Combining GHG Emissions and Soil Carbon Changes as a Single Metric to Evaluate Agricultural Policy Promoting Biomass for Biofuels

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Abstract

Incorporating a multi-year grass ley into an arable crop rotation can increase soil organic carbon stocks, reduce carbon emissions and provide feedstock for biogas. This thesis set out to study how a policy promoting agricultural biomass for biogas impacts GHG emissions and carbon sequestration on a regional level over a temporal scale of 20 years. This was done in the specific case of policy promotion of an increased cultivation of two-year grass leys in the Swedish intensive-farming region Götalands Södra Slättbygder (GSS), to a 15% ley cover of the arable land belonging to the high intensity farms. This was studied by combining life cycle analysis methodology with a dynamic economic model, to provide a holistic overview of the impacts on carbon changes in the region. The results showed that the implementation the leys led to a decrease in the total, annual impact from agricultural processes in the magnitude of 22-23% . It also led to a decrease in total impact per the functional unit's cereal unit (9%) and price (18%) in the 20^{th} year. However, the implementation also led to a 15% decrease in food production. The food production also decreased over time in the reference scenario due to decreasing SOC stocks, although the decrease was lower than in the scenario with the added leys. The implementation of leys in specialised crop rotations have the potential to decrease regional GHG emissions from the agricultural processes, while also reducing the rate of loss of SOC content, but it might come at a cost of food loss and iLUC. However, not taking action against decreasing SOC stocks will also lead to loss of food production. Furthermore, methodological choices for the accounting of impacts from soil organic carbon changes were found to have a large impact on the results.

Populärvetenskaplig Sammanfattning

Att lägga till gräsvallar i växtföljden kan reducera den regionala klimatpåverkan från jordbruk som specialiserar sig på spannmål, med 10–20%. Samtidigt förbättrar vallarna jordhälsan och skörden kan användas till biobränsle.

Intensifieringen av jordbruket under de senaste decennierna har lett till en ökad matproduktion, men också till minskande kollager i marken och en försämrad jordhälsa på flera håll. Inte minst bland jordbruk specialiserade på spannmålsproduktion. Halten av organiskt kol i marken är betydelsefull eftersom den påverkar jorden på flera sätt, vilket i sin tur har effekter på ett flertal ekosystemtjänster. Studier har funnit att den organiska kolhalten i marken kan öka genom kolinlagring om en flerårig gräsvall läggs till i spannmålsbaserade växtföljder i områden med låg kolhalt. Gräset, som idag främst används som foder, skulle även kunna användas som biomassa till biogasproduktion. Att införa odling av gräsvallar i växtföljden för att öka jordhälsan och producera biogas är varken något som är vanligt förekommande eller lönsamt på kort sikt i Sverige idag. Eftersom att det däremot skulle kunna flera positiva effekter för både miljön, samhället och bönderna på sikt, är frågan om att stödja införandet av vallar i den här typen av växtföljd genom styrmedel aktuell. Det är därmed även aktuellt att undersöka vilka effekter ett sådant stöd skulle ge. Denna studien syftar till att bidra till ett sådant underlag, genom att undersöka vilken effekt tillägget av gräsvallar i spannmålsbaserade växtföljder har på klimatpåverkan från jordbruket, på regional skala. I dagsläget är det vanligt att klimatpåverkan från kolinlagring genom alternativa jordbruksmetoder inte inkluderas i beräkningar av klimatpåverkan från olika former av jordbruksprodukter, då det inte finns någon standardiserad metod för det. I denna studien inkluderas klimatpåverkan från förändringarna i kollagren i marken i beräkningarna av klimatpåverkan från odlingen. I studien beräknades klimatpåverkan från odlingen av grödorna i ett scenario i jordbruksregionen Götalands Södra Slättbygder, där gräsvallar lades till i växtföljden. Detta jämfördes sedan med klimatpåverkan från odlingen i ett referensscenario. Studien visade att den regional klimatpåverkan från jordbruket minskade med ca 10–20% i sceneriet med gräsvallar, jämfört med referenssceneriet. Dock minskade även matproduktionen i sceneriet med gräsvallarna, vilket skulle kunna leda till ytterligare miljö- och klimatpåverkan om denna förlorade matproduktion förflyttas.

Abbreviations

EF – Ecological footprint

GHG – Greenhouse gases

GSS – Götaland Södra Slättbyggder

GWP – Global Warming Potential

Ha - Hectare

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

RW – Responsibility Window

SOC – Soil organic carbon

Definitions

Agribalyse – French life cycle database (Agribalyses, 2022).

Biogenic carbon – Carbon that is stored in biological materials, such as plants or soil.

Carbon sequestration – The process of capturing and storing atmospheric carbon dioxide.

Inventory Analysis – The part of a life cycle analysis where data of emissions that are produced and resources that are used during the life cycle of the product or service are collected.

Impact Assessment – The part of a life cycle analysis where emissions and resources that were quantified in the inventory analysis are related to different categories of environmental issues and combined into common metrics.

Reference state – The soil organic carbon stock in the reference year.

Responsibility window - The time frame over which the impacts and benefits which are due to losses and gains in the carbon stock are being accounted for.

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Introduction

Intensive cultivation of arable land has led to an increase in food production over the past decades, but it has also come at a cost of soil degradation and related environmental issues (Albizua, Williams, Hedlund & Pascual, 2015; Montanarella, 2007). This has, among other things, led to decreasing soil organic carbon (SOC) stocks in several arable lands in Europe, including certain areas in Sweden (Montanarella, 2007; Brady et al., 2019). SOC content affects several soil parameters, such as nutrient availability, soil temperature, soil bulk density and water retention capacity (Brady et al, 2019, Prade, Kätterer, Börjesson, 2017; Bronic & Lal, 2005). In turn, it also affects several ecosystem services (Albizua, Williams, Hedlund & Pascual, 2015). It can for example affect water quality in near waters and higher nutrient availability can lead to lower needs of fertilizer use (Bronick & Lal, 2005). SOC content can further affect soil productivity and crop yields, which in turn can affect food security (Oelofse et al, 2015; Prade, Kätterer, Börjesson, 2017, Brady et al., 2019).

Decreasing SOC concentrations in arable land is a widespread problem, but one of special concern in agricultural areas specialized in cereal cropping (Prade, Kätterer, Börjesson, 2017). The build-up in SOC content from root biomass can be relatively low in these rotations compared to the build-up in grass leys, while the availability of animal manure can simultaneously be low in these areas (Bertilsson, 2006; Nilsson & Bernesson, 2009).

Studies have shown that incorporation of multi-year grass leys into specialized crop rotations have the potential to increase SOC content and mitigate greenhouse gas emissions by carbon sequestration (Lal, 2004; Brady et al, 2019; Prade, Kätterer & Björnsson, 2017; Tideåker et al., 2016). The increase in SOC content can in turn increase crop yields and enhance several ecosystem services (Persson, Bergvist & Kätterer, 2008, Brady et al., 2019; Arvidsson & Håkansson, 1991; SOILSERVICE, 2012, Smyth et al., 2009; Börjesson & Tufvesson, 2011). Adding leys into the crop rotation can lead to a reduced need for herbicides, which in turn reduces the risk for herbicide resistance (Andersson & Milberg, 1996). Leys with clover can increase nitrogen fixation which reduces the need for nitrogen fertilizers (Larsson et al., 2005). The leys can also decrease the risk of nitrogen leaching as long as they are kept, however when the leys are changed to another crop in the rotation, the risk for nitrogen leaching increases (Larsson et al, 2005.; Francis et.al, 1992). In addition, the leys also have a positive effect on ground structure (Lindén, 2008) and ground productivity (Persson et.al, 2008). It further increase hummus content, which in turn can increase the grounds water retention capacity (Tideåker et al., 2016; Cederberg et.al., 2012, Eriksson et a., 2010). In summary, adding leys into a cereal based crop rotation can have several positive environmental effects (Tideåker et al., 2016; Andersson och Wivstad, 1992, Bolinder et.al, 2010, Tideåker, 2014). Higher SOC content have also been found to lead to higher crop yields, but the effect is larger when the SOC content increases from a low level (1%) than a high (2%) (Tideåker et al., 2016; SOILSERVICE, 2012). This has however been questioned by Oelofse et.al (2015) who conducted a long-term study over 20 years where no significant effect could be detected for the soil organic carbon contents effect on the wheat yields in fields with low SOC content (>1%). Although, adding leys into the crop rotation comes at a cost of reducing total arable land dedicated to food crops, but increases in yields can partially compensate for this food loss in some cases (Lal, 2004; Brady et al, 2019).

Grass leys can, in addition to being used as forage, also be utilized as biomass for biogas (Prade et al., 2017). Growing leys as feedstock for biogas has been proposed as a strategy for increasing SOC content in carbon-depleted intensive farming regions, while simultaneously mitigating climate change by sequestering carbon and providing feedstock for biofuels (Prade, Kätterer, Börjesson, 2017). This has, the potential to improve specialized crop rotations in regions where production of leys is not a currently feasible option (Prade, Kätterer, Börjesson, 2017; Tidåker et al., 2016). Specialized crop rotations are generally more profitable than grass leys and tend to be cultivated in areas where specialized crop rotations are not feasible to grow.

Simultaneously, the demand for feedstock for biofuels are high and rising. Sweden is currently dependent on a large increase in biofuel use in order to meet its climate targets of having zero net emissions by 2045, and reducing domestic transport emissions by at least 70% by 2030 compared to 2010’s levels (The ministry of environment, 2021; Energimyndigheten, 2019; Börjesson, 2021; SOU 2013:84; Prade et al, 2017, Fossilfritt Sverige, u.å). The reductions in the transport sectors emissions are expected to be realized through a combination of increased energy efficiency and a shift from fossil fuels to electrified vehicles as well as alternative fuels, such as biofuels (Trafikverket, 2016; Fossilfritt Sverige, u.å).

Biofuels account for about 21% of the total energy use in the Swedish transport sector today and most of these fuels are imported (Energimyndigheten, 2020; Energimyndigheten, 2021). Demands for biofuels are currently increasing globally while resources to meet them are limited (Börjesson Hagberg, Pettersson & Ahlgren, 2016). When considering this together with the fact that Sweden is a country with a high amount of biomass resources per capita, it raises the question of whether Sweden can or should keep relying on imported biomass for biofuels to meet its increasing demands (Börjesson Hagberg, Pettersson & Ahlgren, 2016).

Some studies have estimated the Swedish biomass potential available for biofuels, while accounting for a range of technological and environmental constraints (Börjesson, 2021; Börjesson, 2016; Prade et al., 2017). The larger part of the estimated potential biomass that can be utilized comes from the forest, but agricultural biomass also accounts for a substantial part (Börjesson, 2021; Börjesson, 2016; Prade et al., 2017). The focus for these studies is biomass utilization that does not contribute to direct or indirect land use changes (LUC) by displacing food production, to avoid the negative environmental and societal consequences of such changes (Prade et al., 2017; Börjesson, 2021, Börjesson 2016). The potential biomass that can be utilized for biofuels is therefore focused on byproducts and residues as well as land that is currently not used or suitable for food production (Prade et al., 2017; Börjesson, 2021; Börjesson 2016). Competition for arable land and the consequences of land use change is one of the main problems with utilization of land-based biomass for biofuels (Miyake et al. 2012). However, while the focus on utilization of arable land that is not used for food production targets this problem, agricultural biomass production is still intertwined with the rest of the agricultural system (Grahn and Hansson, 2015). Economic policies with the aim to mobilize agricultural biomass for biofuels can therefore still have systematic effects on food production.

In summary, an incorporation of grass leys into specialized crop rotations have the potential to help resolve issues of decreasing SOC stocks. While simultaneously providing feedstock for biogas and mitigate climate change through carbon sequestration. While In addition, it also helps to ease other environmental issues such as for example eutrophication and herbicide resistance. Utilization of grass leys as biomass for biogas is however not a common practice today as grass leys are generally less profitable than specialized cash crops (Tideåker et al., 2016). Therefore, they tend to be grown in areas where specialized crops are not feasible to grow.

The incorporation of grass leys into cash crop rotations can however also be very costly for the farmer initially (Brady et al., 2019). Impacts on SOC content and associated ecosystem services can on the other hand also have positive economic impacts for farmers in the long term (Brady et al., 2019). This is not always known, recognized or accounted for by the farmers when choices of agricultural practices are made (Brady et al., 2019). Brady et al (2019) studied the impacts on societal welfare from changes in soil natural capital and associated ecosystem services which were caused by different agricultural management practices. They studied these changes in impacts by quantifying and evaluating them in economic terms. What they found was that an implementation of a two-year grass ley into an eight-year specialized crop rotation had a positive impact on soil productivity and associated ecosystem services, which in turn had a substantial impact on societal welfare in the long term. However, the incorporation of leys also generated a substantial initial loss of regional profits from the lost crop production that was replaced with leys. On the other hand, the measures for conserving the soil also benefited the farmers economically in the long term in some aspects, as it provided higher yields and lower fertilizer needs. This partially compensated for the initial losses of profit in the long term (20 years), although it did not compensate fully for the loss in the scenarios which they tested (their tested scenarios were two-year grass ley, covering 5%, 15% or 20% or the arable land). The incorporation of the leys thus served as an investment in soil natural capital, which repaid most of itself through improved soil productivity over time. In addition, Brady et al (2019) also found that the annual changes in yield due to changing SOC content in the soil was so small that it was hard to detect by the farmers, as the annual change was lower than the natural variations in yields from variations in weather. However, while the short term (annual) changes were small, the long-term impacts (20 years) on the yields were substantial.

This displays a market failure and a case of a “tragedy of the commons”. Where the value of the long-term effects on the farmers soil natural capital, the public goods and the societal welfare provided by the ecosystem services, are not accounted for or valued in the decisions of land management practiced. Or it’s devalued over the short-term effects on farmers welfare. This further highlights a need for policies that incentivizes farmers to manage the land in ways that enhance ecosystem services instead of degrade them.

Sweden has introduced a subsidy of this kind that targets grass leys by giving farmers 500 SEK per ha leys as a measure to support restoration of soil organic carbon in soils with depleted carbon stocks in intensive farming regions (Jordbruksverket, 2021). The subsidy was however deemed ineffective as it was thought to have mainly compensated farmers for existing leys which would have been there either way. Certifying the age of the leys and the environmental gains from them was also deemed difficult and uncertain, and requiring heavy administrate work to resolve the issues. The Swedish Board of Agriculture has therefore suggested that the subsidy should be removed, as evidence that the subsidy encouraged implementations of new leys was lacking (Jordbruksverket, 2021). Nevertheless, they still acknowledge that it is important to increase or at least sustain the current soil organic carbon stocks in the agricultural soil (Jordbruksverket, 2021).

In summary, there are several reasons for implementations of policy instruments that support alternative agricultural management methods that preserve soil natural capital, increase SOC stocks, increase carbon sequestration and provide biomass for biofuels. The implementation of grass leys into specialized crop rotations have the potential to contribute to all of these goals. There is therefore a need of environmental assessments that quantify the magnitude of the potential as well as consequences of such policy interventions, to inform policy decisions and policy design.

Several studies have found that grass leys can increase SOC content and enhance several ecosystem services (Brady et al., 2019), but few have assessed the potential on a regional level in detail. Brady et al. (2019) created a roadmap for assessing the impacts on societal welfare from changes in soil natural capital on several spatial levels (farm, regional and national), when grass leys in different proportions was incorporated into a specialized crop rotation. They also quantified the impact that this incorporation had on climate change. However, this assessment was limited by only including the impact from the sequestered carbon in the grass leys and the impacts from the greenhouse gas (GHG) emissions from the production of mineral N fertilizer.

Several life cycle analysis's and other forms of environmental assessments have also been made for biofuels from various feedstocks (Jeswani, Chilvers Andrew, & Azapagic Adisa, 2020). These have found that the climate change impacts from the production of biofuels vary greatly and are highly situational depending on several factors such as type of feedstock, production routes, methodological choices of the assessment and data variations (Jeswani, Chilvers Andrew, & Azapagic Adisa, 2020). It is further known that utilization of biomass for biofuels at a large scale can cause substantial negative environmental impacts (Wu et al., 2018). Potentially also lead to systematic negative feedback which increase greenhouse gas emissions and jeopardize the climate change mitigation potential of the biofuel (Kalt et al., 2020). At the same time, lifecycle assessments of agricultural products or biofuels seldomly included impacts from carbon sequestration that are due to alternative agricultural land management practices, since there is currently no standardized or commonly used method for the acutance of these impacts (Goglio et al., 2015; Jeswani et al., 2020; Ernstoff, Sangines de Carcer & Lindsay, 2021; Brandao, milai Canals & Clift, 2011).

This further calls for a need of a holistic assessment of how policy promotion that mobilize biomass for biofuels, and/or promotes alternative agricultural practices that increase SOC stocks or enhance ecosystem service would affect environmental impacts from these processes. This study aims to do this for the climate change impact from the agricultural processes on a regional level, including the impact from changes in the SOC stock.

Aim

The aim of this thesis is to study how policy promoting agricultural biomass for biogas impacts GHG emissions and carbon sequestration on a regional level over a temporal span of 20 years, which is a time frame that allows for SOC changes to cause perceptible effects (Brady et al., 2019). This is done in the specific case of policy promoting an increased cultivation of grass leys in the Swedish intensive-farming region of Götalands södra slättbygder (GSS). The goal is further to combine life cycle analysis methodology with a dynamic economic model to provide a holistic overview of the impacts on carbon in a cradle-to-farm-gate life cycle perspective, as well as impacts on food production in the region.

Research Questions

What are the regional impacts on GHG emissions and carbon sequestration from an increased production of biomass for biogas from grass leys in the regions of Götalands södra slättbygder (GSS)?

Limitations

The scope of this study is limited to a quantification of the impacts from cradle-to-farm-gate. This limit has been drawn as the focus of this study is on the impacts on carbon from an increased production of agricultural biomass that can be used for biogas, not the impacts from the whole production of biogas. The study is further limited to a quantification of the impacts on carbon emissions and sequestration only. It does therefore not include other forms of environmental impacts, even if other environmental impacts are relevant and important for environmental assessments that can inform policy decisions.

2. Method

Overview of the methodology

The aim of this thesis was to study how policy promotion of agricultural biomass for biogas could affect climate impacts from the agricultural processes in the region of Götalands Södra Slättbygder (GSS). A previously modeled scenario by Brady et al. (2019) was used as an illustration of how the agriculture in GSS could change over 20 years, if agricultural biomass for biogas would be promoted by policy. A reference scenario by Brady et al (2019) of what the agriculture in the area could look like over the course of 20 years if no leys were added was also used for comparison. The climate impact from the agricultural processes in the region was quantified using life cycle assessment (LCA) methodology. The climate impact for a kg crop was collected for each of the main crops in the area from a life cycle inventory database. Impacts from changes in the soil organic carbon stock were also accounted for separately, since these were not included in the impact from the database. The impacts from the soil carbon changes were quantified per ha land for the whole rotation in both the scenario with the added leys and the reference scenario, using methods by Ernstoff, Sangines de Carcer & Lindsay (2021). Both the impacts from the database and the soil carbon changes were then combined with the results from the modeled scenarios to obtain a total impact from the agricultural processes in the region in the two scenarios. This was done for five specific years from the modeled scenarios, year 5 and 20 in both scenarios and year 0 in the reference scenario. This way, the results could then be compared between scenarios and over time in order to answer the first research question. An overview of the method of this study is displayed in Figure 1.

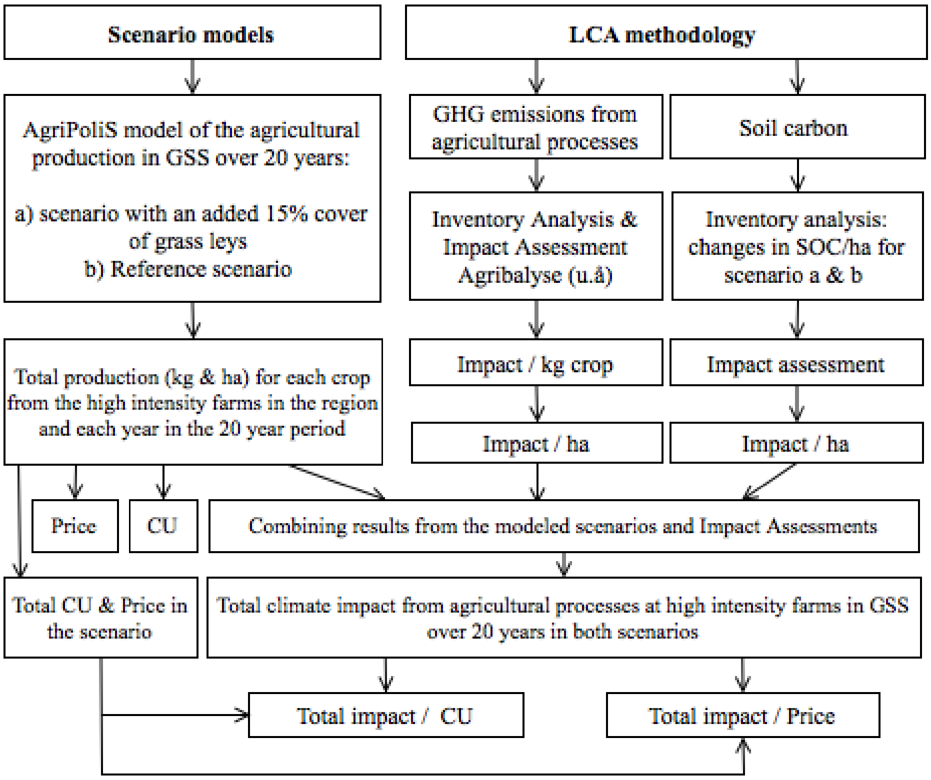

Figure 1. Overview of the method of the study

2.1 Modeled scenarios displaying the changes in agricultural practices over time in scenarios with and without added grass leys

2.1.1 About the region

The effects on climate impacts and food production were assessed on a regional level, since this increases relevance for policy-making support, as policy schemes customed for local conditions are usually made at this level (Brady et al. 2019). The chosen region for the study was one of Sweden's eight naturally defined agricultural regions, Götalands Södra Slättbygder (GSS) (Figure 2). This region was chosen partly because it's a region with decreasing soil organic carbon (SOC) stocks and high intensity farming that specializes mainly in cereal crops. It was also chosen because there were existing modeled scenarios available that could be utilized for assessing the climate impact for the implementation of the grass leys (Brady et al., 2019; Hristov et al, 2017).

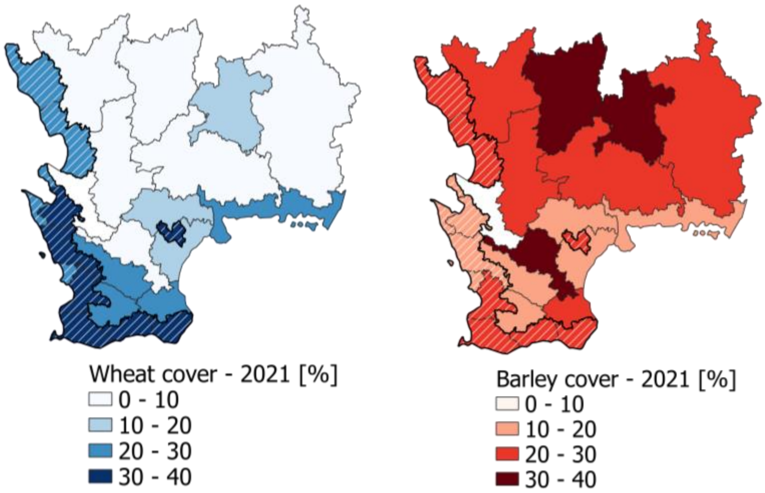

Figure 2. Map of GSS

Showing the wheat and barley cover in GSS and neighboring agricultural areas. GSS is the outlined production area along the west and south coast. The rest of the area is part of Götalands mellanbygder and Götalands skogsbygder.

GSS is a region with high intensive farming, it's relatively homogeneous and has high yields compared to the rest of Sweden (Brady et al., 2017). Agricultural land dominates the landscape and fields are usually large, open and well connected with farm centers (Brady et al., 2017). The most common crops are: winter wheat, spring barley, winter rapeseed and sugar beets. Together these crops account for 95% of the arable land in specialized crops (SCB, 2013). Standard yields for these crops are: 7900 kg ha^{-1} for winter wheat, 5700 kg ha^{-1} for spring barley, 3600 kg ha^{-1} for winter rapeseed and 60 000 kg ha^{-1} for sugar beets (SCB, 2013). The area has a long history of intensive arable cropping and lack of inputs of organic matter to the soil, such as application of stable manure (Brady et al, 2019). Because of this, the soil organic carbon (SOC) content in the area is relatively low compared to other, bordering regions that have a high percentage of livestock production and perennial grass crops. While GSS is mainly dominated by arable crop rotations, some livestock farms are still present in the region. These areas have demonstrated higher SOC stocks in the fields than the farms which are solely crop based. Despite having a low SOC stock, GSS still have Sweden's highest standard yields, due to the soils having an overall highest productivity (Brady et al., 2019).

2.1.2 About the modeled scenarios

The scenarios from Brady et al (2019) that were used in this study were modeled using AgriPoliS, which is an empirical agent-based model, that simulates farmers responses to economic policy changes (Happe, Kellermann & Balmann, 2006; Balmann, 1997; Hristov et al, 2017). It models a population of heterogenous farmers, who compete for agricultural land in a spatial and dynamic environment in a defined region (Happe, Kellermann & Balmann, 2006). The model is set up so that each farm maximizes their income through optimization of their production activities, investments and allocation of capital as well as family labor (Brady et al., 2019)

Both scenarios that were used in this study were modeled over 20 years, with 2016 as the base year (Brady et al., 2019). In one of the scenarios, a two-year grass ley was added into the crop rotation to the extent to which they covered 15% of the arable land at the high intensive crop farms (Brady et al., 2019). No additional grass leys were added in the other scenario, which worked as a reference scenario. The farmers were assumed to use conventional practices and it was also assumed that no particular measures were taken to maintain soil carbon, other than incorporation of harvest residues in the soil through plowing in both scenarios (Brady et al. 2019). The farms in the scenarios reflects the farms in GSS as they were based on data for farm sizes, production activities and soil properties in GSS, that were collected from the Farm Accountancy Data Network (FADN) survey and calibrated into AgriPoliS by Hristov et al (2017). Most farms in the region are crop farms, but some livestock farms exist. However, only high intensity arable farms and no livestock farms were included in the final assessment of the regional climate change impacts in this study. Since only these farms have declining SOC stocks and benefits from the restoration measure of incorporating the leys. This also meant that one of the main crops, barley, was not included in the assessment, as all barley in the scenarios were grown on the farms with less intensive production, on land with low productivity.

The modeled scenarios give plenty of information on the agriculture in the region. The information that was used in this study was the amount of the crops that were produced (in kg) at the high intensity crop farms in the region in five assessment years in the scenarios. The five assessment years that were chosen were year 0 in the reference scenario and year 5 and 20 in both the scenario with the added grass leys and the reference scenario without the added leys. These years were chosen to display changes in agricultural practices in the region over time and between the scenarios. The amount of crops produced were collected for all of the main crops (except barley) and the additional grass leys. Additional grass leys that were implemented due to the changes in the scenarios, were kept separate from already existing grass leys used for feed at livestock farms in the region in the model. The results from the models were then coupled with the collected climate impact per kg produced crop from the life cycle database and the calculated climate impact from the soil carbon changes. This way, a total climate impact for the agricultural processes in the region in all assessment years could be obtained. The total production of crops in the region was also used to assess how food production and total revenues in the region changes over time in the two scenarios.

2.2 Life Cycle Assessment (LCA) methodology

The climate impacts from the agricultural practices in the modeled scenarios were assessed using techniques from life cycle assessment (LCA) methodology. LCA is a commonly used method for assessing environmental impacts for various products. It has, among other things, been used frequently to assess the impacts from greenhouse gas emissions from crop production systems and biofuel production (Goglio et al., 2015; Jeswani et al. 2020). The goal of a life cycle assessment is to provide an overview of the total environmental impact from all the stages of a product's or a service life (Baumann & Tillman, 2004). From the extraction of raw materials, to the disposal or remanufacturing of the product (Baumann & Tillman, 2004). In this study, the aim was not to make a full life cycle analysis, but instead to draw on some of the techniques in LCA methodology, in order to assess and quantify the impacts on climate change arising from the modeled scenarios. As well as to assess the climate impacts from the soil carbon changes in the region and combine both these impacts with the dynamic economic model to provide a holistic overview of the impacts on carbon and food production in the region. Figure 3. shows the framework for the life cycle assessment methodology.

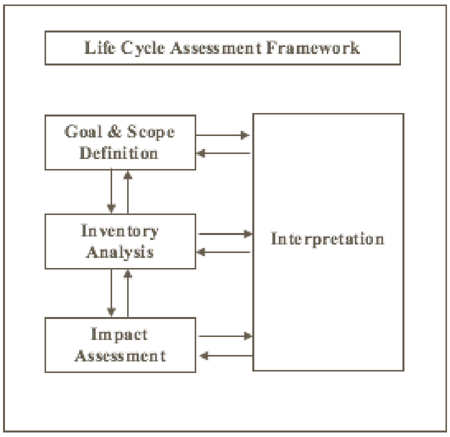

Figure 3. Overview of the Life Cycle Assessment Framework (Baumann & Tillman, 2004).

The first step of a life cycle assessment is to specify the *goal and scope of the study* (Baumann & Tillman, 2003). In this step, the reason for carrying out the study and the intended application and audience of the study should be defined. The geographical, temporal, natural and technical boundaries of the system that are being studied should also be defined here. This has been done in the introduction of this study as well as in previous and later sections of the methodology.

The second step of an LCA is the *inventory analysis*, where data of emissions that are produced and resources that are used during the life cycle of the product or service are collected. The inventory can be created using raw data, but it's also common practice to collect data from life cycle inventory (LCI) databases where environmental impacts from various processes and products are collected (Baumann & Tillman, 2003).

The third step in an LCA is *the impact assessment*. Here, the emissions and resources that were quantified in the inventory analysis are related to different categories of environmental issues and combined into common metrics that describe the impacts in a more simplistic way (figure 5). For example, greenhouse gas emissions are classified into the category global warming and then characterized into the common metric CO_2eq (figure 5). The emissions are characterized into this common metric using *characterization factors*, which are based on the physio-chemical mechanisms that determine how the substances contribute to the impact categories. They are also defined by a common determinator that is shared by the parameters in the group. For example, the common metric for greenhouse gases and global warming potential is CO_2eq and the characterization is based on the extent to which the gas enhances the radiative forcing in the atmosphere.

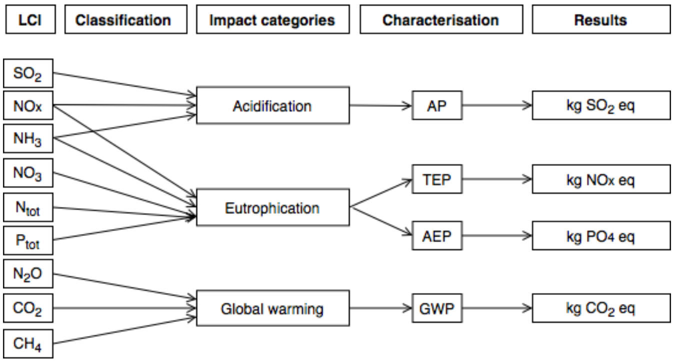

Figure 5 Illustration of the classification and characterization process. Over the impact assessment process.

2.2.1 Impact assessment for the agricultural processes in the region using the database Agribalyese

The data of the climate impacts from the agricultural processes for cultivating the main crops in the region were collected through the life cycle inventory (LCI) database Agribalyse in this study (Agribalyse, 2022). Agribalyse is an opensource LCA database that provides reference data on environmental impacts from the production of agricultural products produced in France. The scope of the agricultural products in the database is cradle-to-farm-gate, thereby including all stages of production up until they leave the farm. This matches the inventory needed for this study, as the scope of this study only extends to the production of biomass at the farm level and does not include later processing steps of the produce after the products have left the farm. The data was assumed be appropriate for Swedish conditions as agricultural practices in France are similar to Swedish agricultural practices, despite having somewhat different conditions (personal communication, Mark Brady, researcher in biodiversity and conservation science, 2022). Processes with similar yields to the average yields in GSS was also chosen, as largely differing yields would have had a great impact on the results. Other factors were reasoned to have a lower impact on the results as these are fairly similar between the regions (personal communication, Mark Brady, researcher in biodiversity and conservation science, 2022). The data was collected in the form of kg CO_2eq per produced kg crop for all of the main crops in the region and the grass leys. This data, as well as more detailed information on what is included in the processes, can be found in Appendix 2.

Agribalyse (2022) uses the life cycle impact assessment (LCIA) method Ecological Footprint (EF) 2.0 (Fazio et al, 2020) for the impact assessment calculations (Agribalyse, 2022). It has been shown that the choice of LCIA methods in impact assessment can have a vast impact on the results (Chen, Matthes & Griffin, 2021). However, results for global warming tend to vary less between different impact assessment methods (Chen, Matthes & Griffin, 2021), which makes the LCIA method choice in this study less impactful.

The Ecological Footprint (EF) 2.0 includes fossil and biogenic carbon emissions and removals, as well as carbon emissions from land use and land use change in the impact assessment (Fazio et al, 2020). A more detailed description of what these categories include can be found in Appendix 5. It does however not include accumulation or uptake of soil carbon through improved agricultural management and recommends that these impacts are modeled separately (Fazio et al, 2020). Changes in the soil carbon stock due to the incorporation of grass leys, as well as the declining SOC content from the specialized crop production, falls into this category and was therefore accounted for separately in this study.

2.2.2 Inventory analysis and impact assessment for changes in the soil organic carbon stock

Impacts from changes in the soil carbon stock were accounted for separately, as these were not included in the impact collected from Agribalyse. There is, as mentioned before, no standardized or commonly used method available for the accounting of soil carbon changes at the moment (Ernstoff, Sangines de Carcer & Lindsay, 2021; Goglio et al., 2015). However, some studies that have developed methods for accounting for these types of changes are still available (Ernstoff, Sangines de Carcer & Lindsay, 2021; Goglio et al., 2015).

The method used for the accounting of impacts from the changes in the soil carbon stock in this study was developed by Ernstoff, Sangines de Carcer & Lindsay (2021). Ernstoff, Sangines de Carcer & Lindsay (2021) provides a guidance for accounting for climate impacts and benefits from changes in soil and biomass carbon stocks that originate from changes in land management practices on farm level, which makes it suitable for this study. The method was developed through the C-seq project by a team of global academia from various universities in collaboration with specialists, industry stakeholders and the consultancy agency Quanties. The project was also funded and driven by several big actors in the beef and dairy industry.

There are two main inventory flows that are of interest for the inventory analysis when accounting for SOC changes according to Ernstoff, Sangines de Carcer & Lindsay (2021). That is 1) Carbon that has been removed from the atmosphere and stored in soil or biomass and 2) Carbon losses from the carbon stock. These flows should be kept separate and considered per ha of land according to the guidance (Ernstoff, Sangines de Carcer & Lindsay, 2021).

A reference carbon stock per ha for the year before the first year in the scenarios (year 0) was first calculated, in order to later calculate the changes in SOC content over the 20 years. This was calculated based of average data for soil properties in the region (Brady et al., 2019, supplementary material), using equation 8 from Brady et al (2019) (Appendix 3). The change in the carbon stock over the modeled 20 years was then calculated using two different rates of change for the two different crop rotations, in the two different scenarios. An annual increase of 1% of the SOC stock was used for the rotation with added grass leys, since studies have found that this can be accomplished if a multi-year grass ley is included in a rotation of annual cash crops (Brady et al., 2019). For a rotation without leys, the annual decrease is -0,5%. This was because studies have shown that the SOC content in the region of GSS used to be in the range 2.7-4.4% fifty years ago (Albizua et al, 2015). While today, the average is 1,7% (Brady et al. 2019). It has thereby been decreasing with a rate of 0,5% per year over the last 50 years. The calculations of these changes in the carbon stock over the 20 years in both scenarios can be found in Appendix 4.

The research area for estimations and measurements of changes in carbon stocks is currently under development. Ernstoff, Sangines de Carcer & Lindsay, (2021) does therefore not require a certain model or approach to estimate the stock change. However, they do recommend using high tier models when possible. The order of a Tier refers to the methods degree of complexity, where higher tiers refers to methods with higher complexity (Ernstoff, Sangines de Carcer & Lindsay, 2021). For example, methods that are simpler and uses default values which are based on aggregated empirical data, are referred to as the Tier I models. On the other hand, simple methods with a high level of data disaggregation, as for example on a country level, are referred to as Tier II. Tier III models refers to methods that are more complex and based on primary data collection and monitoring (Ernstoff, Sangines de Carcer & Lindsay, 202). High quality data that has gone through a third-party verification that is trusted or high tier models, such as tier III models, are viewed as high-quality data that is recommended by the guidance (Ernstoff, Sangines de Carcer & Lindsay, 2021). While lower tier models without third-party verification are viewed as data of lower quality. The calculations of the carbon stock and the changes in it are based of 50-year long experiments in the relevant area that are peer-reviewed, published studies. It can therefore be seen as highly reliable.

Ernstoff, Sangines de Carcer & Lindsay (2021) provides two different choices for characterization factors for the impact assessment (Table 1). This is because Ernstoff, Sangines de Carcer & Lindsay (2021) gives the choice of applying what they call a responsibility window. The responsibility window marks the time over which impacts from emission and uptake of carbon are being accounted for. In the IPCC GWP100 framework, which is one of the most commonly used frameworks for accountings of climate change impacts, it's implied that the impact from 1 kg of CO_2eq is equivalent to the impact from 1 kg of CO_2 emissions that has an impact on the atmosphere *over a time frame of a 100 years* (Stocker et al., 2013). This makes accountancy of impacts from carbon sequestration more complicated, as a consequence of this is that 1 kg of sequestered carbon can only be equal to -1 kg CO_2eq if that carbon stays sequestered for 100 years. Ernstoff, Sangines de Carcer & Lindsay (2021) recognizes that 100 years is an unpractical time frame for the accounting of carbon sequestration impacts from agricultural processes, as it's hard to guarantee that carbon from a certain management practice has or will be stored for a hundred years. Since there's always a possibility that a future change in land management, land use or some other relevant event such as a fire or a flood can occur, which can affect the carbon stock and release the stored carbon again (Ernstoff, Sangines de Carcer & Lindsay, 2021).

They solve this issue by recommending a responsibility window of 20 years for agricultural processes, as it is a more reasonable timeframe to inventory changes and calculate impacts for than a hundred. The choice of responsibility window also affects the characterization factor, as it has to be adjusted to the chosen responsibility window to align with the GWP100 framework.

Ernstoff, Sangines de Carcer & Lindsay (2021) suggest two characterization factors (Table 1) for a responsibility window of 20 years and two characterization factors for the responsibility window of a hundred years (Table 1). One of the characterization factors is for emissions from the carbon stock and the other is for gains in the carbon stock compared to the carbon stock at the reference state (year 0 of the responsibility window).

The characterization factor for emissions when using a responsibility window of a 100 years is the same as in the GWP100 framework: 1 kg of CO_2 emissions is equal to 1 kg CO_2eq and accounted for a time frame of 100 years (Table 1). While the characterization factor for stored carbon is adjusted to -0,01 kg CO_2eq per every kg CO_2 that is stored in a year. This way, when the impacts are accounted for over a time period of one hundred years, they add up to -1 kg CO_2eq. If a 20-year responsibility window is applied, then the characterization factor is adjusted to 0,5 kg CO_2eq per kg emitted CO_2 in a year and -0,05 kg CO_2eq per kg stored CO_2 in a year. Which again adds up to the full credit of – 1 kg stored CO_2eq only after the carbon has been stored for 20 years.

Tabell 1 Characterization factors for soil carbon sequestration

Characterization factors for stored and emitted CO_2 inventoried as net gains and losses of the carbon stock in the given year S_n, from the reference state (S_0), as recommended by Ernstoff, Sangines de Carcer & Lindsay (2021).

Inventory flows	Inventory unit	Characterization factor	Adjusted characterization factor given a 20-year responsibility window
S_{LCI} When $S_n < S_0$	kg CO_2 stock emitted - year	1 kg CO_2 eq/ kg CO_2 stock emitted - year	0.05 kg CO_2 eq/ kg CO_2 stock emitted – year (expires after 20 years)
S_{LCI} When $S_n > S_0$	kg CO_2 stock stored - year	-0.01 kg CO_2 eq/ kg CO_2 stock stored - year	-0.05 kg CO_2 eq/ kg CO_2 stock stored – year (expires after 20 years)

For this study, the application of a 20-year responsibility window was first considered, since the scenarios are modeled over 20 years and this is a more practical timeframe for accountancy of sequestered carbon as mentioned by Ernstoff, Sangines de Carcer & Lindsay (2021). It was also considered because the initial idea was to account for the impacts from both the emissions and sequestration of carbon for each year in the simulations. However, in the end, the characterization factor for emissions from the IPCC GWP100 framework that corresponds to the responsibility window of a hundred years was chosen. This choice was made because the changes of soil carbon could only be accounted for on a level that resulted in net emissions in the case of this study, according to the guidance (Ernstoff, Sangines de Carcer & Lindsay, 2021). The shorter responsibility window and corresponding characterization factors are a way to handle the previously mentioned issues regarding the accountancy of impacts from stored carbon. Since the result ended up in net emissions in both scenarios, there was no need to account for stored carbon in the end in this case. Thus, it made more sense to choose the original characterization factor for emissions from the IPCC framework, than the adjusted characterization factors for the responsibility window of 20 years. The calculations of the impact for the SOC changes in GSS in the studied scenario can be found in appendix 3.

2.3 Functional units

The impact from a product or a service is quantified in impacts per a *functional unit* in life cycle assessment methodology (Bryman & Tillman, 2011). The functional unit of an LCA relates the environmental impacts of a product to the function of the product system in a quantitative unit (Bryman & Tillman, 2011).

The function of the agricultural production in the region of GSS in the scenarios in this study can be seen as several different things. It can be seen as the function of providing food, feed or biomass for energy. In this case, a functional unit of biomass produced, energy content or nutritional content in the produced crops could for example all be relevant functional units for the aim of the study. Generating income for the farmers in the area or creating revenue could also be seen as a function of the agricultural production in the region that is relevant for policy decision. Two functional units were used for the impact on the regional level: the cereal unit (CU) and price of the produce (SEK). The first one targeting the function of providing food and feed, the second targeting the function of generating income.

The CU is a well-established unit, developed by German agricultural authorities and scientists (Brankatschk & Finkbeiner, 2014). It expresses the nutritional value for animals feeding in a common unit and can also serve as a common unit of nutritional value for products that are not used for livestock feed. While this is a unit that is more adjusted towards animal feed and a simplification of the nutritional value, it is a unit that is applicable to crops grown for both animal feed, human food and energy crops that makes them comparable in nutritional value (Brankatschk & Finkbeiner, 2014). The CU makes a suitable unit for the functional unit of the study since it integrates several of the relevant functions into one unit. It integrates mass and energy content, and to some extent economic value too (Brankatschk & Finkbeiner, 2014). Since the feeding value is influenced by the amount of substance with a certain energy value, which is reflected in the CU value. While the economic value is integrated in the CU, the additional functional unit of price was still chosen as well to illustrate a more precise impact on the farmers revenue, since this is an important factor for policy-making decisions.

CU's for all crops in the region were collected from Brankatschk & Finkbeiner (2014). The CU's for a specific crop was then multiplied with the results for the total annual production of that crop from the modeled scenarios. This was done for all the main crops and the grass leys in the region and for all assessment years (year 5 and 20 in both scenarios and year 0 in the reference scenario) (Appendix 4). The total CUs for each crop in a specific assessment year was then multiplied together in order to obtain a total CU for the total production in the region in each assessment year (Appendix 4).

The price per kg crop for each crop in the region also was gathered from (Agriwise, u.å). The price for each crop was then multiplied with the total production of that crop in each assessment year, in order to obtain a total price for the total production of each crop in each assessment year (Appendix 4). The total price for all produce in each assessment year was also multiplied together to obtain a total price for the crops produced in each assessment year (Appendix 4).

2.4 Regional impacts

The impacts that were collected from Agribalyse and the impacts from the soil carbon changes were then combined with the results from the modeled scenario, in order to aggregate them from crop level to a total regional climate impact. The impacts per kg crop produced that was collected from Agribalyse were first converted to impacts per ha by multiplying the impact with the standard yields for the crop. This impact per ha was then multiplied with the amount of ha used for the cultivation of that crop in each assessment year. The same thing was done for the impact per ha from the soil carbon changes. The total impacts were also divided by the total CU and the total price for each assessment year, to get a total impact per each functional unit (Appendix 4).

The total production of crops in the region was also used to assess how food and feed production in the region changes over time in the two scenarios, and the total price in was used to see how total revenues in the region changes over time and between scenarios.

Result

3.1 Effects on climate change impacts over time and between scenarios

The total annual climate impact from the cultivation of the main crops and grass leys at the high intensity farms in the region decreased substantially when a two-year grass ley was added into the arable crop rotation, mainly because of a decreased impact from the soil carbon changes (Diagram 1-3).

3.1.1 Effects on climate Impact from the agricultural process

The *total annual, regional impact* from the agricultural processes in the region which were collected from the database *Agribalyse* and then aggregated to regional level, decreased in the scenario with the added leys, while it stayed almost the same in the reference scenario (Diagram 1, Table 2). In the scenario with the added leys, it was 6% lower than in year 0 in both year 5 and 20, which corresponded to a 3 836 ton CO_2eq decrease. The same impact in reference scenario was 0,1% higher in year 5 and 0,2% higher in year 20 than in year 0. This corresponded to an increase of 63 tons CO_2eq in year 5 and 147 tons CO_2eq in year 20.

The results for same impact divided per the functional units, turned out different (Diagram 2, Table 2). The total annual, regional impact from the agricultural processes collected from *Agribalyse* per the functional unit the cereal unit (CU) was 0,28 kg CO_2eq/CU in year 0. In the scenario with the added leys, it was 0,30 kg CO_2eq/CU in year 5 and 0,31 kg CO_2eq/CU in year 20. The impact in was thus 9% higher than in year 0 in year 5 and 11% higher in year 20 (Diagram 2, Table 2). The same impact in the reference scenario were the 2% higher in year 5 than in year 0 (28 kg CO_2eq/CU), while in year 20 it was 0,29 kg CO_2eq/CU and thereby 6% higher than in year 0.

The total annual impact from the agricultural processes collected from *Agribalyse* per the functional unit price (SEK) stayed very similar through the years (Diagram 3, Table 2). The impact was 0,146 kg CO_2eq/SEK in year 0. In the scenario with the added leys, the it was 0,145 kg CO_2eq in year 5 (1% decrease) and in year 20 it was 0,147 CO_2eq/SEK (0,1% increase). In the reference scenario, it was 0,49 in year 5 (2% increase) and 1,54 CO_2eq/SEK in year 20 (5% increase).

3.1.2 Effects on climate impacts from the soil carbon changes

The difference in impacts from the soil carbon changes between the scenarios were substantially larger than for the rest of the impact. In the scenario with the added leys, the total annual impact from the *SOC changes* decreased with 46% (20 374 t CO_2eq) in year 5 and 48% (21 342 t CO_2eq) in year 20 compared to the year 0 (Diagram 1, Table 2). While in the reference scenario, the impact from the annual SOC changes decreased with 3% (1153 t CO_2eq) in year 5 and 16% (7321 t CO_2eq) in year 20, compared to year 0 (Diagram 1, Table 2).

The decrease in impact per the functional unit, the cereal unit were lower than decrease for just the impact alone, but still substantial. The annual, regional impact per CU was 0,174 kg CO_2eq/CU in year 0. In the scenario with the added leys, it had decreased by 37% to 0,110 kg CO_2eq/CU in year 5 and by 39% to 0,107 kg CO_2eq/CU in year 20, compared to year 0. In the reference scenario, it decreased by 1% to 0,173 kg CO_2eq/CU in year 5 and by 12% to 0,154 in year 20, compared to year 0.

The total annual, regional impact per price from the SOC changes was 0,103 kg CO_2eq/SEK in year 0. In the scenario with the added leys, it decreased by 46% to 0,056 kg CO_2eq/SEK in year 5 and by 48% to 0,054 kg CO_2eq/SEK in year 20. In the reference scenario, it decreased by 6% to 0,097 kg CO_2eq/SEK in year 5 and by 17% to 0,086 kg CO_2eq/SEK in year 20, compared to year 0.

While the decrease in the scenario with the added leys was mainly due to the addition of the leys leading to a decreased rate of change at which the SOC stock was decreasing. The decrease in emissions over time in the reference scenario (and partially also in the scenario with the added grass leys) was a result of the SOC stock decreasing over time. Because as the total SOC stock got smaller over time (due to the emissions of carbon) the carbon that was being emitted each year also decreased. Since these emissions were assumed to be a certain percentage of the total, decreasing, carbon stock. For example, the total SOC stock was 73,669 tons per ha in the scenario with the added leys in year 5 and 70,688 tons per ha in year 20 (Appendix 3, Table 3). While in the reference scenario it was 72,841 tons per ha in year 5 and 67,565 tons per ha in year 20 (Appendix 3, Table 3). This responded to an annual emission of 744,8 kg CO_2 in year 5 and 714,8 kg CO_2 in year 20 in the grass ley scenario (Appendix 3, Table 3). While in the reference scenario it responded to annual emissions of 1342,1 kg CO_2 per ha in year 5 and 1244,9 kg CO_2 in year 20 (Appendix 3, Table 3). The changes in annual impact between year 5 and year 20 are small in comparison to the differences in impacts between the two scenarios. But it does explain the differences in annual impact (per ha) over time in the reference scenario, and contributes to the difference over time in the grass ley scenario. This also explains why the total impacts from the SOC changes stayed almost the same in year 0 and year 5 in the reference scenario but decreased with 16% in year 20. Most of this decrease was due to annual emissions decreasing as the total SOC stock decreased. However, part of the decrease was due to variance in land used for cultivating the crops, which were slightly lower in year 20 than in year 5.

3.1.3 Effect on the total climate impact

When the impacts from the agricultural processes (which was collected from Agribalyse and aggregated to a regional level) was combined with the impacts from SOC changes, then it resulted in a decrease of 9-23%. In the scenario with the added leys, the total annual, regional impact was 22% (24 210 t CO_2eq) lower in year 5 and 23% (25 114 t CO_2eq) lower in year 20 than in year 0. In the reference scenario, it was 1% (1090 t CO_2eq) lower in year 5 and 6% (7173 t CO_2eq) lower in year 20 than in year 0.

The decrease in total annual, regional impact per the functional unit the cereal unit was lower. The impact per the cereal unit was 0,44 kg CO_2eq/CU in year 0. In the scenario with the added leys, it decreased by 9% to 0,40 kg CO_2eq/CU in both year 5 and 20, compared to year 0. In the reference scenario, it increased by 1% in year 5 and decreased by 1% to 0,43 kg CO_2eq/CU in year 20, compared to year 0.

The total annual, regional impact per price was 0,244 kg CO_2eq/SEK in year 0. In the scenario with the added leys, it decreased by 18% in both year 5 and 20 to 0,201 kg CO_2eq/SEK in year 5 and 0,202 kg CO_2eq/SEK in year 20, compared to year 0. In the reference scenario, it increased by 1% to 0,246 kg CO_2eq/SEK in year 5 and decreased by 2% to 0,240 kg CO_2eq/SEK in year 20, compared to year 0.

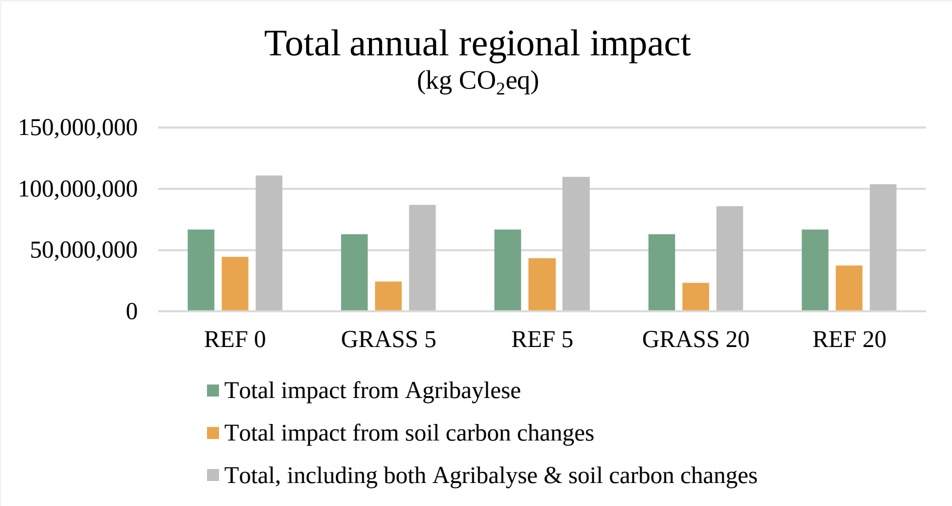

Diagram 1. Total regional impact per year

The diagram shows the results for the total climate impact per year from the cultivation of the main crops and leys at all of the high intensity farms in the region of GSS. This is shown for all assessment years (0, 5 & 20) in both the modeled scenario where the two-year grass leys were added into the crop rotation (x-axsis category "Added leys") and the reference scenario where no additional grass leys were into the crop rotation (x-axsis category "Refernece").

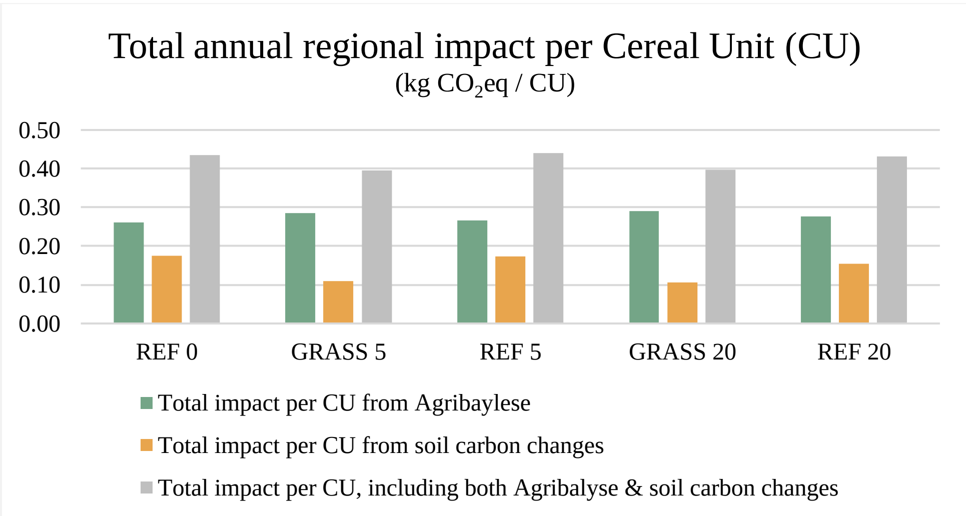

Diagram 2. Total annual, regional impact per Cereal Unit (CU)

The diagram shows the results for the total annual climate impact per the total cereal unit from the cultivation of the main crops and leys at all of the high intensity farms in the region of GSS. This is shown for all assessment years (0, 5 & 20) in both the modeled scenario where the two-year grass leys were added into the crop rotation (x-axsis category "Added leys") and the reference scenario where no additional grass leys were into the crop rotation (x-axsis category "Refernece").

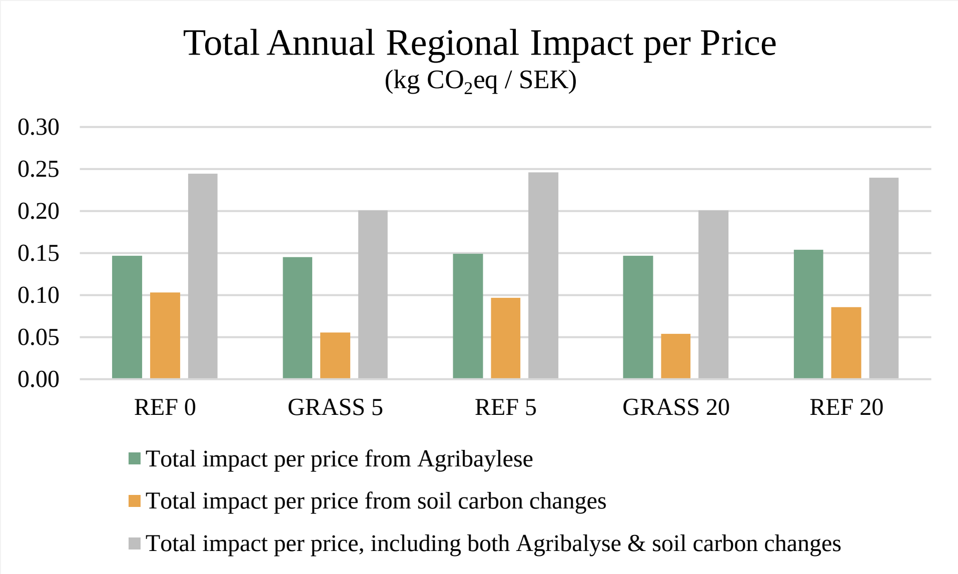

Diagram 3. Total annual, regional impact per price)
The diagram shows the results for the total annual climate impact per the total revenue (price) from the cultivation of the main crops and leys at all of the high intensity farms in the region of GSS. This is shown for all assessment years (0, 5 & 20) in both the modeled scenario where the two-year grass leys were added into the crop rotation (x-axsis category "Added leys") and the reference scenario where no additional grass leys were into the crop rotation (x-axsis category "Refernece").

Table 2 Percentual change in impact between year 0 in the reference scenario and the other assessment years.
Procentual change for the total annual impact, impact per ceral unit (CU), impact per price between year 0 in the reference scenario with no added grass leys and year 5 and 20 in both the scenario with the added grass leys and the reference scenario without any added grass leys.

Scenario & Year	Total annual impact			Impact / CU			Impact / price		
	Agri-balyse	SOC	Total	Agri-balyse	SOC	Total	Agri-balyse	SOC	Total
Added leys Year 5	- 6%	- 46%	- 22%	+ 9%	- 37%	- 9%	- 1%	- 46%	- 18%
Added leys Year 20	- 6%	- 48%	- 23%	+11%	- 39%	- 9%	0%	- 48%	- 18%
Reference Year 5	0%	- 3%	- 1%	+ 2%	- 1%	+ 1%	+ 2%	- 6%	+ 1%
Reference Year 20	0%	- 16%	- 6%	+ 6%	- 12%	- 1%	+ 5%	- 17%	- 2%

3.2 Effects on food and feed production

The AgriPoliS model also simulates the total amount of crops that is produced (in kg) for each crop in the region in each simulated year. Changes in food and feed production were also included in the results to illustrate the effect that the addition of the leys had on the production of food in the region (Table 3). The amount of food that were produced per year decreased over time in the scenario with the added grass leys. In year 5 in the scenario with the added leys, the annual amount of food produced was 12% lower than in the reference year (year 0) and 15% lower in year 20 than in the reference year (year 0). The food production in the reference scenario decreased too, but to a lower extent, with 4% in year 5 and 10% in year 20 compared to the reference year (year 0) (Table 3). Table 4 shows that the total CU produced showed similar trends, as the total annual CU also decreased over time in both the scenario with the added leys and the reference scenario, but with a higher decrease in the scenario with the added leys (14% in year 5 and 15% in year 20) than in the reference scenario (2% in year 5 and 6% in year 20) (Table 4).

The loss of food production in the scenario with the added grass leys was mainly due to farmers replacing wheat production with grass leys, while the production of the other main crops stayed more stable over time and between scenarios (Diagram 4).

Table 3. Differences in amount of produced food and energy crops (kg) between scenarios and over time

The table shows the amount of produced food and energy crops (kg) in the region in both the scenario with the added grass leys and the reference scenario, in all assessment years. It also shows the difference (%) in produced food crops between the reference year and later assessment years.

Scenario	Year	Food crops (kg)	% of year 0	Energy crops (kg)
Reference	0	401 795 500		0
Added leys	5	353 597 800	88%	33 354 125
Reference	5	386 200 300	96%	1 929 363
Added leys	20	341 136 930	85%	37 752 320
Reference	20	361 921 640	90%	8 313 088

Table 4. Total CU for the total production in the region

Total CU for the total production in the region in all assessment years, for both scenarios, and the percentual difference in total CU between the different assessment years and the reference year.

	Reference Year 0	Added leys Year 5	Reference Year 5	Added leys Year 20	Reference Year 20
Total CU	254 607 760	219 143 134	249 685 998	215 804 156	240 278 504
Percentage of the total CU in year 0 (%)		86%	98%	85%	94%

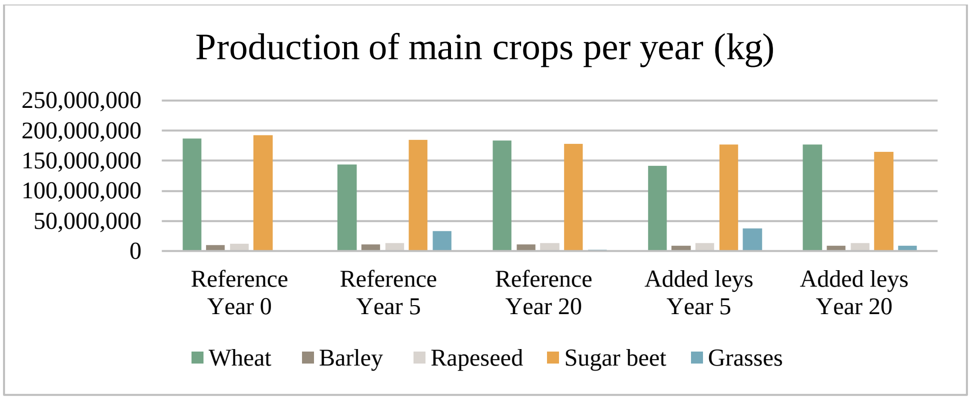

Diagram 4. Total **production (kg) in the region for each crop**
The total annual production (kg) of the main crops in the region for the assessment years (0, 5, 20).

Crop yields for the main crops in the area varied slightly over time, but generally decreased less over time in the scenario with the added grass leys than in the reference scenario (Table 5). Yields in the 5th year of the reference scenario were 97%-100% of the yields in the reference year, while the yields in the 20th year of the reference scenario were 88-99% of the yields in the reference year. In the scenario with the added leys, the yields where 98-101% the size of the yields in the reference year in year 5 and 93-100% in year 20 (Table 5).

Table 5. Change in average yields over time in the scenario with the added grass leys compared to the reference scenario
The graph shows the average crop yields for all food/feed crops in the region over time in both the scenario with the added grass leys and the reference scenario. It also displays the percentual change in yield between the reference year and the later assessment years.

Scenarios	Wheat	%	Barley	%	Rapeseed	%	Sugarbeet	%
Reference Year 0	7923	-	5822	-	3627	-	32013	-
Reference Year 5	7836	99%	5818	100%	3623	100%	30983	97%
Reference Year 20	7585	96%	5745	99%	3461	95%	28070	88%
Added leys Year 20	7883	99%	5834	100%	3659	101%	31532	98%
Added leys Year 20	7739	98%	5798	100%	3578	99%	29853	93%

3.3 Differences in impact depending on choice of method

The methods used for the choice of responsibility window and corresponding characterization factors for the impact from the changes in SOC content, had a large impact on the results. The characterization factor that was chosen for the calculations of the impacts from the soil carbon changes in this study was 1 kg CO_2eq per kg CO_2 emissions from the GWP100 framework by IPCC (Stocker et al., 2013). This characterization factor was also suggested by Ernstoff, Sangines de Carcer & Lindsay (2021) for the responsibility window of 100 years or for when permanency of sequestered carbon could be ensured. The results for the impact per ha for the SOC changes was 744,8 kg CO_2eq per ha in year 5 in the scenario with the leys when the characterization factor for emissions from the GWP100 framework was used (Table 5). When a 20-year responsibility window was used then the result for the same impact was 1342,1 kg CO_2eq per ha. For year 20 it was 714,8 kg CO_2eq per ha with the responsibility window of a 100 years and 1306,2 kg CO_2eq per ha if a 20-year responsibility window was used. While the impacts in the reference scenario were 1342,1 kg CO_2eq per ha in year 5 and 1244,9 kg CO_2eq per ha in year 20 if the responsibility window of a 100 years was used and 1408 kg CO_2eq per ha in year 5 and 1306,2 CO_2eq per ha in year 20 if a responsibility window of 20 years was chosen (Table 5).

Table 6. Differences in soil impact per ha depending on choice of characterization factor

The difference in resulting impact (in kg CO_2eq) per ha soil and year for all of the assessment years, between impacts calculated with a responsibility window of a 100 versus 20 years.

Scenario & year	GWP100/RW100 (kg CO_2eq)	RW20 (kg CO_2eq)
Added leys, year 5	744,8	1256,514
Reference, year 5	1342,1	1408,194
Added leys, year 20	714,8	733,8
Reference, year 20	1244,9	1306,2

Discussion

4.1 The effects on the regional climate impact from the implementation of leys into the crop rotation

Growing grass leys as feedstock for biogas has been proposed as a strategy for increasing SOC content in carbon-depleted intensive farming region, while simultaneously mitigating climate change by sequestering carbon and providing feedstock for biofuels (Prade, Kätterer, Björnesson, 2017; Tideåker et al., 2017). Previous studies have found grass leys to increase SOC content and enhance several ecosystem services such as soil production and crop yields (Persson, Bergvist & Kätterer, 2008, Brady et al., 2019; Tideåker et al., 2017; Arvidsson & Håkansson, 1991; SOILSERVICE, 2012; Andersson & Milberg, 1996; Larsson et al., 2005; Lindén, 2008; Persson et.al, 2008; Cederberg et.al., 2012, Eriksson et a., 2010). While this thesis set out to study how a promotion of incorperations of grass leys into cereal-based crop rotations in GSS would affect regional GHG emissions and carbon sequestration from the agricultural processes in the region. This study showed that the implementation of grass leys into the crop rotations at the high intensity farms in the region, had little effect on the impact from the agricultural processes when the impact from the soil carbon changes were not included. However, the impact from the soil carbon changes almost halved at the introduction of the leys. Which resulted in a 22-23% decrease of the total impacts when the impact from the soil carbon changes were included with the rest of the impacts. Furthermore, when the impacts were calculated per the functional units, the total regional impacts decreased 9% instead from 0,44 kg CO_2eq/CU to 0,40 kg CO_2eq/CU and 18-19% from 0,24 CO_2eq/SEK to 0,2 CO_2eq/SEK.

These results are in line with other studies, which also exanimated the climate impacts from a cereal based crop rotation were leys were added into the rotation and used for biofuels and compared these rotations to rotations without leys (Tideåker et al., 2017; Prade, Kätterer & Björnsson, 2017). The results are in line in the sense that they both lead to reductions, but the extent of the reductions differ. They are also hard to compare as they use different functional units, type of system and system boundaries compared to this study and compared to each other.

Tideåker et al. (2016) studied the environmental and economic effects, as well as the effects on yields from an introduction of a two-year grass ley into a cereal based crop rotation with perennial crops in Uppland. They too found that greenhouse gas emissions were larger for the rotation with only cereal crops. More specifically, they found GHG emissions to be 308 kg CO_2-eq per ton cereal for the rotation with only cereal crops and the impact for the rotation with leys to be -28 kg CO_2eq per ton cereal crops for non-fertilized mixed leys, 33 kg CO_2eq per ton cereal for the fertilized mixed leys and 104 kg CO_2eq per ton cereal for fertilized grass leys. The results are hard to compare as they use a different functional unit (1 ton cereal) than in this study, but it's clear that they also the leys to contribute to a substantial decrease in impact.

Prade, Kätterer & Björnsson (2017) also studied effects on SOC content and GHG emissions from an inclusion of grass leys into a cereal based crop rotation. However, this study was done for a pig farm in southern Sweden where a one-year grass ley incorporated into a four-year crop rotation with rapeseed, winter wheat and oat, where it replaced the oat. The farm also converted the grass and pig manure to biogas on the farm, which was included in the studied impact through system expansion of the LCA. The total net emissions of the system without leys resulted in 2.1 tons CO_2eq/ha/year, while the system with the leys resulted in avoided emissions of 0,9 tons CO_2eq/ha/year, thereby resulting in a total impact of 0,62 t CO_2eq/ha/year.

Both Prade, Kätterer & Björnsson (2017) and Tidåker et al. (2017) included impacts from sequestered carbon into the calculation of the impacts just like in this study. This is also why the impact for the non-fertilized leys resulted in a negative impact and why the leys have such a low impact in general in Tideåker et al (2016). Tideåker et al. (2016) assumed the impact from the carbon sequestration to be 192 kg per ha for the rotation with leys, based on a previous study by Tidåker et al. (2014). They further assumed the carbon sequestration per ha to be 24 kg/ha for the cereal based rotation without leys based on the same study. This can be compared to Prade, Kätterer & Björnsson (2017), were he SOC changes also played a significant part in the reductions as these were -2,9 tons CO_2eq/ha/year in the rotation with the leys and 0,9 tons CO_2eq/ha/year in the rotation without. While in this study a 1% increase SOC for the grass leys which covered 15% of the land resulted in net emissions of 744,8 – 714,8 kg CO_2/ha for the rotation with the leys and the rotation without leys had an annual net loss of SOC corresponding to emissions of 1342,1 – 1244,9 kg CO_2/ha.

4.1.1 Inclusion of impacts from biogas production and fossil fuel replacement

This study was limited to only assessing the impacts from the cultivation at cradle-to-farm-gate. With the perspective of how climate impacts change in the case of a policy promotion of biomass for biofuels, it would also be interesting to extend the analysis to include climate impacts from the production of biofuels and its replacement of fossil fuels. The infrastructure for the production is also not yet present and the impact from its implementation would also be interesting to examine. This type of impact falls out of the scope of this study, but would provide further useful information on the climate impacts from such a policy decision to policy makers.

Both Tideåker et al. (2016) and Prade, Kätterer & Björnsson (2017) did however, unlike this study, include the climate impact from the production of biogas from the grass leys. Tideåker et al. (2016) included the usage of both the digestate and the biodiesel. For the later impact, the impact from the fossil energy usage that could be replaced with the produced biogas was subtracted from the impact of the rotation with the leys. This added a negative impact of -358 to -463 kg CO_2eq per ton cereal for the replacement of fossil fuels with biofuels and emissions of 149-189 kg CO_2eq per ton cereal for the production of the biogas (Tideåker et al., 2016). This had a huge impact on their results as impacts for just the production without the carbon sequestration was more similar and in one case higher for the rotation with leys (non-fertilized mixed: 387 kg kg CO_2eq per ton cereal, fertilized mixed 293 kg CO_2eq per ton cereal, fertilized grass 377 kg CO_2eq per ton cereal) than the cereal rotation 307 kg CO_2eq per ton cereal. While when carbon sequestration was included then impact decreased to become lower for the non-fertilized mixed leys (183 kg CO_2eq per ton cereal), lower but similar for the fertilized mixed leys (293 kg CO_2eq per ton cereal) and still higher for the fertilized grass leys (377 kg CO_2eq per ton cereal). However, when the biogas production and fossil fuel replacement was included, then the impact for the rotation with leys became significantly lower (non-fertilized mixed: -29 kg CO_2eq per ton cereal, fertilized mixed 34 kg CO_2eq per ton cereal, fertilized grass 103 kg CO_2eq per ton cereal) than the cereal rotation (307 kg CO_2eq per ton cereal).

Prade, Kätterer & Björnsson (2017) also used system expansion where biogas replaces fossil fuels added in a negative impact slightly below 2 t CO_2eq/ha/year for the replacement, which resulted in total net emissions of about 0,6 tons CO_2eq/ha/year for the rotation with leys (Prade, Kätterer & Björnsson, 2017). Which was substantially lower than the impact for the rotation without leys which was 2,1 t CO_2eq/ha/year.

The results from Tideåker et al. (2016) and Prade, Kätterer & Björnsson (2017) demonstrates that including the impacts from the biogas production and beyond the farm gate can have a huge impact on the results. This further shows the importance of including these impacts for a more holistic and representative result of the impact that the promotion of biomass for biofuels by promotion of implementations of leys into cereal crop rotation could have. It would therefore be of interest to expand the scope of this study to also include these impact in future studies to inform policy decisions further.

4.2 Effects on food production and inclusion of impacts from indirect land use changes

While this study showed that the implementation of leys led to decreased regional GHG emissions and a decrease rate of loss of SOC content, it also showed that the implementation of leys led to a decrease in food production. Which can in turn lead to indirect land use changes as the pressure to either intensify production in current fields or to convert more grass or forest land to farm land, when the demand for the food crops that are being replaced remains (Tideåker et al., 2017; Prade et al, 2017). This conversion of land then leads to release of carbon that was bound in the ground (Tideåker et al., 2017).

Unlike in this study, Tideåker et al. (2016) and Prade, Kätterer & Björnsson (2017) also included climate impacts from indirect land use changes (iLUC). Tideåker et al. (2017) included climate impacts from indirect land use changes (iLUC) in a sensitivity analysis of the study, for the decrease in the amount of cereals that were being produced in the area when the leys were incorporated. They also point out that the impacts from these indirect changes are important to take into account, but hard to quantify and there is no consensus on how to account for them. Tideåker et al. (2016) reported these impacts separately in accordance with Flysjö et al. (2012) and used a general LUC-factor for arable land by Audsley et al. (2009) of 1430 kg CO_2 per ha. This resulted in an added impact from LUC of 268 kg CO_2 for cereal crops only, 414 kg CO_2 for the non-fertilized mixed leys and fertilized mixed leys and 424 kg CO_2 for the fertilized grass leys. When this was added to calculation, the impacts for the crop rotations were much higher and did no longer differ as much between the crop rotation with cereal crops only and the rotations with leys, even though the total impact for the rotation with leys were still lower than the rotation without. The results with the iLUC impacts included were 576 kg CO_2 for the rotation without leys, 385 kg CO_2 for the non-fertilized mixed leys, 447 kg CO_2 for the fertilized mixed leys and 527 kg CO_2 for the fertilized grass leys. The effect that the inclusion of the impact from the iLUC had on the results were in other words substantial.

Impacts from iLUC from the food production that was replaced by leys were not included in this study and would most likely have a large impact on the results, if they were added with the same assumption as in Tideåker et al. (2016) study. Considering both the impact it had on their results and that the impact per ha in calculations for this study were about 715 – 744 kg CO_zeq / ha for the rotation with the leys and 1245 – 1342 CO_zeq / ha for the rotation without leys and the magnitude of the food production that were lost converted to leys.

Prade, Kätterer & Björnsson (2017) also included iLUC in their assessment. The inclusion of iLUC changes for the oat cultivation that was replaced in the rotation with the leys resulted in an extra impact of about 20 g CO_2eq/MJ fuel produced. However, net emissions were still negative at -26 g CO_2eq/MJ in this scenario, even without including the benefit of replacing fossil fuels. Which is also in line with other regional studies on grass as feedstock for biofuels, where negative impacts have also been reported, with 84 g CO_2eq/MJ as the reference GHG emission value for fossil fuels according to Prade, Kätterer & Björnsson (2017).

The usage of different functional units in the studies makes it again hard to compare, but it's clear that the effect that the impacts from LUC can have on the total impact can vary, but that it can have a substantial impact on the results. This shows that it is important to include them in the assessment. However, like Prade, Kätterer & Björnsson (2017) pointed out, it is just as important to also include impacts from SOC changes in crop rotations, as it may result in substantial bias in the assessments if impacts for iLUC effects are included, but benefits from carbon sequestration is not. This again shows that it would also be of interest to follow up and expand the scope of this study to include not only biofuel production and other forms of crop refinement, but also impacts from iLUC to provide more holistic results for the climate impacts of the promotion of grass leys as biomass for biofuels.

4.2.1 Decreasing SOC content & effects on yields

Several studies have found a higher SOC content to increase to increase crop yields (Persson, Bergkvist & Kätterer, 2008; Brady et al., 2015; lal, 2004; Arvidsson & Håkansson, 1991; Lal, 2010; Quiroga, Funaro, Noellemeyer, & Peinemann, 2006; Bauer & Black,1994), even though this have been questioned by others (Oelofse et al. 2015). The increased yields from the increased SOC content have also been suggested and found to partially compensate for lost food production when leys have been introduced into cereal-based crop rotation where they replace food crops (Persson, Bergkvist & Kätterer, 2008; lal, 2004).

Even though the implementation of leys in this study increased SOC content during their growth, the implementation still only led to a decrease in the rate at which SOC content was lost when looking at the net SOC changes for the whole rotation in this case. Thus, the SOC content still decreased in both the scenario with the added leys and the reference scenario in this study. Even though the decrease and emissions were lower in the scenario with the leys than in the reference scenario.

Food production did also not just decrease in the scenario with the added leys, but in the reference scenario too, although to a lower extent. However, the main reason for the loss of food production in the two scenarios differed. In the reference scenario, food production was decreasing due to decreasing yields, from decreasing SOC content. This was a partial reason in the scenario with the added leys too, since SOC content was still decreasing in this scenario too, but at a lower rate. While the main reason for the decrease in the scenario with the added leys was that food crops (mainly wheat) was switched to grass leys.

Consequently, food security and potential indirect land use changes from food production displacement is an issue in both scenarios, but to different degrees and caused by partly different reasons. Incorporating a higher proportion of grass leys than 15% could potentially lead to an increase in SOC content, which in turn could lead to increases in yields. However, then more land used for food production would also have to be converted to grass leys.

4.3 Uncertainties

The results of this study also showed that the total price for all sold produce in the region stayed fairly similar between scenarios and years as it only differed about 2-5% in year 5 and 20 in both scenarios, compared to the reference year. This implies that the incorporation of grass leys did not lead to any substantial decrease in income for the farmers. However, these results are highly uncertain, as the price for sold grass ley produce was an implicit price. Which means that it might not be realized if the demand and infrastructure for utilizing the leys is not realized. Utilizing grass leys as biomass for biofuels is not common today in Sweden and the infrastructure for it is therefore not present today either (Tideåker et al., 2016) The current cultivated grass leys are usually used as forage on the farm that cultivates them, or sometimes sold to neighboring farms. There is therefore is little data available for the price of grass leys and high uncertainties regarding the available data. The additional leys that were added in the scenario would most likely not be sold as forage in this type of scenario as the demand for forage is already supplied and it is instead assumed that the biomass from the grass leys is sold for biogas. However, it is not certain that a policy promotion of grass leys would promote utilization of the biomass for biofuels, as it could also promote more animal farming, depending on the formation of the policy. It is further not possible to assess if adding more animals would be a preferred choice by farmers in the model in the study, since this was not a choice that was made possible in the model.

It should also be said that the results of the climate change impact in this study include several other uncertainties as well. For example, while the data from Agribalyse of the climate impacts from the agricultural processes are deemed representative enough for the agricultural processes in the region of GSS, there are still differences between the processes. These could be investigated and finetuned further for the local conditions in GSS for more precis results. While the agricultural processes for cultivation of crops with similar yields to the ones in the region of GSS was chosen, there are also still differences between the average yields in the region of GSS and the average yields in the processes from

Agribalyse, as can be seen in the appendix 2. Overall, it should be noted that the results in general are an approximation of the magnitude of the impact and the potential to reduce them by implementing grass leys, not a precise measure of the impact and potential.

4.4 Effects of methodological choices

Another factor that had an effect on the results were the choice of responsibility window. One factor that makes the accountancy of impacts from SOC changes different from accounting of other impacts, and more complicated to handle, is that it involves sequestration of carbon not just emissions. The choice of the reference window had a large impact on the result, as demonstrated in the results. The difference in *annual* impact was because all of the emissions from one year was accounted to just one year when the GWP100 framework was used. However, when the responsibility of 20 years was applied, then the impacts were accounted over a period of 20 years. Which means that changes from a 20-year period prior the assessment year will be used in the calculation of the impacts. This resulted in the annual impact in the beginning of the scenario being much higher than in the end, as it includes changes prior the introduction of the leys. While in the 20^{th} year, the sum of the average impact over the responsibility window of 20^{th} years added up to similar impacts as when the characterization factor from the GWP100 framework was used. These differ slightly since the impact for the responsibility window of 20 years reflects an average impact over the years, while the impact for the GWP100 framework reflects the exact emissions in that year. Because of this it was thought that the GWP100 framework made more sense to use in this specific case, since no impacts from gains in SOC was accounted for in the end. Because accountancy could not be made at this level of detail, even if this was the intention in the beginning of the study. As mentioned before, the addition of the shorter responsibility window is a useful tool for handling calculations of impacts from sequestered carbon, but less so when only emissions are accounted for.

Conclusions

The results from this thesis showed that the implementation of a two-year grass ley into an eight-year arable crop rotation, covering 15% of the arable land of the high intensity farms in the region of GSS, resulted in a decrease of annual total impacts from the agricultural processes in the magnitude of 21-23% for just the total impacts and 11-16% lower for the impact per the functional units. However, while the results clearly showed that the implementation of leys led to lower carbon emissions from the agricultural production and a less rapid decrease of the SOC stock while simultaneously provide feedstock for biofuels. It also led to a decrease in food production in the area, due to lost land for food production when crops were replaced with grass leys. The measures to reduce the decrease in the SOC stock was not enough to compensate for the lost food production by contributing to higher yields from higher SOC stocks in the long term, as the SOC stocks were still decreasing in the scenario with that added leys. However, food production also decreased when no grass leys were added into the crop rotation, due to the loss of SOC content. Further investigations into how these issues can be met and mitigated, while simultaneously tackling the issue of lost food production due to lost arable land for food production and the potential negative effects of such a loss, such as indirect land use change, is therefore still needed.

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Appendix 1 – AgriPoliS results

Table 1. AgriPoliS results for amount of ha crops in each year

The table shows that amount of ha that each of the main crops (except for barley, which was only grown at low intensity land, which were excluded) in the region of GSS in the assessment years 0, 5 and 20 in both scenarios. The amount of ha for grasses in year 5 in the reference scenario were set to 0, despite being 39, to simplify calculations of the impact from the soil carbon changes, as these were done on crop level but for the full rotations with and without leys.

Crops	Reference year 0 (ha)	Added leys year 5 (ha)	Reference year 5 (ha)	Added leys year 20 (ha)	Reference year 20 (ha)
Wheat	23 614	18 260	23 333	18287,1	23241,8
Rapeseed	2 688	3 222	3 191	3225,9	3208,78
Sugar beet	5 966	5 863	5 705	5910,26	5817,43
Grasses	0	4 924	0 (39)	4844,73	0

Table 2. Total production (kg) in the region for each crop

The total annual production (kg) of each of the main crops (except for barley, which was only grown at low intensity land, which were excluded) in the region for the assessment years (0, 5 and 20).

Crops	Reference year 0 (kg)	Added leys year 5 (kg)	Reference year 5 (kg)	Added leys year 20 (kg)	Reference year 20 (kg)
Wheat	187 442 000	143 999 000	183 279 000	142 000 000	176 632 000
Rapeseed	11 911 600	13 691 100	13 519 500	13 247 300	12 720 500
Sugar beet	192 100 000	185 131 000	178 172 000	176 998 000	164 348 000
Grasses	0	33 354 124	1 929 363	37 752 320	8 313 088

Table 3. Crop yeilds
Average crop yields for the main crops in GSS (Agriwise kalkylblad, 2021).

Crops	Yeilds
Wheat	6800 kg/ha
Rapeseed	3400 kg/ha
Sugar beet	71 ton/ha (including dirt)
Grasses	6400 kg/ha

Appendix 2 – Agribalyse processes

Crop	CO_2eq	Process name in Agribalyse database	Functional unit	Yield (kg/ha)	Yield in GSS (kg/ha)
Winter wheat	0,29982524	Soft wheat grain, conventional, breadmaking quality, 15% moisture, at farm gate	1 kg of fresh matter	7100 kg/ha	8111 kg/ha (Winter wheat)
Rapeseed	0,68222714	Rapeseed, conventional, 9% moisture, national average, animal feed, at farm gate	1 kg of fresh matter	3243.0 kg/ha	3625 kg/ha (Winter rapeseed)
Sugar Beet	0,028613591	Sugar beet roots, conventional, national average, animal feed, at farm gate, production/FR U	1 kg of sugar beet roots, at a sugar content of 16 %, conventional production.	85 440 kg/ha	71 903 kg /ha
Grass leys	0,19204822	Grass silage, horizontal silo, temporary meadow, with clover, Northwestern region, at farm/FR U	1 kg of dry matter of silage grass (after considering harvesting losses).	4297 kg/ha	6400 kg/ha

Crop	Included	Temporal border	Cuft-off rule, exclusion
wheat, barley, Rapeseed, Sugar Beet.	The inventory includes : (1) the processes of soil cultivation, sowing, weed control, fertilisation, pest and pathogen control, harvest; (2) the machines and shed or surface used to park them; (3) all inputs as seed, fertilizers (mineral and organic), active substances, water for irrigation, fuels as well as the transport to the farm; (4) the direct emissions of the fuel combustion, the abrasion of tyres and the direct emissions on the field.	The temporal border of the inventory is 'harvest to harvest'. Fertilizers (K, P and organic N) have been adjusted in order to account for the whole rotation.	The inventory does not include processes occuring after harvest as 'drying', 'sorting' or 'storing', even if they happen on farm.
Grass leys	The inventory includes : (1) the processes of soil cultivation, sowing, weed control, fertilisation, pest and pathogen control, harvest; (2) the machines and shed or surface used to park them; (3) all inputs as seed, fertilizers (mineral and organic), active substances, water for irrigation, fuels as well as the transport to the farm; (4) the direct emissions of the fuel combustion, the abrasion of tyres and the direct emissions on the field.	The temporal border of the inventory is 'form the plantation to the turn over' (i.e. four years).	The inventory does not include processes occuring after harvest as 'drying', 'sorting' or 'storing', even if they happen on farm.

Appendix 3 – Calculations of the SOC stock and SOC stock changes

The carbon stock at each of the years in both the scenario with the added grass leys and the reference scenario was calculated using equation 8 from Brady et al. (2017). The equation is as follows:

$$C_{store} = SOC \cdot (1\text{-}STONES) \cdot \text{soil bulk density} \cdot \text{soil volume}$$

C_store is the carbon stock in kg ha^{-1}, SOC is the soil carbon content in percentage, STONES is the percentage of stones in the soil, soil_bulk_density is the soil bulk density in kg dm^{-3} and soil volume is the volume of the soil.

Average soil properties for the region of GSS were used for the calculations (Table 1). These averages were based on ca 90 000 field measurements that cover 33% of the arable area in GSS that were carried out by The Rural Economy and Agricultural Societies (The Rural Economy and Agricultural Societies, 2017). Which is the largest agricultural extension service provider in the region. These measurements were not based on a statistical sample. However, it can still be argued that they are representative due to their sheer number and widespread coverage over all districts with yield survey in the region (Brady et al., 2019). A minimum of 20% of the area was covered in each district (Brady et al., 2019). The calculations were made for 1 ha, with a 30 cm depth. The average data was collected from Brady et al (2019) (Table S1 and Table S5 from the supplementary materials).

Tabell 1 Soil properties
Average soil properties in the region of GSS that were used in the calculations of the refence state. The averages were collected from Brady et al. (2019) supplementary material.

Soil properties	
SOC content	1,7%
STONES	8%
Soil bulk density (average to 0,3 m)	1,59 kg dm^{-3}

The reference state ($C_{store(ref)}$), which is the carbon stock at year 0, was calculated as follows:

$$C_{Store(ref)} = 0{,}017 \cdot (1\text{–}0{,}08) \cdot 1590 \text{ kg m}^{-3} \cdot (0{,}3\text{m} \cdot 100\text{m} \cdot 100\text{m}) = 74\,602 \text{ kg ha}^{-1}$$

3.1 Calculations of changes in the SOC stock

A yearly rate of change of a 1% increase in the SOC stock was assumed for the grass ley fields, while a rate of a yearly -0,5% decrease was assumed for specialized crop fields. The added grass leys were assumed to cover 15% of the arable land, which meant that an average rate of change of 0,275% was used in the scenario with the added grass leys. The reference scenario only included food crop fields and thus only a decrease of -0,5% in SOC stock was assumed for the fields in this scenario (Appendix 3, table 2).

Tabell 2. Rates of change in SOC stock for the different types of fields and scenarios
A yearly increase in SOC stock of 1% for grass leys fields and a yearly decrease of 0,5% for food crop fields was assumed in the scenario with the added grass leys, which resulted in an average yearly change of -0,275%. The reference scenario only included food crops and thus a rate of change of -0,5% was assumed for all fields in the reference scenario.

Rates of change		
Added leys scenario		
Crop	*Variation % SOC*	*Fraction land*
Grass leys	1	0,15
Food crops	-0,5	0,85
Total average	-0,275	
Reference scenario	-0,5	

The SOC content in each year in the scenario with the added grass leys and the reference scenario was then calculated using these rates of changes (Table 2). The carbon stock (in kg C) was then calculated for each year, by using equation 8 from Brady et al. (2019), the average data from the Rural Economy and Agricultural Societies (2017) for soil properties (appendix 3, table 1) and the calculated percentage of SOC content for the specific year in question (Appendix 3, table 3).

Table 3. Calculations of rates of changes, SOC stock and carbon emissions for each year in the scenarios.

	SOC %		C stock		Emissions / year		Convesrion to CO2	
	Scenario		Scenario		Scenario		Scenario	
	Leys	Refernce	Leys	Reference	Leys	Reference	Leys	Reference
Year	SOC %	SOC %	Stock	Stock	C emitted	C emitted	CO2 emitted	CO2 emitted
-1		1,711		75 065,9				
0	1,702	1,702	74 690,6	74 690,6	-375,3	-375,3	-1 376,2	-1 376,2
1	1,697	1,693	74 471,1	74 295,6	-219,4	-395,0	-804,5	-1 448,2
2	1,693	1,685	74 280,3	73 945,5	-190,8	-350,1	-699,6	-1 283,6
3	1,688	1,677	74 076,1	73 575,8	-204,3	-369,8	-749,0	-1 355,8
4	1,683	1,668	73 872,4	73 207,9	-203,7	-367,9	-746,9	-1 348,9
5	1,679	1,660	73 669,2	72 841,9	-203,1	-366,0	-744,8	-1 342,1
6	1,674	1,652	73 466,6	72 477,7	-202,6	-364,2	-742,9	-1 335,4
7	1,670	1,643	73 264,6	72 115,3	-202,0	-362,4	-740,7	-1 328,8
8	1,665	1,635	73 063,1	71 754,7	-201,5	-360,6	-738,9	-1 322,0
9	1,660	1,627	72 862,2	71 395,9	-200,9	-358,8	-736,6	-1 315,6
10	1,656	1,619	72 661,8	71 038,9	-200,4	-357,0	-734,7	-1 309,0
11	1,651	1,611	72 462,0	70 683,7	-199,8	-355,2	-732,6	-1 302,4
12	1,647	1,603	72 262,7	70 330,3	-199,3	-353,4	-730,7	-1 295,8
13	1,642	1,595	72 064,0	69 978,7	-198,8	-351,6	-728,8	-1 289,4
14	1,638	1,587	71 865,8	69 628,8	-198,1	-349,9	-726,5	-1 282,9
15	1,633	1,579	71 668,2	69 280,6	-197,7	-348,2	-724,7	-1 276,6
16	1,629	1,571	71 471,1	68 934,3	-197,1	-346,4	-722,6	-1 270,0
17	1,624	1,563	71 274,5	68 589,6	-196,6	-344,7	-720,7	-1 263,8
18	1,620	1,555	71 078,6	68 246,6	-196,0	-343,0	-718,6	-1 257,5
19	1,616	1,547	70 883,1	67 905,4	-195,5	-341,2	-716,7	-1 251,2
20	1,611	1,540	70 688,2	67 565,9	-194,9	-339,5	-714,8	-1 244,9

Appendix 4 – Aggregation of impacts to regional level

Calculations of CU & price for all years, in all scenarios

Table 1. Total production, CU and price for the main crops in year 0
The total production (kg), the CU value, CU totals (total production of a crop multiplied with the CU for the same crop), price per crop and price totals (total production of a crop multiplied with the price of the crop) in year 0. It also shows the sum of the total production of all crops, sum of the CU totals for all crops and sum of the total price for all crops.

Year 0					
Crop	*Total production (kg)*	*CU*	*Price (SEK/kg)*	*CU totals*	*Price totals (SEK)*
Winter wheat	187 442 000	1,04	1,54	194 939 680	288 660 680
Sugar beets	192 100 000	0,23	0,66	44 183 000	126 786000
Winter rape	11 911 600	1,3	3,25	15 485 080	38 712 700
Grass leys	0	0,27	1,31	0	0
Total production	401 795 500		CU TOTAL	254 607 760	454 159 380

Table 2. Total production, CU and price for the main crops in year 5 in the scenario with the added grass leys

The total production (kg), the CU value, CU totals (total production of a crop multiplied with the CU for the same crop), price per crop and price totals (total production of a crop multiplied with the price of the crop) for all main crops in the region in year 5 in the scenario with the added grass leys. It also shows the sum of the total production of all crops, sum of the CU totals for all crops and sum of the total price for all crops for the same year.

Year 5 (Added grass leys scenario)					
Crop	*Total production (kg)*	*CU*	*CU totals*	*Price (SEK/kg)*	*Price totals (SEK)*
Winter wheat	143 999 000	1,04	149 758 960	1,54	221 758 460
Sugar beets	185 131 000	0,23	42 580 130	0,66	122 186 460
Winter rape	13 691 100	1,3	17 798 430	3,25	44 496 075
Grass leys	33 354 125	0,27	9 005 614	1,31	43 693 903
Total production	*386 951 924,8*	*Total CU*	*219 143 134*	*Total Price*	*432 134 898*
		Total % of year 0	86%	Total % of year 0	95%

Table 3. Total production, CU and price for the main crops in year 5 in the reference scenario

The total production (kg), the CU value, CU totals (total production of a crop multiplied with the CU for the same crop), price per crop and price totals (total production of a crop multiplied with the price of the crop) for all main crops in the region in year 5 in the reference scenario. It also shows the sum of the total production of all crops, sum of the CU totals for all crops and sum of the total price for all crops for the same year.

Year 5 (Reference scenario)					
Crop	*Total production (kg)*	*CU*	*CU totals*	*Price (SEK/kg)*	*Price totals (SEK)*
Winter wheat	183 279 000	1,04	190 610 160	1,54	282 249 660
Sugar beets	178 172 000	0,23	40 979 560	0,66	117 593 520
Winter rape	13 519 500	1,3	17 575 350	3,25	43 938 375
Grass leys	1 929 363	0,27	520 928	1,31	2 527 465
Total production	*388 129 663*	*Total CU*	*249 685 998*	*Total Price*	*446 309 020*
		Total % of year 0	98%	Total % of year 0	98%

Table 4. Total production, CU and price for the main crops in year 20 in the scenario with the added grass leys

The total production (kg), the CU value, CU totals (total production of a crop multiplied with the CU for the same crop), price per crop and price totals (total production of a crop multiplied with the price of the crop) for all main crops in the region in year 20 in the scenario with the added leys. It also shows the sum of the total production of all crops, sum of the CU totals for all crops and sum of the total price for all crops for the same year.

Year 20 (Added grass leys scenario)					
Crop	*Total production (kg)*	*CU*	*CU totals*	*Price (SEK/kg)*	*Price totals (SEK)*
Winte rwheat	142 000 000	1,04	147 680 000	1,54	218 680 000
Sugar beets	176 998 000	0,23	40 709 540	0,66	116 818 680
Winter rape	13 247 300	1,3	17 221 490	3,25	43 053 725
Grass leys	37 752 320	0,27	10 193 126	1,31	49 455 539
Total production	*378 889 250*	Total CU	215 804 156	Total price	428 007 944
		Total % of year 0	85%	Total % of year 0	94%

Table 5. Total production, CU and price for the main crops in year 0

The total production (kg), the CU value, CU totals (total production of a crop multiplied with the CU for the same crop), price per crop and price totals (total production of a crop multiplied with the price of the crop) for all main crops in the region in year 20 in the reference scenario. It also shows the sum of the total production of all crops, sum of the CU totals for all crops and sum of the total price for all crops for the same year.

Year 20 (Reference Scenario)					
Crop	*Total production (kg)*	*CU*	*CU totals*	*Price (SEK/kg)*	*Price totals (SEK)*
Winter wheat	176 632 000	1,04	183 697 280	1,54	272 013 280
Sugar beets	164 348 000	0,23	37 800 040	0,66	108 469 680
Winter rape	12 720 500	1,3	16 536 650	3,25	41 341 625
Grass leys	8 313 088	0,27	2 244 534	1,31	10 890 145
Total production	370 234 728	Total CU	240 278 504	Total Price	432 714 730
		TOTAL % of year 0		TOTAL % of year 0	

Table 6. Impact per ha for each crop and each assessment year

The table shows the impact in kg CO2 eq per kg produce that were collected from agribaylese, and the aggregated impact per ha, which was callculated by mulitplying the impact per kg with the standard yeilds in the GSS. The standard yeils used were from Agriwise (2021). The table also shows the impact (kg CO2eq) per ha from the SOC changes for all assessment years in the different scenarios. The calculations of these impacts are presented in Appendix 3.

	Impact Agribalyse		Impact soil	
Crops	Impact Agribaylese (kg CO2eq/kg)	Impact Agribalyse (kg CO2eq/ha/year) (Yeild Agriwise)	Scenario and year	Impact soil carbon (kg CO2eq/ha/year)
Wheat	0,29982524	2038,8	Year 0	1376,2
Rapeseed	0,68222714	2319,6	REF 20	1244,9
Sugar beet	0,028613591	2031,6	GRASS 5	744,8
Grasses	0,19204822	1229,1	GRASS 20	714,8

Table 7. Total annual regional impact

The total annual, regional impact (kg CO_2eq) from the agricultural production in the region in all assessment years in both the scenario with the added grass leys and the reference scenario. This was calculated by multiplying the amount of ha a crop was produced on in the specific year (Appendix 1, table 1), with the impact per ha for the same year and crop or rotation (depending on if it's the impact for the processes or the soil changes) (Appendix 4, table 6).

Crops	Reference year 0 (kg CO_2eq)	Added leys year 5 (kg CO_2eq)	Reference year 5 (kg CO_2eq)	Added leys year 20 (kg CO_2eq)	Reference year 20 (kg CO_2eq)
Wheat	48 144 294	37 229 312	47 571 184	37 283 952	47 385 652
Wheat, soil	32 497 638	13 600 271	31 314 951	13 071 619	28 933 717
Rapeseed	6 234 755	7 472 665	7 401 894	7 482 708	7 442 997
Rapeseed, soil	3 699 096	2 399 425	4 282 722	2 305 873	3 994 610
Sugar beet	12 120 784	11 910 090	11 589 672	12 007 077	11 818 487
Sugar beet, soil	8 210 774	4 366 405	7 656 412	4 224 654	41 582 99
Grasses	0	6 051 664	48 390	5 954 699	0
Grasses, soil	0	3 667 112	0	3 463 013	0
Total impact	110 907 340	86 696 944	109 816 835	85 793 596	103 733 762
% of REF year 0		78%	99%	77%	94%
Total impact, Agribaylese	66 499 833	62 663 730	66 562 750	62 728 437	66 647 136
Total impact soil	44 407 507	24 033 214	43 254 085	23 065 159	37 086 626

Table 8. Total annual regional impact per CU

The total annual, regional impact (kg CO_2eq) (Appendix 4, table 7) from the production of the main crops at the high intensity land in the region, per the total CU, in all assessment years in both the scenario with the added grass leys and the reference scenario.

Crops	**Reference year 0** (kg CO2eq)	**Added leys year 5** (kg CO2eq)	**Reference year 5** (kg CO2eq)	**Added leys year 20** (kg CO2eq)	**Reference year 20** (kg CO2eq)
Wheat	0,25	0,25	0,25	0,25	0,26
Wheat, soil	0,17	0,09	0,16	0,09	0,16
Rapeseed	0,40	0,42	0,42	0,43	0,45
Rapeseed, soil	0,24	0,13	0,24	0,13	0,24
Sugar beet	0,27	0,28	0,28	0,29	0,31
Sugar beet, soil	0,19	0,10	0,19	0,10	0,11
Grasses	0	0,67	0,09	0,58	0,00
Grasses, soil	0	0,41	0,00	0,34	0,00
Total impact	0,436	0,396	0,440	0,398	0,432
% of year 0		91%	101%	91%	99%
Total impact, Agribaylese	0,261	0,286	0,267	0,291	0,277
Total impact soil	0,174	0,110	0,173	0,107	0,154
Procentage, Agribaylese		109%	102%	111%	106%
Procentage, soil carbon		63%	99%	61%	88%

Table 9. Total annual regional impact per price

The total regional, annual impact (kg CO_2eq) from the production of the main crops at the high intensity farms in the region, per total price in all assessment years in both the scenario with the added grass leys and the reference scenario.

Crops	Reference year 0 (kg CO2eq)	Added leys year 5 (kg CO2eq)	Reference year 5 (kg CO2eq)	Added leys year 20 (kg CO2eq)	Reference year 20 (kg CO2eq)
Wheat	0,17	0,17	0,17	0,17	0,17
Wheat, soil	0,11	0,06	0,11	0,06	0,11
Rapeseed	0,16	0,17	0,17	0,17	0,18
Rapeseed, soil	0,10	0,05	0,10	0,05	0,10
Sugar beet	0,10	0,10	0,10	0,10	0,11
Sugar beet, soil	0,06	0,04	0,07	0,04	0,04
Grasses	0	0,14	0,02	0,12	0,00
Grasses, soil	0	0,08	0,00	0,07	0,00
Total impact	0,244	0,201	0,246	0,200	0,240
% of year 0		82%	101%	82%	98%
Total impact, Agribaylese	0,146	0,145	0,149	0,147	0,154
Total impact soil	0,103	0,056	0,097	0,054	0,086
Procentage, Agribaylese		99%	102%	100%	105%
Procentage, soil		54%	94%	52%	83%

Appendix 5 – Definitions of impact categories from EF 2.0

The category for biogenic carbon in EF 2.0 includes carbon emissions in form of CO_2, CO and CH_4 to air, from oxidation and/or reduction of biomass above ground, through transformation or degradation (i.e., digestion, composting, combustion, landfilling) (Fazio et al, 2020). It also includes uptake of carbon dioxide from the atmosphere through photosynthesis during the growth of biomass. This can for example be the carbon content in biofuels, products or above ground plant residues such as dead wood and litter. Carbon exchanges from native forests are not included in this category (Fazio et al, 2020).

The category for fossil GHG emissions includes greenhouse gas emissions to any media that comes from the reduction and/or oxidation of fossil fuels by transformation or degradation (i.e., combustion, landfilling, digestion etc.) (Fazio et al, 2020). It includes emissions from calcination and peat, as well as uptakes from carbonation (Fazio et al, 2020).

Finally, the category for land use and land use change includes carbon emissions and uptake (CO_2, CO and CH_4) from carbon stock changes that are caused by land use and land use change (Fazio et al, 2020). It does however not include uptake from land management change. It includes exchanges of biogenic carbon from deforestation, road construction and other soil activities, including soil carbon emissions. All related CO_2 emissions for native forests are included in this category (including connected soil emissions, residues and products that are derived from native forests), however their uptake of CO_2 is excluded (Fazio et al, 2020).

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