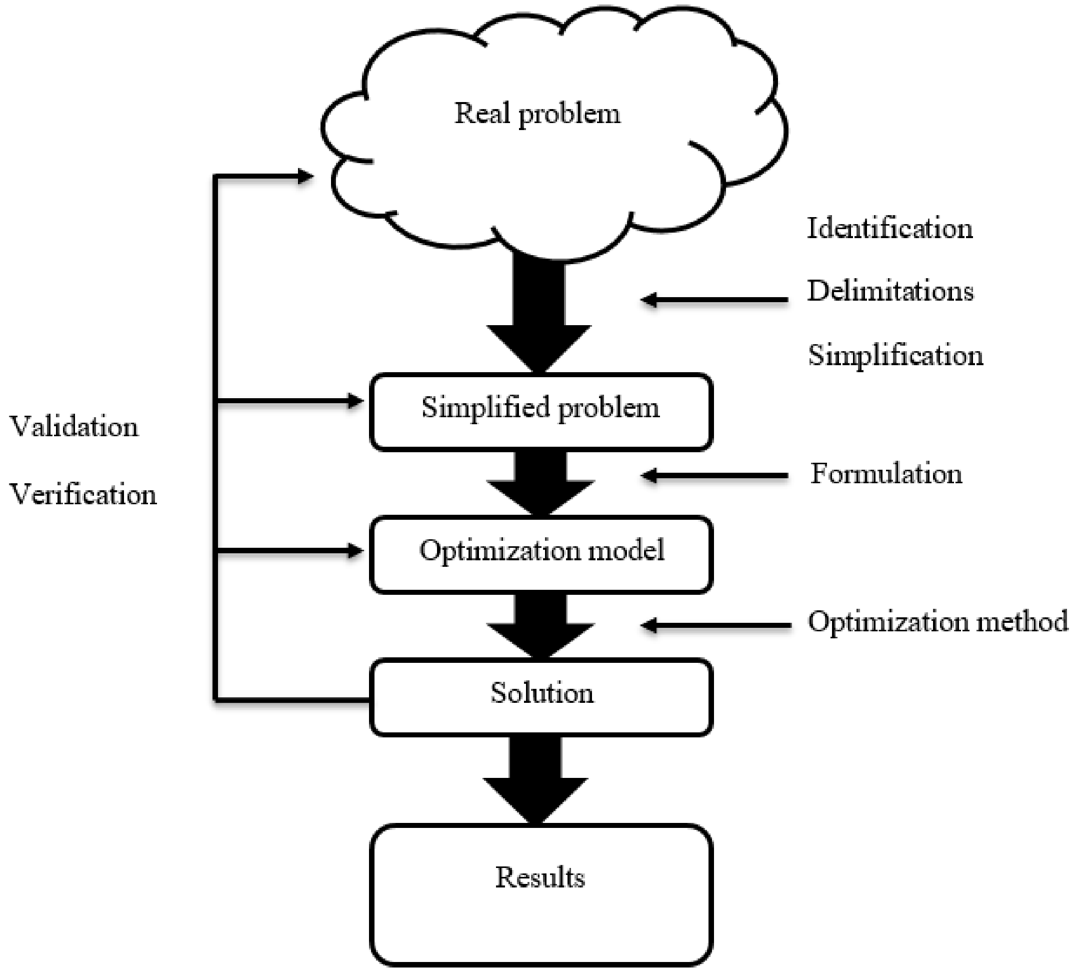

Figure 9. Illustration of the optimization process (Lundgren, 2008) (Own rendering)

In this research, a Simplex LP algorithm is used to solve the linear problem. This algorithm solves the linear problem by finding the corner solutions and is a suitable algorithm in linear optimization (Lundgren, 2008). The algorithm finds the best possible solution concerning the available solutions and maximizes the objective function. For each constraint that is binding, a shadow price is found. The shadow price represents the value that one extra unit of the binding constraint would contribute to the objective function. The results on the indicators and the shadow prices are confirmed and validated through comparison to previous research and theory in the analytical section of the paper and by discussion with crop advisors (Smith *et al.*, 2017; Liu *et al.*, 2016; Magrini *et al.*, 2016; Preissel *et al.*, 2015).

4.5.2 Optimization model

From the fictional case farms, an optimization model is developed. This model includes crop rotational constraints, acreage constraints, and indicators of what happens in the system. The indicators are designed as monitors of identified factors that could show how the system is affected, given different scenarios. These indicators are helpful to assess the effects of diversification on the sustainability of the farm. It is a profit maximization model that tries to find the optimal crop rotation with and without legumes.

The model in equation 7 is a maximization problem where the aim is to maximize profits in the cropping system. This profit maximization problem is subject to the three types of constraints presented in equations 8, 9, and 10. The first constraint is related to the size of the farm and states that the total acreage of grown crops cannot exceed the total size of the farm. The second type of constraint is related to the limitation of how much of each crop can be grown, and these constraints create the possible crop rotations. The third type of constraints state which type of crop that can be grown after each crop. An overview of the constraints is presented in appendix 2. Lastly, the indicators applied in this study are presented in equations 11, 12, 13, 14, and 15. These indicators are average per hectare of profit, nitrogen usage, phosphorus usage, energy production, and protein production. For each state with and without legumes, the indicators will show what happens to the system.

The model is a mathematical representation of the fictional case farms introduced in section 4.3. The mathematical model is inspired by the previous work of Jonasson (1996), Brady (2003), Blad (2004), Larsén (2008) and Andersson and Wall (2009). As explained in the research approach chapter, the model is an experimental model, and it is used to predict the differences between scenarios (Stake, 1995). There is some critique of such an approach because predictions are not always correct. The experimental model in this study tries to explain what happens when more legumes are inserted; if all parameters are not correct, it is possible that the prediction becomes incorrect.

The visualization of the empirical problem is shown below in equation 7.

$$\Pi = \sum_{j=1,m=1}^{J,M} X_{j,m}\, Y_{j,m} P_j - (\sum_{j=1,m=1}^{J,M} X_{j,m}((N(Y_{j,m}) - N_m)P_N + Ph(Y_{j,m})P_{Ph} + C_{j,m})) \quad (7)$$

With constraints:

$$\sum_{j=1,m=1}^{J,M} X_{j,m} \leq \bar{X} \quad (8)$$

$$\sum_{m=1}^{M} X_{j,m} \leq \bar{X_J} \qquad \forall\, j = 1 \dots J \quad (9)$$

$$\sum_{j=1}^{J} X_{j,m} \leq X_m \qquad \forall\, m = 1 \dots M \quad (10)$$

And indicators:

$$\frac{(\sum_{j=1,m=1}^{J,M} X_{j,m} Y_{j,m} P_j - (\sum_{j=1,m=1}^{J,M} X_{j,m}((N(Y_{j,m}) - N_m) P_N + Ph(Y_{j,m}) P_{Ph} + C_{j,m})))}{\bar{X}} = \overline{\Pi} \tag{11}$$

$$\frac{\left(\sum_{j=1,m=1}^{J,M} X_{j,m}\left(N(Y_{j,m}) - N_m\right)\right)}{\bar{X}} = \overline{N} \tag{12}$$

$$\frac{(\sum_{j=1,m=1}^{J,M} X_{j,m} Ph(Y_{j,m}))}{\bar{X}} = \overline{Ph} \tag{13}$$

$$\frac{(\sum_{j=1,m=1}^{J,M} X_{j,m} Y_{j,m} e_j)}{\bar{X}} = \bar{E} \tag{14}$$

$$\frac{(\sum_{j=1,m=1}^{J,M} X_{j,m} Y_{j,m} d_j)}{\bar{X}} = \bar{D} \tag{15}$$

Π	Total profit
$X_{j,m}$	Number of hectares of crop j with pre-crop m
$Y_{j,m}$	Yield per hectare of crop j with pre-crop m
P_j	Price per kg of crop j
$N(Y_{j,m})$	Nitrogen (kg) requirements per hectare of crop j with pre-crop m
N_m	Nitrogen effect kg per hectare from pre-crop m
P_N	Price per kg of Nitrogen
$Ph(Y_{j,m})$	Phosphorus (kg) requirements per hectare of crop j with pre-crop m
P_{Ph}	Price per kg of Phosphorus
$C_{j,m}$	Cost per hectare of crop j with pre-crop m, excluding nitrogen and phosphorous
$\bar{X}$	Total acreage
$\bar{X}_J$	Acreage constraint of crop j
X_m	Number of hectares of pre-crop m
$\overline{\Pi}$	Profit per hectare
$\bar{N}$	Nitrogen usage (kg) per hectare
$\bar{F}$	Phosphorus usage (kg) per hectare
e_j	Energy factor, MJ per kg of crop j
$\bar{E}$	Energy (MJ) per hectare
d_j	Protein factor, kg per kg of crop j
$\bar{D}$	Protein (kg) per hectare

To be able to solve the profit maximization problem, all of the constraints need to be satisfied (Lundgren, 2008). The total acreage is limited to the acreage X-bar, the total acreage of each crop is limited to X_j-bar, and the amount of crops that hold pre-crop properties is limited to the acreage X_m. The restriction to the pre-crop properties creates a possibility for the model to use the crop where it maximizes profitability concerning the pre-crop property. The costs are dependent on the choice of grown crops and changes if the crop changes. The functions for how much nitrogen and phosphorus are response functions to the yield of each crop (Agriwise, 2018b). Since harvest levels depend on the pre-crop, the amount of fertilizer varies if the preceding crop changes.

To obtain a result that reveals how the diversification of a cropping system with legumes affect the sustainability of the farm, the constraint on how much legumes can be grown is changed. This constraint is changed from zero % to one-sixth of the total acreage; one sixth is the maximum allowable amount of legumes in a cropping system to keep diseases at a low level (Fogelfors, 2015). The allowable acreage of other crops does not change, and this creates the experimental dimension of the model.

The maximization problem concerning j amount of crops with pre-crop m as modeled empirically is formulated in equation 16. This linear maximization problem is solved relating to the constraints stated earlier. From the optimal solution of the model below in equation 16, the indicators stated in equation 11, 12, 13, 14, and 15 are calculated.

$$Max\ \Pi\ (X_{j,m}\lambda_1\lambda_{2,j}\lambda_{3,m}):$$

$$\left(\sum_{j=1,m=1}^{J,M} X_{j,m}Y_{j,m}P_j\right) - \left(\sum_{j=1,m=1}^{J,M} X_{j,m}((N(Y_{j,m}) - N_m)P_N + Ph(Y_{j,m})P_{Ph} + C_{j,m})\right)$$
$$+ \lambda_1\left(\bar{X} - \left(\sum_{j=1,m=1}^{J,M} X_{j,m}\right)\right) + \lambda_{2,j}\left(\bar{X}_J - \left(\sum_{m=1}^{M} X_{j,m}\right)\right)$$
$$+ \lambda_{3,m}\left(X_m - \left(\sum_{j=1}^{J} X_{j,m}\right)\right) \tag{16}$$

The problem stated above is a duality problem since the first order derivative is constant and not zero. The only solutions are corner solutions; thus, a simplex algorithm is applied to solve the linear optimization problem (Lundgren, 2008). This algorithm solves for a maximum within the available solutions. It allows finding shadow prices of what an extra unit of the restricted resource would contribute to the total profit. The λ_1-value represents the shadow price on how much total profit changes if the total acreage increase with one unit. The $\lambda_{2,j}$-value shows how much the total profit change if the acreage constraint of crop j increase with one unit. The $\lambda_{3,m}$-value shows how much the total profit changes if the available acreage of pre-crop m changes with one unit. In other words, this is the pre-crop value of crop m within the cropping system.

4.6 Quality assurance

To assure the quality of the research, the two concepts of reliability and validity will be considered. These will be considered to show the considerations taken to assure quality throughout the research.

4.6.1 Reliability

The reliability refers to the consistency of a measure of a concept. In this research, stability and internal reliability will be considered to assure reliability (Bryman & Bell, 2015). Stability is the consideration that data should be stable over time. A question that can be raised when considering the stability is whether the results would stay the same if the measurement is performed at another time. To somewhat eliminate the risk of changes in data, an average of several years is calculated in this study. By using average data, the model might not mirror any single year, but it creates a possibility to examine the data and erase years that are not consistent.

The yields over different years have been rather stable. The year 2018 is excluded due to the severe drought in Sweden this year. In 2018 the average harvest levels were 46 % lower than the five-year average harvest levels (Jordbruksverket, 2018b). Internal reliability relates to whether the data is consistent. It considers whether the variables are related to each other and can be combined. By conducting a thorough literature review, the variables in the model are identified as important, and it is considered that the data is consistent. However, it should be addressed that it is difficult to completely mirror reality when developing an optimization model (Lundgren, 2008).

4.6.2 Validity

The second consideration that is made concerns the validity of the research, which is important to consider as a quality assurance criteria (Bryman & Bell, 2015). The consideration to be made regarding validity is whether the empirical data can be used to answer the research question. In this research, face validity is considered by using the expertise of crop advisors from the specific areas in Sweden. By showing the results to the crop advisors, it is possible to control whether the results should be considered reasonable or if changes are needed. The crop rotation restrictions have been developed through the help of advisors and by using literature. This procedure assures that the proposed results reflect the content of the studied situation (Bryman & Bell, 2015).

External validity will be considered when discussing the generalization of the study (Bryman & Bell, 2015). The study is performed as a two case study of typical cereal-producing farms in GSS and SS. The results might be generalizable to other farms in these regions because the case farms are designed as an average farm. However, the average case farms might not represent any specific farm in these regions, and the results could be misleading. It is difficult to determine whether the results are representative for other regions in Sweden or the world. According to Yin (2009), a case study with only two cases might be difficult to generalize. In the analysis, the results are compared and discussed with previous research. This type of comparison creates a possibility for the reader to form its own opinion of the generalizability of the results (Bryman & Bell, 2015).

4.7 Ethical considerations

Consideration of ethical issues is an important question to address when performing research (Yin, 2009). It is important that when using secondary data as in this study, not alter the data (Bryman & Bell, 2015). It is important to not alter the data for both the quality assurance and the ethics of the paper. As for the ethical consideration of treating sources and references correctly, all figures from other papers are allowed to be used in this paper from the original author. The crop advisors that are cited in this paper are also informed about the scope of the project and how they are treated in the report. The crop advisors that are cited had the choice to participate in the research, and they were informed beforehand about the purpose of this study.

5 Results

The results of the empirical model are presented below. The results are presented concerning the three dimensions of sustainability. First, the results for the case farm in GSS are presented, followed by the results of the case farm in SS.

5.1 GSS

Figure 10 shows the crop rotation for the case farm in GSS when profitability is optimized, and legumes are introduced. The crop rotation includes four crops, winter wheat, barley, rapeseed, and legumes. The main difference from the current state presented in figure 7, chapter 4.3 is that sugar beets are excluded due to its low profitability and that the acreage of winter wheat is increased due to its high profitability.

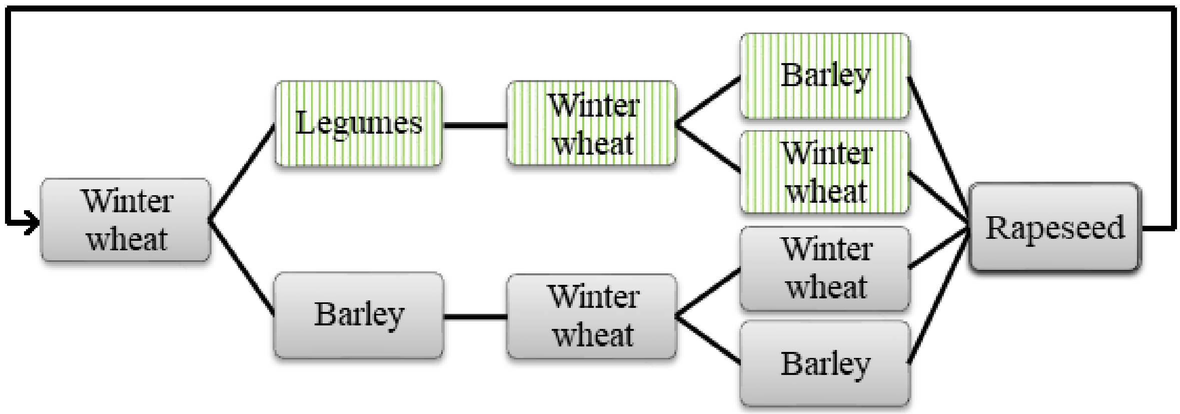

Figure 10. Crop rotation for the farm in GSS when legumes are introduced

Based on the yield levels in the data and the pre-crop properties, the optimal allocation of crops on the case farm in GSS is the grey cropping plan with zero percentage legumes and the green vertical lined cropping plan with 20 % legumes. Figure 10 should be interpreted as the grey part represent zero percentage legumes. When the legumes are increased up to a maximum share of 20 %, the rotation moves over to the green vertical lined part. This is how the farmer is expected to allocate land resources among the years. All the boxes should sum up to 100 % of the land, and each column in the figure represents 20 %. However, the allocation within the column can differ from 0-20 %.

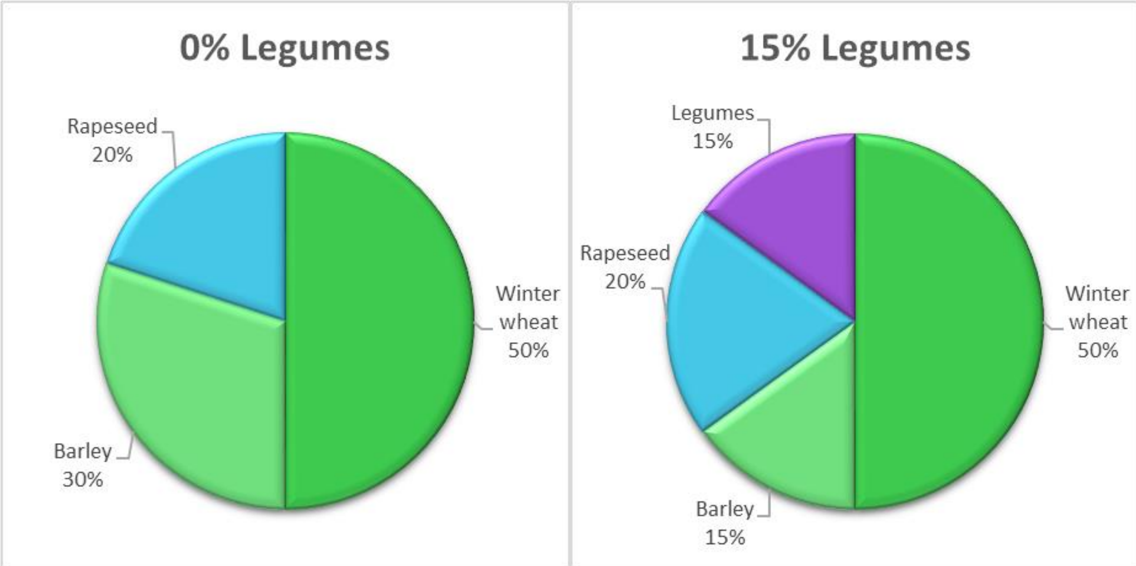

Figure 11. The crop allocation for the farm in GSS with 0% legumes and 15% legumes

In figure 11, the allocation of the crops when the model optimizes at 0 % legumes and 15 % legumes is displayed. It can be noted that the most profitable allocation of resources differs between the state with legumes and without legumes. In the state with 0 % legumes, the acreage of cereals is 80 %, and in the state with 15 % legumes, the acreage of cereals is 65 %. The decrease of cereals and increase of legumes increases the diversification of the case farm in GSS. Compared to the current state in figure 6, with an acreage of cereals at 70 %, the difference is 5 % between the current state and the optimal state with 15 % legumes.

5.1.1 Economic sustainability

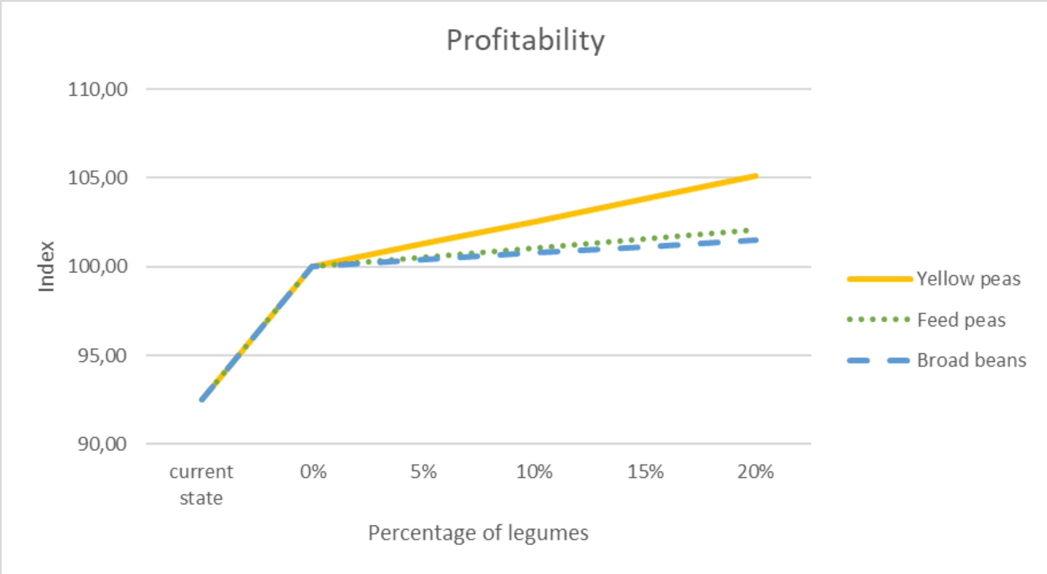

Figure 12. The profitability of the farm in GSS when legumes are introduced

Figure 12 shows how the profitability of the case farm in GSS changes when the three legumes, yellow peas, feed peas, and broad beans are introduced. The low profitability of sugar beets explains the difference between the current state and the optimal state with 0 % legumes. All three legumes contribute to increased profitability.

Table 3. Shadow price and indifferent prices for legumes in GSS

Legumes	Shadow price /hectare	Profit increase /percent legumes	Indifferent sales price	Indifferent nitrogen price
Yellow peas	1 007 SEK	0,256 %	1,63 SEK	1,53 SEK
Feed peas	407 SEK	0,104 %	1,55 SEK	6,93 SEK
Broad beans	300 SEK	0,076 %	1,62 SEK	7,80 SEK

Table 3 displays the three different legumes shadow price, profit increase per percent of legumes, indifferent sales price, and indifferent nitrogen price in GSS. The shadow price is positive for all three legumes and shows how much the total profit increases with an increase of one hectare of the specific legume. The indifferent market price is the selling price where, in terms of profitability, there is no difference if legumes are grown or not. All three legumes have a lower indifferent selling price than the average market price of the legumes (Table A.1.1). The indifferent nitrogen price is the nitrogen price where, in terms of profitability, there is no difference if the legumes are grown or not. All three legumes have a lower indifferent nitrogen price than the average price of nitrogen (Table A.1.1).

5.1.2 Environmental sustainability

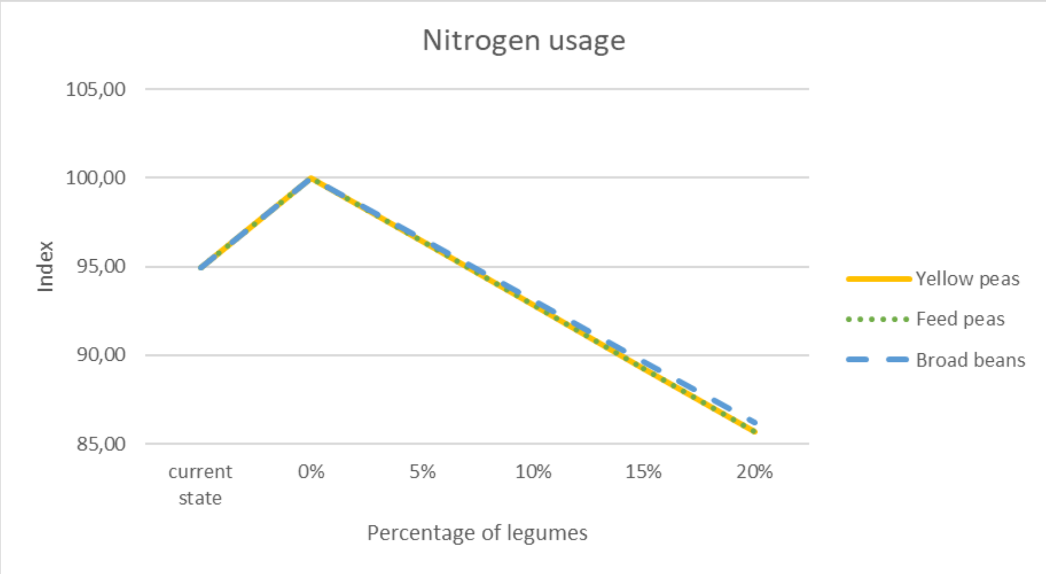

Figure 13. Nitrogen usage on the farm in GSS when legumes are introduced

Figure 13 shows how the nitrogen usage on the farm in GSS is affected when more legumes are introduced in the system. First, there is a difference between the current state and the optimal state without legumes. In the optimal state without legumes, more nitrogen is used, this is because more winter wheat is grown in the optimal state, which requires more nitrogen. Once legumes are introduced the amount of nitrogen usage decreases.

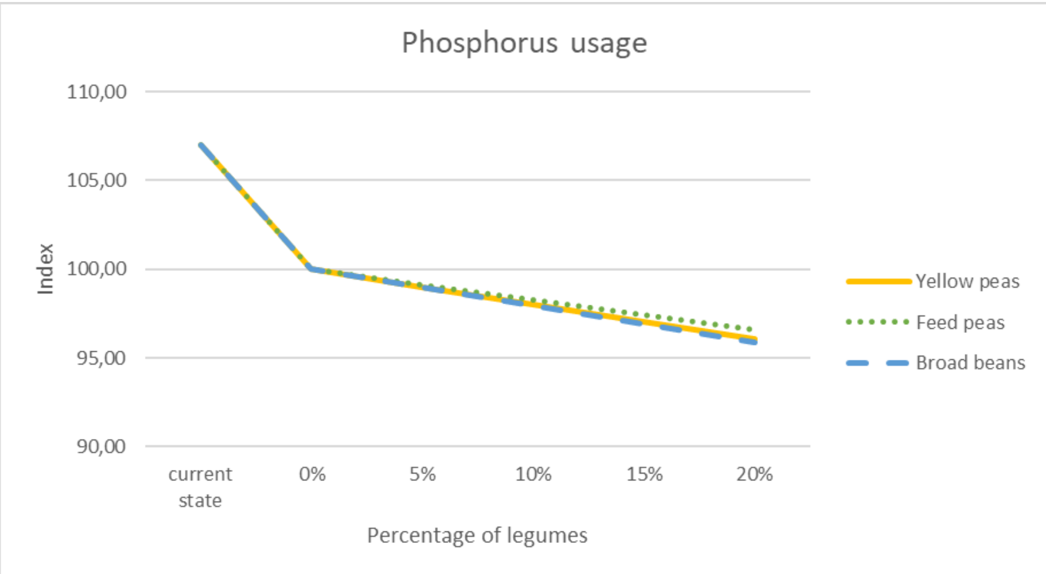

Figure 14. Phosphorus usage on the farm in GSS when legumes are introduced

Figure 14 shows how the phosphorus use of the farm in GSS is affected when more legumes are introduced into the cropping system. In the current state, phosphorus usage is higher than the optimal state without legumes. This is because of sugar beets, which have high phosphorus requirement is included in the current state of the farm but not in the optimal state. The use of phosphorus decreases when legumes are introduced in the cropping system.

5.1.3 Social sustainability

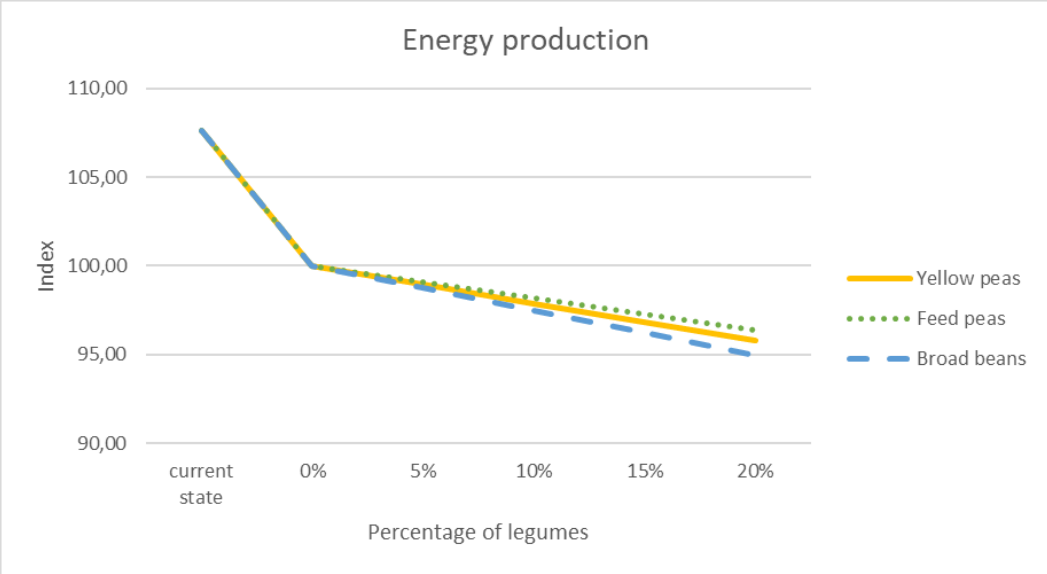

Figure 15. Energy production on the farm in GSS when legumes are introduced

Figure 15 shows how the energy production of the farm in GSS is affected when legumes are introduced into the cropping system. The energy production is higher in the current state than in the optimal state without legumes. The explanation is the sugar beets who contain more energy. Energy production decreases when legumes are included in the cropping system.

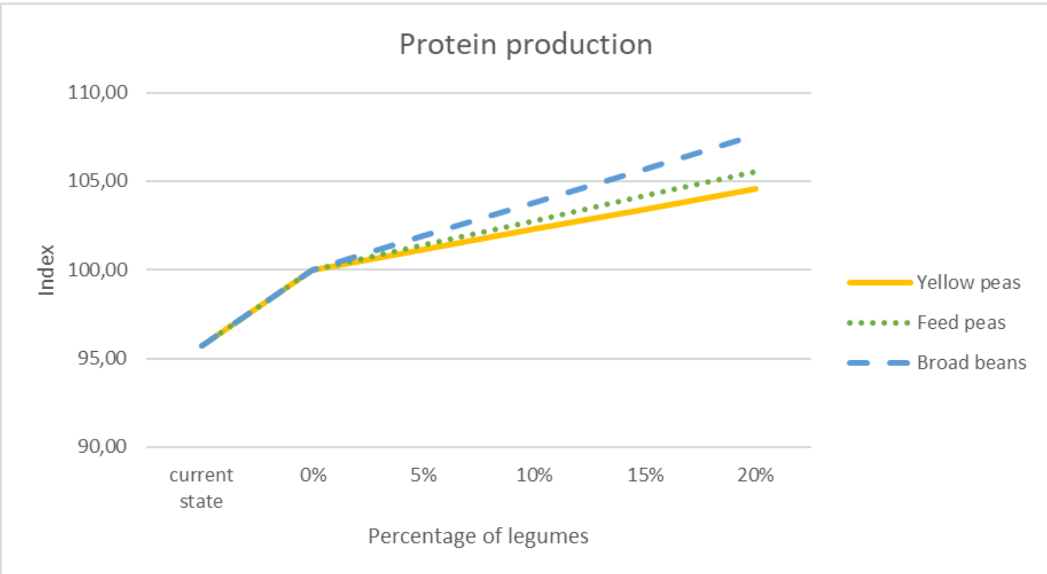

Figure 16. Protein production on the farm in GSS when legumes are introduced

Figure 16 shows how protein production at the farm in GSS is affected when more legumes are introduced. The difference between the current state and the optimal state without legumes depends on the low protein content of sugar beets, which is excluded in the optimal state. Protein production increases when legumes are introduced in the cropping system.

5.2 SS

Figure 17 shows the crop rotation for the case farm in SS when profitability is optimized, and legumes are introduced. The crop rotation includes four crops, winter wheat, barley, rapeseed, and legumes. The main difference from the current state presented in figure 8, chapter 4.3 is that less profitable crops, spring wheat, and oats are excluded, and the amount of winter wheat and rapeseed is increased due to their higher profitability.

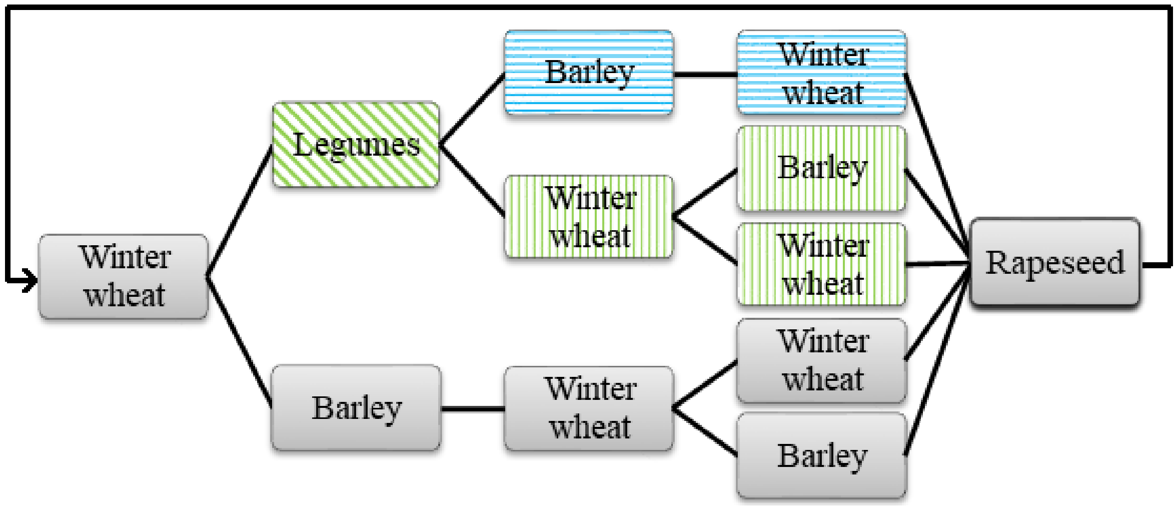

Figure 17. Crop rotation for the farm in SS when legumes are introduced

Based on the yield levels in the data and the pre-crop properties, the optimal allocation of crops on the case farm in SS is the grey cropping plan with 0 % legumes and the green vertical lined cropping plan with 20 % legumes, except broad beans that represent the blue horizontal lined cropping plan. Figure 17 should be interpreted, as the grey part represents zero percent legumes, and the green vertical line represents the maximum acreage of legumes. When the legumes are increased up to a maximum share of 20 %, the rotation moves to the green and blue part. This is how the farmer is expected to allocate land resources across the years. All the boxes should sum up to 100 % of the land, and each column in the figure represents 20 %. However, the allocation within the column can differ from 0-20 %.

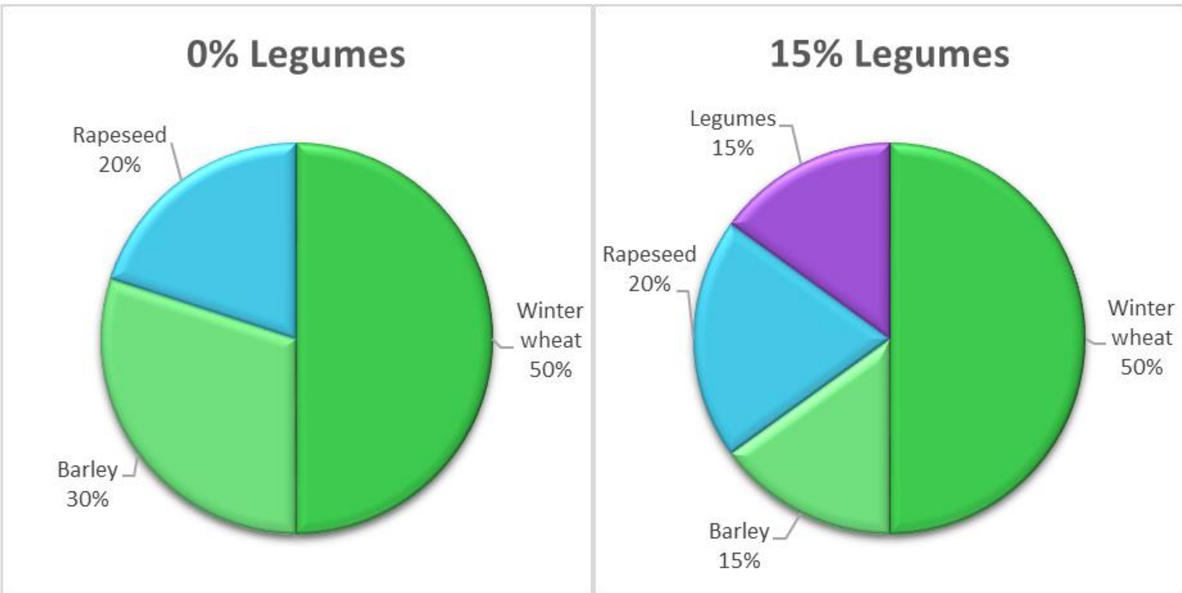

Figure 18. The crop allocation for the farm in SS with 0% legumes and 15% legumes

In figure 18, the crop allocation for the farm in SS is shown when it is optimized with 0 % legumes and 15 % legumes. The results are the same as for the farm in GSS regarding the allocation of crops. The effect of diversification is higher in SS than in GSS compared to the current state shown in figure 6. In the current state, the acreage of cereals is 90 %, and in the optimal state with 15 % legumes, the acreage of cereals is 65 %, and the difference is 25 %.

5.2.1 Economic sustainability

Figure 19. The profitability of the farm in SS when legumes are introduced

Figure 19 shows how the profitability of the case farm in SS changes when the three legumes, yellow pea, feed pea, and broad bean are introduced. The difference between the current state and the optimal state with 0 % legumes can be explained by the increased acreage of winter wheat and rapeseed. Yellow peas and broad beans up to 15 % contributes to increased profitability. A larger acreage than 15 % of broad beans is allocated at the expense of winter wheat, which leads to a decrease in profit. Feed peas contribute to a slight decrease in profitability.

Table 4. Shadow price and indifferent prices for legumes in SS

Legumes	Shadow price /hectare	Percentage increase /percent legumes	Indifferent selling price	Indifferent nitrogen price
Yellow peas	448 SEK	0,184 %	1,74 SEK	5,60 SEK
Feed peas	-14 SEK	-0,006 %	1,67 SEK	10,75 SEK
Broad beans	92 SEK*	0,038 %*	1,67 SEK*	9,55 SEK*

**Applies up to a share of 15 %.*

Table 4 displays the three different legumes shadow price, profit increase per percent of legumes, indifferent sales price, and indifferent nitrogen price in SS. The shadow price is positive for yellow peas and broad beans but slightly negative for feed peas. Yellow peas and broad beans are characterized by a lower indifferent selling price than the average market price of the legumes. Feed peas have a higher indifferent selling price than the average market price (Table A.1.1). Yellow peas and broad beans have a lower indifferent nitrogen price, and feed peas have a higher indifferent nitrogen price than the average price of nitrogen (Table A.1.1).

5.2.2 Environmental sustainability

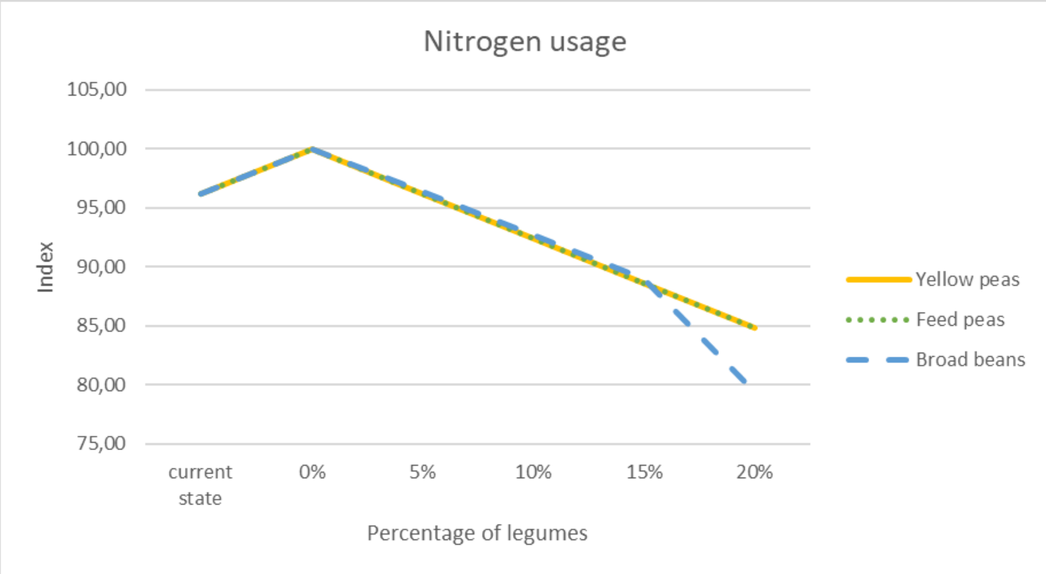

Figure 20. Nitrogen usage on the farm in SS when legumes are introduced

Figure 20 shows how the nitrogen usage on the farm in SS is affected when more legumes are introduced in the system. First, there is a difference between the current state and the optimal state without legumes. In the optimal state without legumes, more nitrogen is used, this is because more winter wheat is grown in the optimal state, which requires more nitrogen. Once legumes are introduced the amount of nitrogen usage decreases.

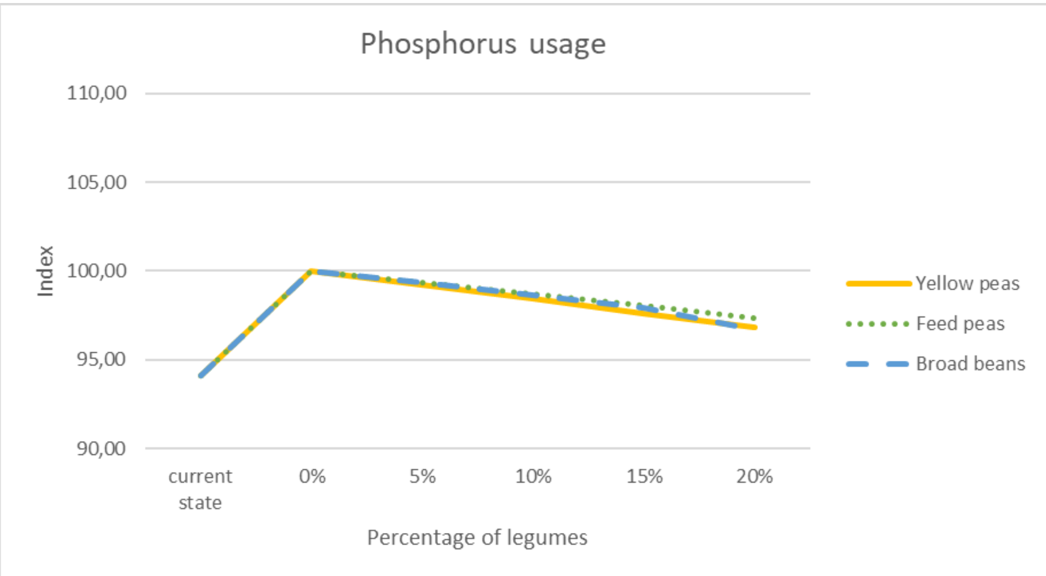

Figure 21. Phosphorus usage on the farm in SS when legumes are introduced

Figure 21 shows how the phosphorus usage of the farm in SS is affected when more legumes are introduced into the cropping system. In the current state, the phosphorus usage is lower than in the optimal state without legumes. This is because of the larger acreage of winter wheat and rapeseed, have a high phosphorous requirement in the optimal state without legumes. The use of phosphorus decreases when legumes are introduced in the cropping system. The reason that less phosphorus is used at 15 % of broad beans is that the acreage of winter wheat decreases. Therefore, the use of phosphorus decreases.

5.2.3 Social sustainability

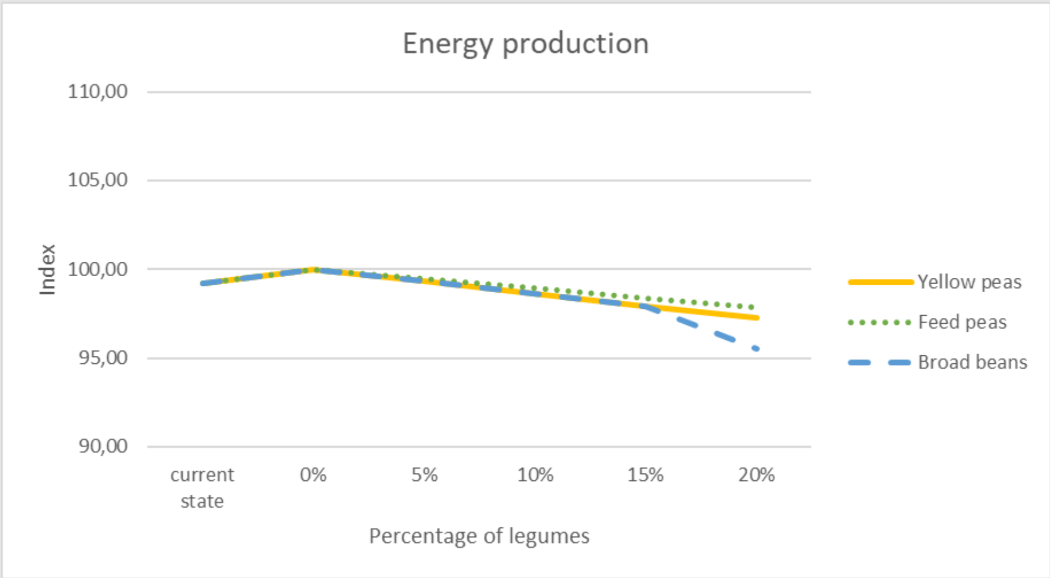

Figure 22. Energy production on the farm in SS when legumes are introduced

Figure 22 shows how the energy production at the farm in SS is affected when legumes are introduced into the cropping system. The energy production is higher in the optimal state without legumes than in the current state, because of the larger acreage of winter wheat, which contains more energy. Energy production decreases when legumes are included in the cropping system.

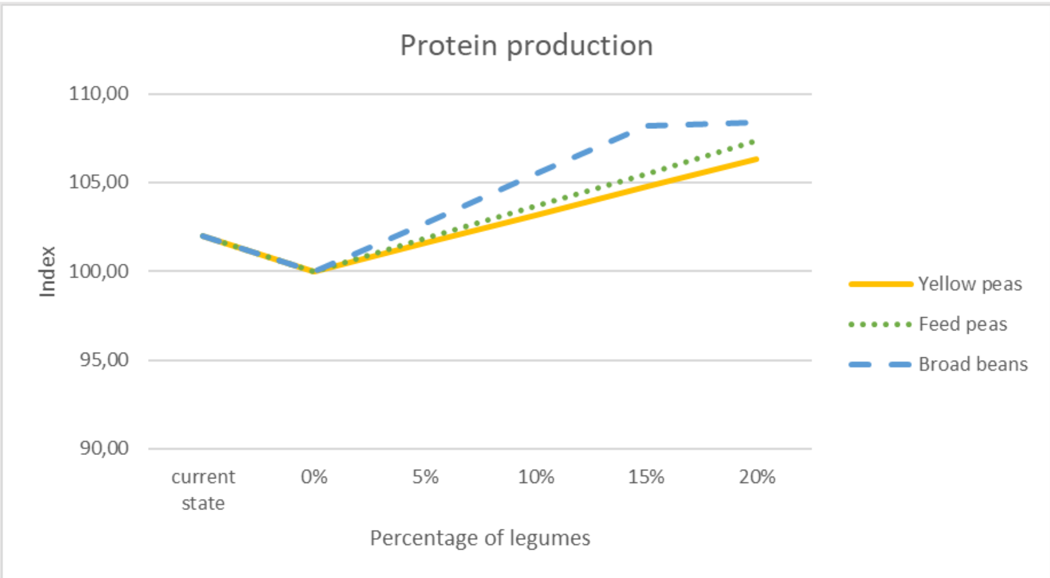

Figure 23. Protein production on the farm in SS when legumes are introduced

Figure 23 shows how protein production at the farm in SS is affected when more legumes are introduced. The difference between the current state and the optimal state without legumes depends on a high protein content of spring wheat, which is excluded in the optimal state. Protein production increases when legumes are introduced in the cropping system.

6 Analysis and discussion

The results point towards different effects in terms of sustainability, depending on what indicator is analyzed. A more in-depth analysis and discussion of each indicator are presented in this chapter. Lastly, a general discussion of what the results imply is introduced.

6.1 Summary of results

A summary of the results in the previous chapter is presented in Table 5. The summary shows how the indicators change from the state no legumes to an amount of 15 % legumes in the two different case farms. Fifteen percent is chosen to get comparable results between the different legumes, as the results for broad beans in SS are changed at 15 %. The profitability increases for all legumes in both cases except for feed peas in SS. Nitrogen usage and phosphorous usage decreases for all legumes in both cases. Energy production decreases, and protein production increases for all legumes in both cases.

Table 5. Summary of empirical results

Sustainability	Economic	Environmental		Social	
	Profit +	Nitrogen -	Phosphorous -	Energy +	Protein +
No legumes	100	100	100	100	100
GSS 15 %					
Yellow peas	103,8	89,3	97,0	96,8	103,4
Feed peas	101,6	89,3	97,4	97,3	104,2
Broad beans	101,1	89,7	96,9	96,2	105,7
SS 15 %					
Yellow peas	102,8	88,6	97,6	97,9	104,7
Feed peas	99,9	88,6	98,0	98,4	105,5
Broad beans	100,6	89,0	97,9	97,9	108,2

The indicators differ in terms of whether it is more or less sustainable if they increase or decrease. The economic and social sustainability increases if the indicators within them increase. The environmental sustainability increases if the indicators within decrease. The interpretation of the indicators is analyzed in more detail below in this chapter.

Table 6. Share of cereals in the different states.

	Current state	Optimal state, no legumes	Optimal state, 15 % legumes
GSS	70 %	80 %	65 %
SS	90 %	80 %	65 %

According to Liu *et al.* (2016), it could be necessary to diversify cropping systems to tackle future problems, with more diseases and climate change. Table 6 shows the share of cereals in the different states for the case farms. At the current state, in GSS there is a trend towards increased diversification, more so than in SS. The diversification is greater in GSS because sugar beets and more rapeseed is grown in this region, and only 70 % of the acreage is covered with cereal crops. The corresponding number in SS is 90 % of cereals and only 10 % alternative crops.

When legumes are introduced in the cropping systems, the acreage of cereals decreases, and the cropping systems diversification increases. The decrease of cereals is higher in SS than in GSS because, in SS, cereals are replaced by legumes and rapeseed. In GSS, cereals and sugar beets are replaced by legumes, and thus legumes replace both cereal and non-cereal crops. With a diversification point of view, legumes are more important in SS than GSS, since GSS is more diversified in the current state. This argument is supported by previous research, Liu *et al.* (2016), argues that a cropping system with only cereal crops is not diversified. This argument is made since cereal crops do not increase biodiversity and might be affected by the same diseases.

6.2 Economic sustainability

The effect on profitability when increasing the amount of legumes in the two case farms of this study is positive for all legumes except feed peas in SS. The crop that contributes the most to the profitability in GSS and SS is yellow peas. This contribution is mainly due to a higher market price of yellow peas compared to feed peas and broad beans. The pre-crop effect is similar between the crops and the main difference between the contributions to profitability is the yield levels and market prices (Table A.1.1; A.1.2; A.1.3; A.1.5). The results in terms of economic sustainability, verify what was proposed by Smith *et al.* (2017), who found that legumes could increase the profitability of Canadian cropping systems. It is also in line with the results proposed by Reckling *et al.* (2016b) and verifies that legumes could increase the profitability of Swedish cropping systems.

The effect of broad beans on profitability is higher in GSS than in SS. This effect is mainly due to the growing conditions of the case farms. In GSS, the crop grown after broad beans is winter wheat; in SS, it is not possible to grow winter wheat after broad beans, due to a shorter growing season. Because of this barley is grown after broad beans in SS, which has a lower gross margin than winter wheat. The lower gross margin on the preceding crop changes the economic performance of broad beans in SS. When calculating the contribution of broad beans at the scale of the cropping system and the total contribution it is positive in both SS and GSS. The shadow price in GSS is 300 SEK and 92 SEK in SS. The shadow price is the total contribution to the profit that one extra unit of this crop would contribute to the total profit per hectare. When considering the theory of profit maximization the most logical decision of farmers in these regions would be to increase the area of legumes since it contributes positively to the profit of the farm (Debertin, 2012).

If farmers behavior were consistent with the theory of profit maximization, the acreage of legumes in the examined regions would be greater, according to the results in this study. However, it should be noted in the statistics presented that only 2% of the total acreage in Sweden is covered with legumes (figure 1). The low frequency of legumes in the two investigated regions is not explained by the results provided by the model developed for this study. It is possible that a low frequency of legume crops might be due to low expertise in growing legume crops (Magrini *et al.*, 2016). According to Magrini *et al.* (2016), it is common for the farmers to consider the gross margin for one single crop and not the contribution of the entire cropping system. It is possible that the results would be different in this study if the calculation would not account the pre-crop properties as an economic effect of the legume crops.

6.3 Environmental sustainability

The environmental indicator of nitrogen shows a decrease when increasing the acreage of legumes in the cropping systems of both case farms, which is shown in figure 13 and figure 20. The amount of nitrogen used decreases between 10-15 percent when 15 percent of legumes are grown in the cropping system. The relationship between the acreage of legumes in the system and the amount of nitrogen is linear. When more legumes are introduced the amount of nitrogen applied in the cropping system decreases. The results that nitrogen decreases are consistent with previous research in the field (Zander *et al.*, 2016). Zander proposes that legumes can reduce the amount of nitrogen that is needed in the cropping system with about 20-30 kg per hectare. Furthermore, the interpretation is made that diversification with legumes could affect environmental sustainability in terms of eutrophication and leakage (Reckling *et al.*, 2016b). Since less nitrogen is added to the cropping system, it is possible that less nitrogen reaches the water, and thus, eutrophication is reduced (Elofsson, 2012). However, Nemecek *et al.* (2008) argue that it is possible that legumes actually could increase the eutrophication. The reason is that it is difficult to monitor the amount of nitrogen in the field when the plants fixate nitrogen.

The empirical results presented in figure 13 and 20 points towards improved environmental sustainability concerning the indicator nitrogen. This interpretation is because the production of nitrogen is energy intensive, and approximately 40 percent of the greenhouse gas emissions from crop farms originate from fertilizer production (Berglund *et al.*, 2009). In a study performed by Nemecek *et al.* (2008), it was found that introduction of legumes into a cropping system could decrease the total greenhouse gas emission with around 10 percent for the whole system. The results in this study do not reveal the total reduction of greenhouse gas emissions but rather points towards a reduction on the dependency of chemical fertilizer. Consequently, the amount of greenhouse gas emissions is reduced as well (Nemecek *et al.*, 2008).

The indicator of phosphorus usage points towards a decrease in the dependency of phosphorus in the cropping systems of GSS and SS. The results shown in Table 5 reveal a decrease of about 2-4 percent of the total phosphorus needed when increasing the area of legumes in the system. These results are not consistent with some previous studies (Lott *et al.*, 2011). The data on phosphorus application in this paper is based on the recommendations from the Swedish Board of Agriculture. This is thought to be the primary cause of the difference in results that are found in this model. If the results are consistent for all systems in Sweden that includes legumes is challenging to assess. However, based on the results in this study, the indicator of phosphorus points towards improved sustainability. Since less phosphorus is used, less of a non-renewable resource is used. This is beneficial from a sustainability perspective (Cordell *et al.*, 2009). In the study by Lott *et al.* (2011), it was found that a legume supported cropping system uses 18 percent more phosphorus, in this paper, the legume supported cropping system uses 2-4 percent less phosphorus. To be sure whether the results in this paper are correct, it could be necessary to monitor more cropping farms and perform research that validates the results proposed in this study.

6.4 Social sustainability

The social sustainability indicator of protein increases when the amount of legumes in the system is increased. These results are mainly due to the high protein content of legume crops (Preissel *et al.*, 2015). The increase in protein production is positive in the perspective of social sustainability because it creates the possibility to supply more plant protein for both livestock production and human consumption compared to the state without legumes. According to Ebert

(2014), a diversification with legumes could play an important role in the future since it contributes to food security.

The indicator, energy production point towards a lower energy production when including legumes in the cropping systems in GSS and SS. These results are consistent with the previous research of Nemecek *et al.* (2008) who found that the energy production in legume supported cropping systems decreased with 1-19 percent, depending on the amount and type of legumes. The results in this study observed a decrease in energy produced of about 2-4 percent compared to the optimal state. This decrease shows that from a food security perspective, in terms of energy production, legumes might not be the best alternative crop. The results in this study on the social indicators are not consistent with the findings by Ebert (2014), who proposed that a legume supported cropping system could increase both energy production and protein production. However, with other case farms or in a different location or climate, it is possible that the results could change and the indicators might show a different result.

The indicators of environmental and economic sustainability measure the effects that take place within the cropping system. The indicators of social sustainability measure something that takes place within the cropping system, but the results of the indicators apply to a more global perspective. The total energy or protein produced might not affect the individual farmer to a great extent, since the farmer often tries to maximize profits. However, it could have a significant effect from a food security perspective (Ebert, 2014). Whether these indicators are the best possible choice to measure social sustainability is difficult to assess. This issue is addressed in the general discussion 6.5.

6.5 General discussion

The indicators applied in this study are chosen after a thorough literature review and are expected to capture some of the effects that take place within the cropping system when diversifying it. All the indicators are also expected to provide useful decision support for both farmers and politicians and could, therefore, be useful from a production economics perspective (Debertin, 2012). If other indicators were to be used the study might reveal different results. Such indicators could be indicators of trading opportunities or how the legumes contribute to the health of the population (Labuschagne *et al.*, 2005). However, an indicator of new trading opportunities would force mapping of the trading network and might be applicable in a paper that investigates the value chain and or the supply chain of the case farms. It is similar with an indicator of health. This type of indicator generally studies a large population to examine the effects a change would have on the population (Röös *et al.*, 2018; Labuschagne *et al.*, 2005). In the research performed in this paper, the indicators are thought to capture relevant effects of legumes in the cropping system.

Something important to address is that a large part of the Swedish farmland is used for producing feed for livestock (Fogelfors, 2015). The results indicate that energy production would decrease if the acreage of legumes increases. However, no evaluation is made of whether Sweden would produce enough energy to supply both humans and livestock when a larger acreage is covered with legumes. Instead, an assessment is made of whether energy and protein production increases or decreases. Since legumes could replace the animal protein that is consumed today, it is possible that the negative effect on social sustainability that the energy indicators show is somewhat reduced (Röös *et al.*, 2018). According to Röös *et al.* (2018), it would be possible to reduce meat consumption in Sweden and substitute meat with legume-based protein. Röös *et al.* (2018) show that an increase in intake of plant-based protein, such as legumes, could increase the health of the consumers. This increase in health could be in terms of a decrease of type 2 diabetes and the risk of cardiovascular diseases. Hence, it is possible that diversification with legumes increases social sustainability on indicators that are not measured in this paper.

The overall effects in the economy are difficult to generalize since this paper investigates two cases (Yin, 2009). One effect that could occur is that the supply of plant-based protein increases if crop farms increase the acreage of legumes. The results in this paper show that legumes could be profitable in the two farms. Magrini *et al.* (2016) argued that farmers often only calculate the gross margins of the single crop and do not consider the effect one crop holds on the subsequent crop. For farmers, the results in this paper could, therefore, be useful when considering growing legumes since the model considers the effects of the preceding crop. It is also possible that farmers could use the results of other indicators in their marketing strategies. However, it is important to note that there could be a lock-in in the industry of Sweden in a similar way as the lock-in proposed by (Magrini *et al.*, 2016). Zimmer *et al.* (2016) found that there was a gap in the knowledge between farmers and researchers in the value of legumes in cropping systems. It is possible that a similar gap in knowledge exists in Sweden. The results in this paper do not provide insight into whether this is the case. However, the findings could help fill this gap.

7 Conclusions

The aim of this study is to examine how diversification with legumes would affect typical Swedish cereal dominated cropping systems in terms of sustainability. The study examines how the economic, environmental, and social sustainability is affected when a cereal dominated cropping system is diversified with legumes. Based on the aim, five indicators are identified to fulfill the aim and answer the research questions.

The conclusion is that the economic and environmental sustainability is affected positively of diversification with legumes. More legumes improve profitability and decrease the environmental impact of cereal dominated cropping systems. Based on the indicators in this study, social sustainability is affected both positively and negatively. It is possible that the results are applicable to other farms in distinct regions if they face the same production conditions. The results could also be generalizable to other regions in Sweden if the farms show similar conditions.

The study examines two case farms, one in the region GSS and one in the region SS. These two farms represent cereal-producing farms in the area. The study concludes that economic sustainability is affected positively when more legumes are introduced into the cropping system. This is based on the fact that the profitability of the whole cropping system increases when more legumes are introduced in the system. Out of the three analyzed legumes, only one is found to decrease the profitability in one of the regions. Diversification with feed peas affects the profitability of the case farm in SS negatively. However, this effect is rather low, and it is possible that the results could change if only a few parameters, such as yield or price changes. The effect when a maximum allowable amount of legumes are introduced in the cropping system is an increase in profit between 0 - 4 percent. The result in terms of economic sustainability visualizes the importance of considering the effects of legumes on the subsequent crop. To fully account for the economic effect of legumes pre-crop effects must be considered since these are valuable attributes of the legume crops.

Environmental sustainability is higher for a legume supported cropping system based on the two environmental indicators assessed in this study. Both nitrogen usage and phosphorus usage decreases with more legumes in the cropping system. Nitrogen production is energy intensive, and around 45 percent of the greenhouse gas emissions from agriculture originate from the production of nitrogen. Therefore, it is concluded that less use of nitrogen increases the environmental sustainability of the cropping system. The decrease in phosphorus usage is also considered to increase environmental sustainability. Phosphorus usage contributes to eutrophication, and the resource is non-renewable. Therefore, it is concluded that a decrease of phosphorus usage decreases the environmental impact of the legumes supported cropping system.

Energy production of the legume supported cropping system decreases compared to the optimal state and the current state. From a global perspective, where more food is needed to support a growing world population, this is negative. Therefore it is concluded that social sustainability, in terms of energy production, is affected negatively. However, the indicator of protein production shows an increase in protein production. Protein is an important nutrient for both livestock production and human consumption. Based on the results of the social indicators, this study cannot conclude whether the effect on social sustainability is positive or negative.

7.1 Further research

Further research on the effects of diversification attributable to legumes in cropping systems is needed. This study could be developed to include more indicators of sustainability. By including more indicators, it is possible that the results could change. Future studies could also include actual case farms with actual yield levels and fertilizer applications. The study could be extended to a dynamic model that accounts for effects such as a possible decrease of pesticides caused by diversification.

Another possible field of research is to investigate the attitudes amongst farmers of growing legumes. This type of research could identify gaps of knowledge and fields that are important to study in the future and could be carried out similarly as the research performed by Zimmer *et al.* (2016).

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Personal messages

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Eriksson, Johan, *Ekonomirådgivare,* Hushållningssällskapet, 2019-03-20

Appendix

Appendix 1 Collected data

Table 1. Market prices of crops and fertilizer.

Crop	Price (SEK/kg)	Fertilizer	Price (SEK/kg)
Winter wheat	1,62	Nitrogen	10,59
Spring wheat	1,72	Phosphorus	20,77
Barley	1,54	Potassium	7,84
Oats	1,28		
Rapeseed	3,51		
Sugar beets	0,26		
Yellow peas	2,17		
Feed peas	1,92		
Broad beans	1,96		

Table 2. Pre-crop properties in GSS and SS.

Pre-crop	Crop							
	Winter wheat		Spring wheat		Oat		Barley	
	Nitrogen (kg/ha)	Yield (kg/ha)	Nitrogen	Yield	Nitrogen	Yield	Nitrogen	Yield
Winter wheat	0	0	0	0	0	0	0	0
Spring wheat	0	0	0	0	0	0	0	0
Barley	0	0	0	0	0	0	0	0
Oat	0	700	0	0	0	0	0	0
Rapeseed	40	1200	25	600	25	600	25	600
Sugar beets	25	500	20	800	20	800	20	800
Yellow peas	35	1000	25	500	25	500	25	500
Feed peas	35	1000	25	500	25	500	25	500
Broad beans	25	700	25	700	25	700	25	700

Pre-crop	Crop							
	Rapeseed		Sugar beets		Yellow peas		Feed peas	
	Nitrogen	Yield	Nitrogen	Yield	Nitrogen	Yield	Nitrogen	Yield
Winter wheat	0	0	0	0	0	0	0	0
Spring wheat	0	0	0	0	0	0	0	0
Barley	0	0	0	0	0	0	0	0
Oat	0	0	0	0	0	0	0	0
Rapeseed	-	-	-	-	0	0	0	0
Sugar beets	-	-	-	-	0	0	0	0
Yellow peas	35	0	25	0	-	-	-	-
Feed peas	35	0	25	0	-	-	-	-
Broad beans	25	0	25	0	-	-	-	-

Pre-crop	Crop	
	Broad beans	
	Nitrogen	Yield
Winter wheat	0	0
Spring wheat	0	0
Barley	0	0
Oat	0	0
Rapeseed	0	0
Sugar beets	0	0
Yellow peas	-	-
Feed peas	-	-
Broad beans	-	-

GSS

Table 3. Yields kg/ha in GSS

Pre-crop	Crop							
	Winter wheat	Barley	Oats	Rapeseed	Sugar beets	Yellow peas	Feed peas	Broad beans
Winter wheat	7 984	6 074	5 299	3 701	67 948	3 628	3 819	3 878
Barley	7 984	6 074	5 299	3 701	67 948	3 628	3 819	3 878
Oats	8 684	6 074	5 299	3 701	67 948	3 628	3 819	3 878
Rapeseed	9 184	6 674	5 899	-	-	3 628	3 819	3 878
Sugar beets	-	6 874	6 099	-	-	3 628	3 819	3 878
Yellow peas	8 984	6 574	5 799	3 701	67 948	-	-	-
Feed peas	8 984	6 574	5 799	3 701	67 948	-	-	-
Broad beans	8 684	6 774	5 999	-	67 948	-	-	-

Table 4. Gross margins SEK/ha in GSS

Pre-crop	Crop							
	Winter wheat	Barley	Oats	Rapeseed	Sugar beets	Yellow peas	Feed peas	Broad beans
Winter wheat	4 346	2 763	1 577	2 882	724	2 250	1 650	1 946
Barley	4 346	2 763	1 577	2 882	724	2 250	1 650	1 946
Oats	5 015	2 763	1 577	2 882	724	2 250	1 650	1 946
Rapeseed	6 117	3 612	2 388	-	-	2 250	1 650	1 946
Sugar beets	-	3 696	2 474	-	-	2 250	1 650	1 946
Yellow peas	5 866	3 532	2 343	3 253	989	-	-	-
Feed peas	5 866	3 532	2 343	3 253	989	-	-	-
Broad beans	5 463	3 669	2 457	-	989	-	-	-

SS

Table 5. Yields kg/ha in SS

Pre-crop	Crop							
	Winter wheat	Spring wheat	Barley	Oats	Rapeseed	Yellow peas	Feed peas	Broad beans
Winter wheat	5 779	4 703	4 478	4 385	2 817	2 788	2 935	3 204
Spring wheat	5 779	4 703	4 478	4 385	-	2 788	2 935	3 204
Barley	5 779	4 703	4 478	4 385	2 817	2 788	2 935	3 204
Oats	6 479	4 703	4 478	4 385	2 817	2 788	2 935	3 204
Rapeseed	6 979	5 303	5 078	4 985	-	2 788	2 935	3 204
Yellow peas	6 779	5 203	4 978	4 885	-	-	-	-
Feed peas	6 779	5 203	4 978	4 885	-	-	-	-
Broad beans	-	5 203	5 178	5 085	-	-	-	-

Table 4. Gross margins SEK/ha in SS

Pre-crop	Crop							
	Winter wheat	Spring wheat	Barley	Oats	Rapeseed	Yellow peas	Feed peas	Broad beans
Winter wheat	2 617	1 812	1 872	785	1 054	764	303	852
Spring wheat	2 617	1 812	1 872	785	-	764	303	852
Barley	2 617	1 812	1 872	785	1 054	764	303	852
Oats	3 287	1 812	1 872	785	1 054	764	303	852
Rapeseed	4 401	2 958	2 888	1 629	-	764	303	852
Yellow peas	4 173	2 849	2 792	1 565	-	-	-	-
Feed peas	4 173	2 849	2 792	1 565	-	-	-	-
Broad beans	-	2 849	2 985	1 697	-	-	-	-

Appendix 2 Constraints

Table 1. Acreage constraints in GSS and SS.

Crop	% of total acreage
Winter wheat	50%
Barley	50%
Oats	50%
Rapeseed	20%
Sugar beets	20%
Yellow peas	16,67%
Feed peas	16,67%
Broad beans	16,67%

Table 2. Pre-crop constraints in GSS.

pre-crop	Crop							
	Winter wheat	Barley	Oats	Rapeseed	Sugar beets	Yellow peas	Feed peas	Broad beans
Winter wheat	X	X	X	X	X	X	X	X
Barley	X	X	X	X	X	X	X	X
Oats	X	X	X	X	X	X	X	X
Rapeseed	X	X	X	-	-	X	X	X
Sugar beets	-	X	X	-	-	X	X	X
Yellow peas	X	X	X	X	X	-	-	-
Feed peas	X	X	X	X	X	-	-	-
Broad beans	X	X	X	-	X	-	-	-

Table 2. Pre-crop constraints in SS.

Pre-crop	Crop							
	Winter wheat	Spring wheat	Barley	Oats	Rapeseed	Yellow peas	Feed peas	Broad beans
Winter wheat	X	X	X	X	X	X	X	X
Spring wheat	X	X	X	X	-	X	X	X
Barley	X	X	X	X	X	X	X	X
Oats	X	X	X	X	X	X	X	X
Rapeseed	X	X	X	X	-	X	X	X
Yellow peas	X	X	X	X	-	-	-	-
Feed peas	X	X	X	X	-	-	-	-
Broad beans	-	X	X	X	-	-	-	-