Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Marte Kristiane Mohn Solberg

Towards a more climate-resilient agricultural sector in Norway

A life cycle assessment of the environmental performance and ecosystem service interactions of cover crops and buffer zones

Master's thesis in Industrial Ecology
Supervisor: Francesco Cherubini
Co-supervisor: Nariê Rinke Dias de Souza, Xiangping Hu
June 2023

NTNU
Norwegian University of
Science and Technology

Marte Kristiane Mohn Solberg

Towards a more climate-resilient agricultural sector in Norway

A life cycle assessment of the environmental performance and ecosystem service interactions of cover crops and buffer zones

Master’s thesis in Industrial Ecology
Supervisor: Francesco Cherubini
Co-supervisor: Nariê Rinke Dias de Souza, Xiangping Hu
June 2023

Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

NTNU
Norwegian University of
Science and Technology

Abstract

Numerous connections exist between climate change and agriculture. Agriculture is perhaps the most significant industry dependent on stable ecosystems, but it is also responsible for 19-29% of global greenhouse gas emissions and is the number one driver of biodiversity loss worldwide. Consequently, agriculture will take part in strategies to limit further global warming and biodiversity loss.

Cover crops (CC) and buffer zones (BZ), both climate-smart agriculture practices, are increasingly recognized as effective measures for adapting to and mitigating the impacts of climate change in agriculture in Norway. They provide ecosystem services (ES) such as habitat quality, reduced soil erosion, carbon sequestration and increased microbial activity. However, many life cycle assessments (LCA) fail to incorporate interaction with ES.

This study aims to assess the life cycle impact potentials of CC, BZ, and conventional farming on 1 ha of barley to assess how the impacts of farming activities vary through an LCA including interaction with ES.

The results show an average decrease in environmental impacts of 7.6% and 19.79% with 1 ha as the functional unit, for CC and BZ respectively, when compared to conventional farming. Both practices contribute to reduced climate change impacts through carbon sequestration. CC improve interactions with ES and reduce impacts on the environment with minimal reductions in yields of the main crop (3%). BZ, despite large reductions in environmental impacts, lead to yield reductions of 10%, indicating that the practice should be implemented where the mitigation potential of especially marine eutrophication and soil erosion is the highest.

The results emphasize the importance of including ES in LCA and carefully choosing functional units based on the objective of the study. For sustainable land management this thesis argues that a functional unit of 1 ha captures more environmental impacts and interactions with ES than a functional unit of 1 kg. Doing so may contribute to a smoother transition towards more sustainable land management in Norway, where agricultural land is a very limited resource. Implementing CC and BZ can contribute to a more climate-resilient agricultural sector.

Future field studies should explore whether reduced nitrogen fertilizer in cover crops is possible without compromising yields. If so, the potential environmental benefits are great.

Sammendrag

Landbruk og klimaet påvirker hverandre i stor grad. Landbruket er svært avhengig av stabile økosystemer, samtidig som det er ansvarlig for 19-29% av globale drivhusgassutslipp og den viktigste driveren til biodiversitetstap globalt. Som følge av dette vil landbruket spille en viktig rolle i enhver strategi for å begrense ytterligere global oppvarming og tap av biologisk mangfold.

Fangvekster og buffersoner, begge klimasmarte landbruksmetoder, blir stadig mer anerkjent som effektive tiltak for både tilpasning til og begrensning av klimaendringenes påvirkning på landbruket i Norge. De sørger for økosystemtjenester som habitat for arter, redusert erosjon, karbonlagring og økt mikrobiell aktivitet. Imidlertid inkluderer de færreste livssyklusanalyser (LCA) interaksjon med økosystemtjenester.

Denne studien har som mål å vurdere livssykluspåvirkningen av fangvekster og buffersoner på 1 hektar bygg for å vurdere hvordan påvirkningen varierer i forhold til konvensjonell drift.

Resultatene viser at den samlede miljøpåvirkningen, inkludert interaksjon med økosystemtjenester, er 7.6% lavere for fangvekster og 19.79% lavere for buffersoner, sammenliknet med konvensjonell drift, for funksjonsenhet 1 hektar. Begge praksisene bidrar til karbonlagring. Fangvekstene viser god interaksjon med økosystemtjenester og redusert miljøpåvirkning med minimal avlingsnedgang (3%). Buffersonen, til tross for store reduksjoner i miljøpåvirkning, har avlingstap på 10%, noe som indikerer at praksisen bør hensynta lokale forhold og gjennomføres der marin eutrofiering og erosjon kan reduseres mest.

Resultatene understreker betydningen av å inkludere økosystemtjenester i LCA og valg av funksjonsenhet basert på målet til studiet. Oppgaven argumenterer for at i arbeidet for mer bærekraftig forvaltning av land vil 1 hektar være den beste funksjonsenheten, da den legger større vekt på interaksjoner med økosystemtjenester enn funksjonsenhet 1kg. En slik tilnærming vil kunne bidra positivt i politikkutforming for mer bærekraftig forvaltning av land i Norge, hvor spesielt landbruksjord er en svært begrenset ressurs. Etablering av fangvekster og buffersoner kan bidra til en mer robust landbrukssektor.

Ytterligere forskning er nødvendig for å undersøke om mengden nitrogen i gjødslet kan reduseres uten at det går på bekostning av avlinger. Hvis dette viser seg å kunne gjøres vil de miljømessige fordelene være svært gode.

Preface

This thesis concludes my Master of Science in Industrial Ecology at the Norwegian University of Science and Technology (NTNU). It continues the work of my project thesis from the autumn semester of 2022, "Assessing agricultural management practices for more sustainable agriculture in Norway", where cover crops and buffer zones were identified as climate-smart agricultural practices with great potential under Norwegian conditions. In this thesis, the two practices and conventional farming are assessed to unravel their life cycle impacts and interactions with ecosystem services.

I am very grateful to my professor and main supervisor, Francesco Cherubini, for his insightful comments and valuable feedback.

I would also like to express my sincere appreciation to my co-supervisor, Nariê Rinke Dias de Souza, for her invaluable assistance, expert advice, and constant encouragement. Her thoughtful comments and constructive criticism have helped me a lot this semester. In addition, I would like to thank Xiangping Hu for his contributions to the ecosystem service assessment of this study.

Finally, I would like to express my gratitude to my classmates, friends and family who have supported me in various ways during my academic journey. It has been five very rewarding years, and I am proud of myself for daring to choose a challenging study program. I see the world more clearly now, and for that, I am very grateful.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

BZ	Buffer Zones
CC	Cover Crops
CH_4	Methane
CO_2	Carbon Dioxide
CONV	Conventional Agriculture
CSA	Climate Smart Agriculture
ES	Ecosystem Services
FAO	Food and Agriculture Organization
FU	Functional Unit
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
N	Nitrogen
N_2O	Nitrous Oxide
P	Phosphorus
SOC	Soil Organic Carbon

1 Introduction

1.1 Background

Numerous connections exist between climate change and agriculture (Frank et al., 2017). On the one hand, the intensification of climate change has emerged as an astounding task due to the persistent increase in anthropogenic carbon dioxide (CO_2) emissions, destabilizing the earth's ecosystems (Shukla et al., 2019). Agriculture is paramount among the various sectors dependent on stable ecosystems (de Pinto et al., 2020). Accordingly, the sector needs a rigorous adaptation framework to tackle the many challenges posed by climate change (Frank et al., 2017). Furthermore, owing to its land-based nature, agriculture has the potential to play a crucial role in climate change mitigation, primarily through carbon sequestration and storage in soil and biomass (Rogelj et al., 2018).

On the other hand, agricultural activities are responsible for 19-29% of global greenhouse gas (GHG) emissions (Vermeulen et al., 2012), in addition to being the most significant contributor to non-CO_2 emissions, namely CH_4 and N_2O, with a share of 56% of these (Blandford & Hassapoyannes, 2018). The research conducted by Ritchie and Roser (2020) highlights that food production is accountable for 70% of global freshwater withdrawal and 78% of pollution in freshwater and ocean ecosystems. The Food and Agriculture Organization of the United Nations (FAO) states that agricultural land spans around five billion hectares, representing 38% of the global land surface (FAO, 2020). That makes agriculture one of the main drivers of land use, which again is the most significant driver of biodiversity loss worldwide due to habitat loss and fragmentation (Willett et al., 2019). Consequently, "the agricultural sector will play a vital role in any global strategy to stabilize the climate" (Frank et al., 2017).

However, despite the knowledge of the importance of ecosystems and the services they provide, food production often favor product over impact (Bommarco et al., 2013). Bommarco et al. (2013) emphasize the potential of ecological intensification, including regulating and supporting ecosystem services (ES) in agricultural practices to enhance crop productivity. As climate change makes food production more prone to risk, such stabilizing measures will likely become more critical in the future (Lobell et al., 2008). Conventional agriculture (CONV) has been the predominant method of farming for many years, characterized by high inputs of synthetic fertilizers, agrochemicals, and intensive tillage (Sumberg & Giller, 2022). Since the emergence of synthetic fertilizer, food production has become more stable and predictable, saving millions of lives (Stewart & Roberts, 2012). CONV aims to maximize yields and profits but often results in adverse environmental impacts such as soil degradation, water pollution, and GHG emissions (Sumberg & Giller, 2022).

In contrast, climate-smart agriculture (CSA) is an approach that aims to increase agricultural productivity and incomes while reducing GHG emissions and improving resilience to climate change (de Pinto et al., 2020). CSA integrates sustainable practices such as conservation agriculture, agroforestry, and livestock management, promoting soil health, biodiversity, and ES (Lipper et al., 2014). Overall, CSA is a more holistic and sustainable approach to agriculture, considering the interconnectedness of farming, climate change, and environmental stewardship.

1.2 Literature review: Climate change effects on Norwegian agriculture

A systematic literature review on opportunities, challenges, and adaptation action to climate change in Nordic agricultural crop production finds that although benefits from climate change are expected in the region, changes in precipitation patterns leading to both drought and heavy rains will increase soil erosion, surface run-off and the risk of floods, in addition to increased risk of pests and diseases, consequently reducing yields (Wiréhn, 2018).

Cover crops (CC) and buffer zones (BZ), both CSA practices, are increasingly recognized as effective measures for both adapting to and mitigating the impacts of climate change in agriculture in Norway, especially for their ability to reduce soil erosion and surface run-off (Blankenberg et al., 2017; Bøe et al., 2019, 2020; Gundersen et al., 2010; Holmen, 2020; Syversen, 2005). CC provides soil cover in periods where the soil otherwise would be bare. They can help farmers adapt to climate change by reducing soil erosion, improving soil moisture retention, increasing soil microbial gene abundance, and suppressing weeds and pests (Bøe et al., 2019; Wang et al., 2021). In addition, CC may help mitigate climate change by sequestering carbon in the soil, reducing GHG emissions, and enhancing soil health and resilience (Bøe et al., 2019, 2020; Holmen, 2020). BZ, which are vegetated strips along waterways can help farmers adapt to climate change by reducing soil erosion and surface nutrient run-off, providing flood protection, and increasing biodiversity and habitat quality (Blankenberg et al., 2017; Skarbøvik & Blankenberg, 2019). In 2022 Oslo and Viken, the most grain producing regions in Norway, had 226 798m of grass-covered BZ near waters and 7 773,1 ha of CC sown together with the main crop (Landbruksdirektoratet, 2023).

The Nordic countries are not large crop producers. According to FAO STAT Norway produced 0.68% of European barley, 1.99% of oats, 0.33% of rye, and 0.1% of wheat in 2021 (FAO, n.d.-a). Nevertheless, as climate change makes food production in south and eastern Europe more complex, the Nordic countries, despite their intricate relationship with climate change, are expected to play a more significant role in food production in the future as this region's food production is expected to be less affected than many others (Wiréhn, 2018). Norway produces more barley than any other type of grain (SSB, 2022b). The statistics over the production of the four dominating grains, wheat, barley, oat, and rye, from 2003-2021 are visualized in Figure 1 below.

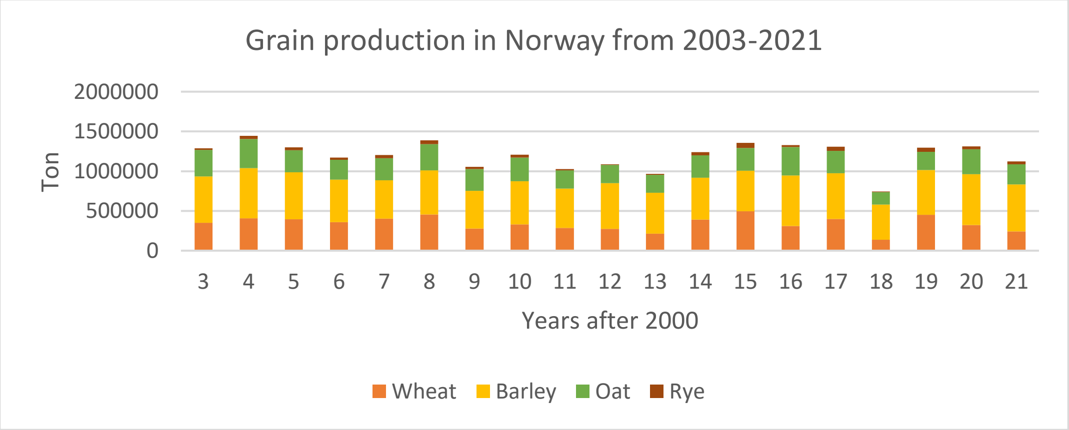


Figure 1 Overview of the production of different grains in Norway from 2003-2021. Barley is the dominating grain.

1.3 Identifying the research gap

CC and BZ are considered promising practices for adapting to and mitigating climate change, making them attractive options for Norwegian agriculture. However, the lack of information on their overall environmental impacts is a concern. To better understand the potential impacts of land management on ES it is necessary to more comprehensively and explicitly include ES in Life Cycle Assessment (LCA) (van der Werf et al., 2020). LCA is a widely used approach for assessing the environmental impacts of goods and services (International Organization for Standardization, 2006). However, by focusing on negative impacts rather than including positive impacts it typically focuses on resource availability and ecosystem quality impacts without explicitly considering ES (van der Werf et al., 2020). The International Organization for Standardization (ISO) describes the functional unit (FU) in LCA as the reference base describing the function of the product or process, thus enabling comparison of different systems. Common FUs in LCAs related to agriculture are mass, weight, and, more recently, nutritional value (Heller et al., 2013; Schau & Fet, 2008). Many studies aiming to unravel the environmental impact of agricultural production systems use units of food, typically 1 kg, as the FU (M. Clark & Tilman, 2017; Dick et al., 2015; González-García et al., 2018), rather than impact per area. Consequently, often favoring production-intensive farming over CSA, which focus on improved interaction with ES (van der Werf et al., 2020). The lack of focus on ES occurs even though many processes and conditions in the technosphere rely on ES (Chaplin-Kramer et al., 2017). According to Alejandre et al. (2019), LCA studies should consider direct interactions with ES as they are increasingly recognized as critical in the relationship between human society and the environment. In their study, Chaplin-Kramer et al. (2017) bring attention to the drawbacks of commonly utilized LCA methodologies, stating that they fail to incorporate ecological information, preventing the ability to identify important impacts on climate, water, and biodiversity.

1.4 Research question and objective

This thesis' research question is:

> ***To what extent do conventional farming and farming practices incorporating cover crops or buffer zones differ in their environmental impacts?***

To answer this, the thesis has the following objectives listed below:

1. Perform an LCA of CONV, CC, and BZ practices using different FUs to emphasize the discussion of ES versus yields.
2. Assess the practices' interaction with the following ES using LCA methodology: habitat quality (HQ), soil erosion (SE), carbon sequestration (CS), and crop production (CP).
3. Identify and discuss the shortcoming of LCA when assessing ES.

2 Methodology

This section gives an overview of utilized methods.

2.1 Scenario description

There are three scenarios. The baseline scenario, CONV (Figure 2a), is 1 ha of barley alongside a fictive river at 60.0903N, 11.0680E, located in Gjerdrum, in the south-eastern part of Norway, and is conventionally farmed. The reasoning behind the location is explained further in Chapter 2.1.1. The remaining scenarios are located near the same fictive river at the same location. The second scenario, CC (Figure 2b), is 1 ha of barley with perennial ryegrass as a cover crop, sown simultaneously as the barley. The perennial ryegrass is not harvested, but terminated in spring, before tillage and harrowing. The third scenario, BZ (Figure 2c), is 0.9ha of barley and 0.1 ha of a BZ consisting of trees next to the river. The trees are not planted but come from natural revegetation.

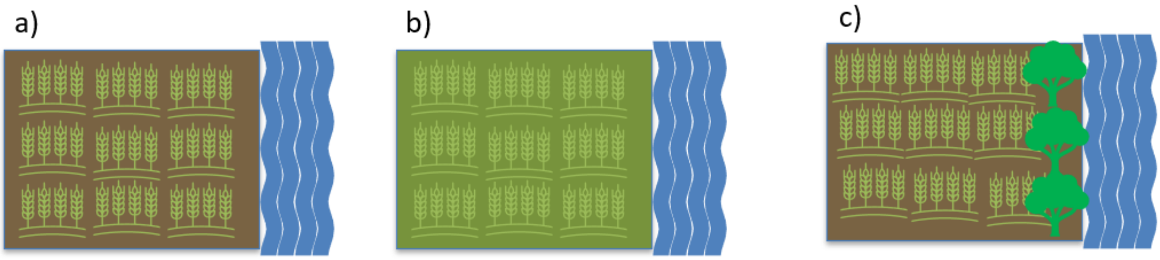


Figure 2 The three scenarios: a) CONV, b) CC, and C) BZ visualized next to a fictive river in south-eastern Norway.

2.1.1 Study area

A representative location in Norway is chosen to perform the environmental assessment, including LCA and ES. The location is chosen due to its high SE rate and for being located in Norway's most producing region. As much as 87% of all grains produced in 2020 were produced in the central-eastern counties, namely Innlandet, Vestfold and Telemark, Oslo, and Viken (SSB, 2022a). An overview of the production of grains in all counties is displayed in Figure 3 below.

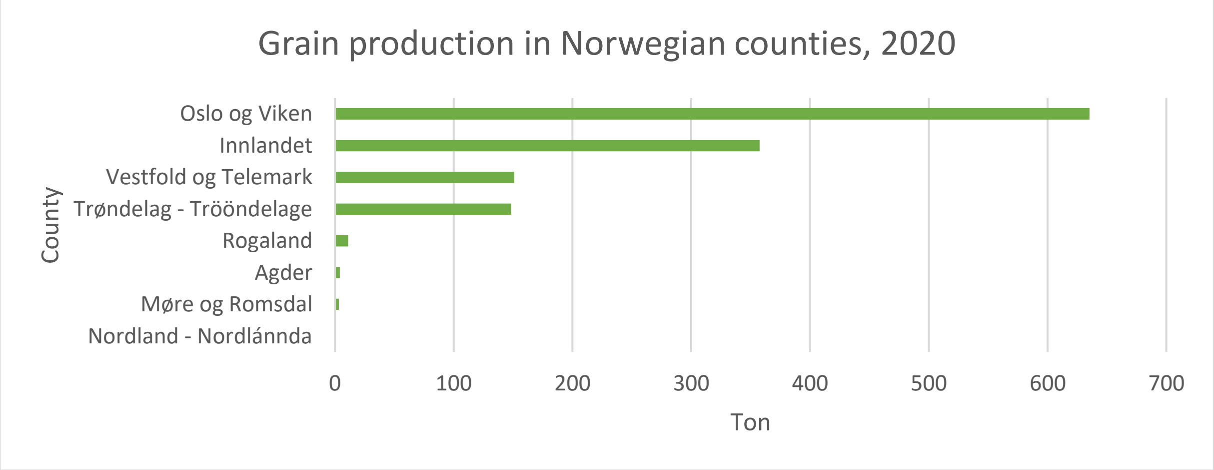


Figure 3 Grain production in Norwegian counties in 2020, with Oslo and Viken being the largest producers.

Maps issued by ESA and the European Centre for Medium-Range Weather Forecasts are used. These have a spatial resolution of 0.002778 degrees, approximately 300m at the equator (ESA, 2013). Data was collected on an annual basis from 1992 to 2018. These maps use the classification system developed by the UN and FAO, dividing all land into 37 different categories. Zhou et al. (2021) also used this classification to identify recent land cover changes, forest harvest areas, and soil erosion trends in Nordic countries. Four of these categories go under what the International Panel on Climate Change (IPCC) has classified as agriculture, according to ESA (2013). These four are:

1. Rainfed cropland
2. Irrigated cropland
3. Mosaic cropland (> 50%) / natural vegetation (tree, shrub, herbaceous cover) (< 50%)
4. Mosaic natural vegetation (tree, shrub, herbaceous cover) (> 50%) / cropland (< 50%)

Two different maps are used to identify the erosion rates on cropland in Norway. The first is a 25km soil erosion map from 2012 measured in ton ha^{-1} year $^{-1}$. The second, cropland maps using the classification from the IPCC, identified above. Combining these two maps resulted in Figure 4 below, where the color represents soil erosion rates in ton year^{-1}, from -5 to 5.

Using the map from Figure 4, coordinates 60.0903N and 11.0680E are chosen in the dark blue circle.

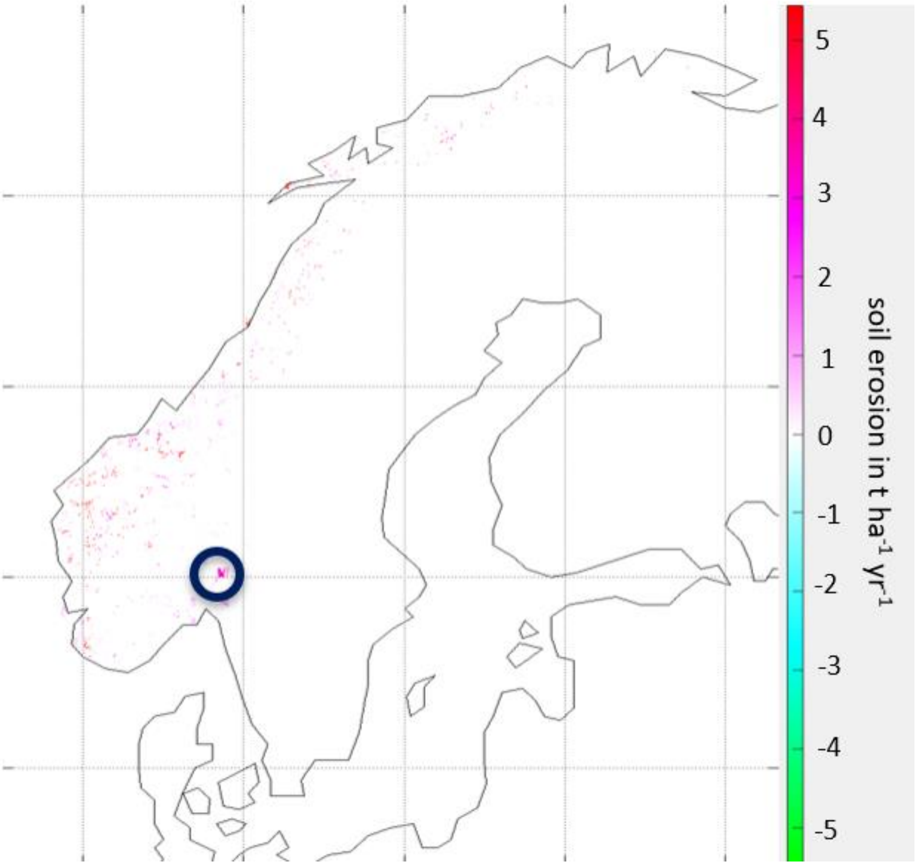


Figure 4 Map of agricultural land with its corresponding soil erosion rates in Norway, and the chosen location in the blue circle. Colored areas are agricultural land, and the shade of the color represents the extent of soil erosion.

2.2 LCA

The LCA is split into two parts: a traditional LCA performed using an LCA tool to assess the life cycle impacts of the three scenarios and an ES assessment to investigate the remaining ES' interaction with the three scenarios. Life cycle emissions to water, soil, and air are calculated using LCA methodology, while effects on carbon sequestration (CS), soil erosion (SE), habitat quality (HQ), and crop production (CP) are adapted from methodology from (Bøe et al., 2019; Cook-Patton et al., 2020; Fischer et al., 2021; Hu et al., 2021, 2023). The extended LCA is here defined as the synthesized results of both the LCA and the ES assessment.

2.2.1 Goal and scope

The conducted LCA comply with the methodology and standards of ISO14044 (International Organization for Standardization, 2006). This LCA aims to assess the environmental impacts of CC, BZ and CONV on barley production to assess how the life-cycle impact potentials of farming activities vary. For that, two FUs are explored: 1 ha of barley and 1 kg of produced barley. Chapter 3, Results and discussion, discuss the reasoning behind this. The system boundary considers all necessary inputs to produce 1 ha of barley in the three assessed scenarios (e.g., NPK fertilizers, agrochemicals, machinery, fuel) presented in Figure 5. ReCiPe 2016 Midpoint Hierarchist for impact categories freshwater eutrophication, marine eutrophication, human toxicity, freshwater ecotoxicity, and terrestrial acidification is used, while the IPCC 2013 GWP100 is used to assess for climate change. HQ, CS, CP, and SE are not captured in the LCA, and are thus calculated differently, explained in Chapter 2.3, Ecosystem services. Figure 5 illustrates the system boundaries of the study.

Figure 5 System boundary of the study. All inputs are to the left, the farm processes occurr withing the dotted lines, and impacts on the environment are to the right.

2.2.2 Life cycle inventory modeling

The foreground inventory is built for the three scenarios and detailed further. The background inventory uses the Ecoinvent database version 3.8 cut-off to perform the LCA.

2.2.2.1 The CONV Scenario

CONV uses synthetic fertilizers and pesticides, intensive tillage practices, and monoculture cropping systems (Sumberg & Giller, 2022). This type of agriculture is typically focused on maximizing crop yields and profits. The inventory for the first scenario, Table 1, addresses 1 ha of barley performed with CONV methods based on Tisserant et al. (2022). The main inputs to the inventory are summarized in Table 1 below. See Appendix 1 for the complete inventory, including references. Tisserant et al. (2022) base their inventory on the Bioforsk Report *Inventory of Norwegian grain production* (Henriksen & Korsaeth, 2013).

For inventory for FU 1 kg, all inputs are divided by the yields for the corresponding scenario, which for CONV is 4200 kg barley ha^{-1} year^{-1} (Fischer et al., 2021).

Table 1 Main inventory for the CONV scenario

Input	**Value**	**Unit**
Fertilizer		
Ammonium nitrate, as N	112	kg ha^{-1} year^{-1}
Ammonium nitrate, as N	15.5	kg ha^{-1} year^{-1}
Inorganic phosphorus fertilizer, as P2O5	39.5	kg ha^{-1} year^{-1}
Inorganic potassium fertilizer, as K2O	75.9	kg ha^{-1} year^{-1}
Packaging, for fertilizers	426.3	kg ha^{-1} year^{-1}
Emissions to air (due to fertilizer)		
Ammonia	7.75	kg ha^{-1} year^{-1}
Dinitrogen monoxide	2.43	kg ha^{-1} year^{-1}
Nitrogen oxides	5.1	kg ha^{-1} year^{-1}
Emissions to water (due to fertilizer)		
Nitrate	28.7	kg ha^{-1} year^{-1}
Emissions to soil (due to agrochemicals)		
Glyphosate	0.93	kg ha^{-1} year^{-1}
Other		
Barley seed, for sowing	160	kg ha^{-1} year^{-1}
Transport, tractor and trailer, agricultural	30	tkm ha^{-1} year^{-1}
Grass seed, organic, for sowing	0	kg ha^{-1} year^{-1}
Carbon sequestration aboveground	0	kg CO_2 ha^{-1} year^{-1}
Carbon sequestration belowground	0	kg CO_2 ha^{-1} year^{-1}

2.2.2.2 The CC Scenario

In this scenario, the cover crop is perennial ryegrass sown together with the barley in spring. The CC' primary functions are protecting the soil from soil erosion, contributing to carbon sequestration, increased biodiversity, reduced nutrient loss, and improved soil health (Aronsson et al., 2016; Bøe et al., 2020; Garland et al., 2021; Holmen, 2020; Poeplau & Don, 2015). Aronsson et al. (2016) use the term cover crop for both catch crops, meant to deplete the soil of mineral nitrogen (N) and CC, which includes the function of preventing soil erosion. The same is done in this thesis. The inventory for scenario CC, Table 2, is built by modifying the CONV scenario based on CC' interaction with ES (Bøe et al., 2019, 2020). See Appendix 2 for a translation of the CC' interaction with ES from Bøe et al. (2019) and Appendix 3 for the complete inventory and references.

Table 2 Main inventory for the CC scenario

Input	**Value**	**Unit**
Fertilizer		
Ammonium nitrate, as N	112	kg ha^{-1} $year^{-1}$
Ammonium nitrate, as N	15.5	kg ha^{-1} $year^{-1}$
Inorganic phosphorus fertilizer, as P2O5	39.5	kg ha^{-1} $year^{-1}$
Inorganic potassium fertilizer, as K2O	75.9	kg ha^{-1} $year^{-1}$
Packaging, for fertilizers	426.3	kg ha^{-1} $year^{-1}$
Emissions to air (due to fertilizer)		
Ammonia	7.75	kg ha^{-1} $year^{-1}$
Dinitrogen monoxide	2.43	kg ha^{-1} $year^{-1}$
Nitrogen oxides	5.1	kg ha^{-1} $year^{-1}$
Emissions to water (due to fertilizer)		
Nitrate	14.35	kg ha^{-1} $year^{-1}$
Emissions to soil (due to agrochemicals)		
Glyphosate	6.03	kg ha^{-1} $year^{-1}$
Other		
Barley seed, for sowing	160	kg ha^{-1} $year^{-1}$
Transport, tractor and trailer, agricultural	60	tkm ha^{-1} $year^{-1}$
Grass seed, organic, for sowing	8	kg ha^{-1} $year^{-1}$
Carbon sequestration aboveground	0	kg CO_2 ha^{-1} $year^{-1}$
Carbon sequestration belowground	403.7	kg CO_2 ha^{-1} $year^{-1}$

Tillage happens in the spring rather than the fall, and harrowing happen once in spring instead of fall and spring (Statsforvalteren i Innlandet, n.d.). There are no changes to the inventory for sowing, liming, rolling, and combined harvesting. Research shows that the CC reduce weeds (Blanco-Canqui et al., 2015) and break the plague cycle (Bøe et al., 2019). Consequently, less agrochemicals are needed. Bøe et al. (2019) found that 20% less agrochemicals were needed. Hence the same value is used in the inventory. The same factor is used for the amount of emissions to soil due to agrochemicals. Bøe et al. (2020) state that 3 liters of glyphosate are needed per ha to terminate the CC in spring, meaning 5.1 kg per hectare, in addition to the 0.93 kg needed of agrochemicals in the growing season (Tisserant et al., 2022). 60tkm instead of 30tkm is required due to termination in spring (Bøe et al., 2020). 8 kg of rye grass seeds are required to establish the BZ (Bøe et al., 2020). The Ecoinvent database does not have rye grass seeds; hence organic grass seeds are used. There is a 50% reduction in nitrogen (N) run-off due to the CC (Bøe et al., 2019). Field studies from 11 sites in southern Scandinavia indicate that under sown ryegrass CCs can reduce N loss by 43% (Aronsson et al., 2016). Studies from the Nordic region indicate that perennial ryegrass under sown in cereals with no extra fertilizing in fall takes up between 7 to 38 kg N ha^{-1} (Aronsson et al., 2016). This prevents the N from leaving the field as nutrient run-off during the winter; hence nitrate emissions to water are reduced by 50% from 28.7 kg nitrate in CONV to 10.045 kg nitrate in the CC scenario. P and K requirements are assumed to be the same. The amount of carbon sequestered multiplied by 3.67 gives the amount of CO_2 due to the molar masses of C and CO_2, which are 12 and 44 g/mole, respectively. The CC increase SOC of 330 kg C ha^{-1} year^{-1} (Bøe et al., 2019; Qin et al., 2023), which coincides with 1211.1 kg CO_2-eq (Rautiainen et al., 2018). Considering saturation rates of carbon sequestration of 10 years for SOC, the 30-year average annual CS rate for the CC scenario is 403 kg CO_2-eq ha^{-1}. For inventory for FU 1 kg, all inputs are divided by the yields for the corresponding scenario, which for CC is 4074 kg barley ha^{-1} year^{-1}.

As discussed in Chapter 3.4 Uncertainties, there are diverging scientific evidence for whether fertilizer can be reduced when applying CC. A precautionary approach with no reduction is used in this thesis, but an alternative scenario with 30% reduction in N fertilizer is also assessed to investigate the significance of N fertilizer for the overall environmental impact.

2.2.2.3 The BZ Scenario

BZ are part of the agroforestry method, along with alley cropping, windbreaks, and forest farming (Wilson & Lovell, 2016). It is essential to distinguish between agroforestry and the type of BZ referred to in this thesis. Agroforestry is intensive forestry for commercial purposes (Wilson & Lovell, 2016), while the BZ used in this thesis comes from natural revegetation – assuming no seeds are needed for the establishment of the zones and the trees are not harvested. Riparian BZ, used in the BZ scenario, are BZ around waterways, such as rivers, streams, and lakes (NIBIO, n.d.), that decrease erosion risk, nutrient leaching, and habitat loss (Solberg, 2022; Staubo et al., 2019). The BZ filters nutrients and pesticides and acts as an essential biotope (NIBIO, n.d.; Solberg, 2022).

The inventory for scenario BZ, Table 3, considers 90% of the values from the CONV scenario, as the regular bBZ is 10m wide (Blankenberg et al., 2017), meaning 10% of a 1 ha field. Most inputs are merely 90% of the inventory used in the CONV scenario. The exceptions are all emissions to water, as the BZ the nutrients in the runoff, consequently, emissions to water in the inventory are reduced. Added fertilizer is, however, not changed, as the BZ does not affect how much fertilizer stays on the field. The BZ with trees had a 100% surface run-off reduction in an experiment by Krzeminska et al. (2020). The share of the infiltrated water transported to the river via pore systems is unknown but assumed to be low (Krzeminska et al., 2020). To account for this uncertainty, the emissions to water due to fertilizer are therefore reduced to 90% compared to the base scenario. Emissions to air and soil due to fertilizer are assumed to be the same as in the base scenario, only reduced by 10% due to a smaller field. Natural revegetation will lead to changes in carbon uptake (Næss et al., 2023). Lindroos et al. (2022) finds an annual increase in SOC in boreal forest stands in Finland of 36g C m^{-2} year^{-1}, which corresponds with 36 kg C on 100m^2 or 132.12 kg CO_2-eq (Rautiainen et al., 2018). According to Cook Pattern data, the trees will sequester 1000 kg C ha^{-1} yr^{-1} in above-ground biomass (Cook-Patton et al., 2020). As the BZ is 10m wide and 100m long, the trees in the BZ will sequester 100 kg C annually, corresponding to 367 kg CO_2-eq. Taking into account saturation rates of carbon sequestration of 10 years for, the 30-year average annual CS rate for the BZ scenario is 367 kg CO_2-eq ha^{-1} in above-ground biomass, and 44.04 kg CO_2-eq ha^{-1} in SOC.

For inventory for the FU 1 kg, all inputs are divided by the yields for the corresponding scenario, which for BZ is 3780 kg barley ha^{-1} year^{-1}. Table 3 presents the significant changes to the inventory for the BZ scenario compared to the CONV scenario. See Appendix 4 for the complete inventory and references.

Table 3 Main inventory for the BZ scenario

Input	**Value**	**Unit**
Fertilizer		
Ammonium nitrate, as N	100.80	kg ha^{-1} year^{-1}
Ammonium nitrate, as N	13.95	kg ha^{-1} year^{-1}
Inorganic phosphorus fertilizer, as P2O5	35.55	kg ha^{-1} year^{-1}
Inorganic potassium fertilizer, as K2O	68.31	kg ha^{-1} year^{-1}
Packaging, for fertilizers	383.67	kg ha^{-1} year^{-1}
Emissions to air (due to fertilizer)		
Ammonia	6.98	kg ha^{-1} year^{-1}
Dinitrogen monoxide	2.19	kg ha^{-1} year^{-1}
Nitrogen oxides	4.59	kg ha^{-1} year^{-1}
Emissions to water (due to fertilizer)		
Nitrate	2.87	kg ha^{-1} year^{-1}
Emissions to soil (due to agrochemicals)		
Glyphosate	0.84	kg ha^{-1} year^{-1}
Other		
Barley seed, for sowing	144.00	kg ha^{-1} year^{-1}
Transport, tractor and trailer, agricultural	27.00	tkm ha^{-1} year^{-1}
Grass seed, organic, for sowing	0.00	kg ha^{-1} year^{-1}
Carbon sequestration aboveground	367.00	kg CO_2 ha^{-1} year^{-1}
Carbon sequestration belowground	44.04	kg CO_2 ha^{-1} year^{-1}

2.3 Ecosystem services

HQ, CS, CP, and SE are not captured in the conventional LCA and are thus calculated in the proposed expanded LCA. First, a representative location in Norway is chosen. The location is chosen due to its high SE rate.

2.3.1 Habitat quality

The INVEST Habitat Quality model calculates habitat quality (HQ) (Hu et al., 2023). According to Sharp et al. (2014), INVEST views biodiversity as a characteristic of natural systems and uses habitat quality (HQ) as a measure. To calculate HQ for the selected location, the habitat quality is assessed. Habitat quality is a proxy for biodiversity and refers to the ability of ecosystems to provide suitable conditions for individual and population survival (Hall et al., 1997). By using HQ as a measure of biodiversity, INVEST can assess the quality of habitats and ecosystems and work towards promoting sustainable practices that support biodiversity conservation.

Equation 1 is applied to calculate HQ for the three scenarios based on Hu et al. (2023), where constants such as threat level and scaling are imbedded in x, while S represents the habitat suitability score from 0-1, 0 being the worst and one the best. S equals to 0.52 for CONV considering rainfed cropland, 0.96 BZ for tree-covered BZ, and 0.82 CC for the field with continuous cover.

$$(1) \qquad HQ = S \cdot x$$

The HQ for coordinates 60.0903N and 11.0680E was 0.11 in 2018, according to the model from Hu et al. (2023). The CC scenario has conventional cover from sowing in spring until harvest in fall and CC cover from harvest until termination in spring. Thus, a factor of 0.5 for both the land cover types gives an average HQ score for the CC scenario of 0.14. For BZ, 10% has S=0.96, while the remaining 90% has S=0.52. The HQs for the three different scenarios are presented in Table 4 below.

Table 4 Habitat quality (HQ) scores for CONV, CC, and BZ using equation *HQ=S · x.* CC has 50% of each *S*, BZ has 10% of 0.96, and 90% of 0.52.

Scenario	*S*	*x*	HQ score
CONV	0.52	0.211	0.11
CC	0.82 and 0.52	0.211	0.14
BZ	0.96 and 0.52	0.211	0.12

2.3.2 Soil erosion

The selected study location has a soil erosion (SE) rate of 3.6t ha^{-1} year $^{-1}$ (ESA, 2013; Zhou et al., 2021a), one of the highest in south-eastern Norway. This coordinate is agricultural land and is thus used in all scenarios.

For the BZ scenario, maps from Borrelli et al. (2017) using the revised universal soil loss equation (RUSLE) are used to find the change in SE when going from cropland to forest, of which the BZ consists of. Based on statistical values, Hu et al. (2021) finds that the agricultural land has 2.4 times higher SE rates than the forest. This rate, 1.5t ha^{-1} yr^{-1}, is applied to the 10% of the field that is the BZ, while the remaining 90% are assumed to have the same SE rate as the CONV scenario.

Changes in SE for the CC scenario are based on findings in the literature, especially the extensive report from Bøe et al. (2019), which summarizes findings from several different studies. The effect CC have on soil erosion is challenging to estimate. Bøe et al. (2019) state that it is difficult to know whether the decrease in particles in nearby waters the year after CC is due to the cover crop or because there was no tillage in the fall. Bechmann et al. (2005) finds a 95% reduction in suspended matter concentration when using Italian ryegrass as CC compared to bare soil. The experiment also finds that this effect is reduced by 50% when the soil is frozen. A not yet published article by Øgaard shows in an experiment in Hellerud in the winter period of 2017/2018 particle concentrations for patches with no-tillage and CC of 107mg/L, while patches with no-tillage and no CC had particle concentrations of 84mg/L. However, the scientific consensus is that CC reduces soil erosion (Chen et al., 2022; A. Clark, 2015; Holland et al., 2021; Poeplau & Don, 2015; Sharma et al., 2018). Fendrich et al. (2023) reports a 15 to 23% reduction in SE due to CC. An average SE reduction rate of 20% is used to estimate the changes in SE for the CC scenario compared to the CONV scenario. SE rates for FU 1 kg are calculated by dividing the original SE rate by the corresponding CP rate for the same scenarios.

2.3.3 Carbon sequestration

The CONV scenario is the base for comparison; hence no carbon sequestrations is accounted for in this scenario. The amount of carbon sequestered multiplied by 3.67 gives the amount of CO_2 due to the molar masses of C and CO_2, which are 12 and 44 g/mole, respectively.

The CS rates for the CC scenario are based on findings from the literature on changes in SOC under CC in Norway and the Nordics. Poepleau & Don (2015) finds 320 kg C ha^{-1} yr^{-1}, Qin et al. (2023) finds 330 kg C ha^{-1} $yr^{-1,}$ and Van Eerd et al. (2023) finds between 200-560 kg C ha^{-1} yr^{-1}, together with a more comprehensive list of results from Bøe et al. (2019) the average rate of 330 kg C ha^{-1} yr^{-1} or 1211.1 kg CO_2-eq is used. Above-ground carbon sequestration is assumed to be zero. Considering saturation rates of carbon sequestration of 10 years for SOC, the 30-year average annual CS rate for the CC scenario is 110 kg C ha^{-1} yr^{-1}.

For the BZ scenario, changes in above-ground biomass are calculated using Cook Patton-data for the chosen coordinate (Cook-Patton et al., 2020). This is 1000 kg C ha^{-1} $year^{-1}$, meaning 100 kg ha^{-1} yr^{-1} as BZ is applied on 10% of the field. Changes in SOC are found from literature findings and assumed to be 36 kg C ha $^{-1}$ yr^{-1} for 10% of the field (Lindroos et al., 2022), which in CO_2-eq. would be 367 kg and 132.12 kg CO_2-eq., for above and below-ground, respectively. Considering saturation rates of carbon sequestration of 10 years for SOC, the 30-year average annual CS rate for the BZ scenario is 112 kg C ha^{-1} yr^{-1}.

2.3.4 Crop production

Crop production (CP) for the base scenario CONV is found using the GAEZ model for crop yields (FAO, n.d.-b; Fischer et al., 2021). Using the coordinates found in the SE section, barley yields of 4200 kg ha^{-1} yr $^{-1}$ for the CONV scenario are found. For changes in yields for CC, a 3% reduction in yields from Bøe et al. (2019) and Aronsson et al. (2016) is used, corresponding to barley yields of 4074 kg ha^{-1} yr $^{-1}$. The CP change for the BZ scenario is assumed to be 0 besides the 10% reduction in arable land, meaning 3780 kg ha^{-1} yr $^{-1}$.

3 Results and discussion

This section presents and discuss the results from the extended LCA. Potential trade-offs between sustainable agriculture, productivity, and climate change mitigation are discussed.

3.1 The relative environmental impact of the three scenarios

The extended LCA, including results from both the conventional LCA and the ES assessment show that CC and BZ perform better on all indicators besides crop production and terrestrial acidification for FU 1 ha, Figure 6. CC and BZ impacts are normalized in comparison with CONV impacts. The closer to the center of the figure, the lesser the impact the practice has. Marine eutrophication, climate change, and soil erosion stand out as the most promising results for the alternative methods CC and BZ. As the two latter are not traditionally included in LCAs, the results emphasize the importance of including these when evaluating land management systems. The most improvement is for marine eutrophication, and the most worsening is for crop production for both CC and BZ. Neither results are unanticipated, as changes in N run-off and crop yields are some of the most significant changes compared to the CONV scenario. An unforeseen result is the minimal improvements for freshwater eutrophication, measured in kg P-eq. However, CC do not impact on P run-off (Bøe et al., 2019), which explains the lower impact, discussed in Chapter 3.4.3. The absolute results are presented and discussed in the following sections. See Appendix 5 for the detailed normalized synthesized results from the extended LCA.

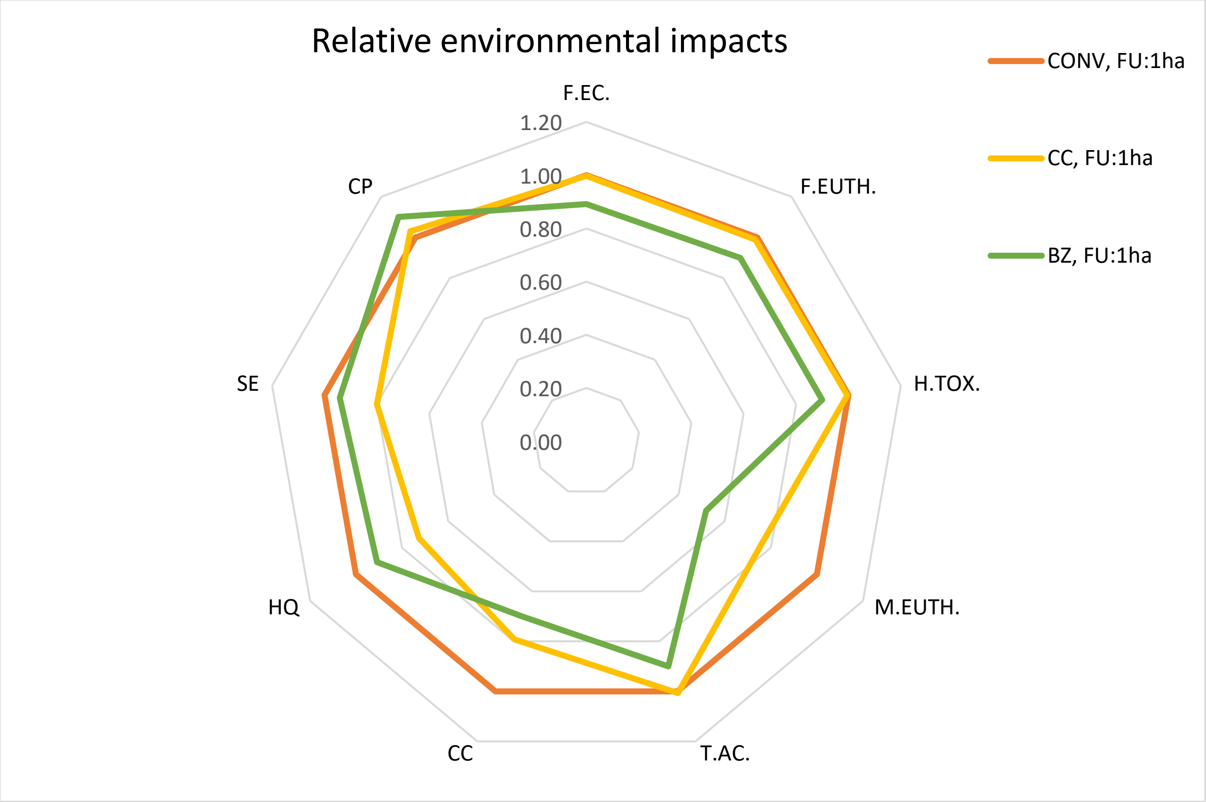


Figure 6 Synthesized results of the extended LCA with FU 1 ha. The closer to the center of the figure, the less impact the practice has. F.EC.=freshwater ecotoxicity, F.EUTH.= freshwater eutrophication, H.TOX.= human toxicity, M.EUTH.= marine eutrophication, T.AC.= terrestrial acidification, CC= climate change, HQ= habitat quality, SE= soil erosion, CP= crop production.

3.2 LCA

3.2.1 Functional unit 1 ha

To understand the difference between the three scenarios, the six impact categories freshwater ecotoxicity, freshwater eutrophication, human toxicity, marine eutrophication, terrestrial acidification, and climate change are compared, as they capture the most considerable changes from CONV to CC and BZ scenarios. The lower the score, the lesser the impact applies for all six categories. The CONV scenario has the highest environmental impact for all impact categories due to smaller fertilizer inputs, soil disturbance, and agrochemicals in the CC and BZ scenarios, except for terrestrial acidification, where CC has a 0.68% higher impact than CONV. Figure 7 a)-f) and Table 5 show the results from running the LCA with FU 1 ha.

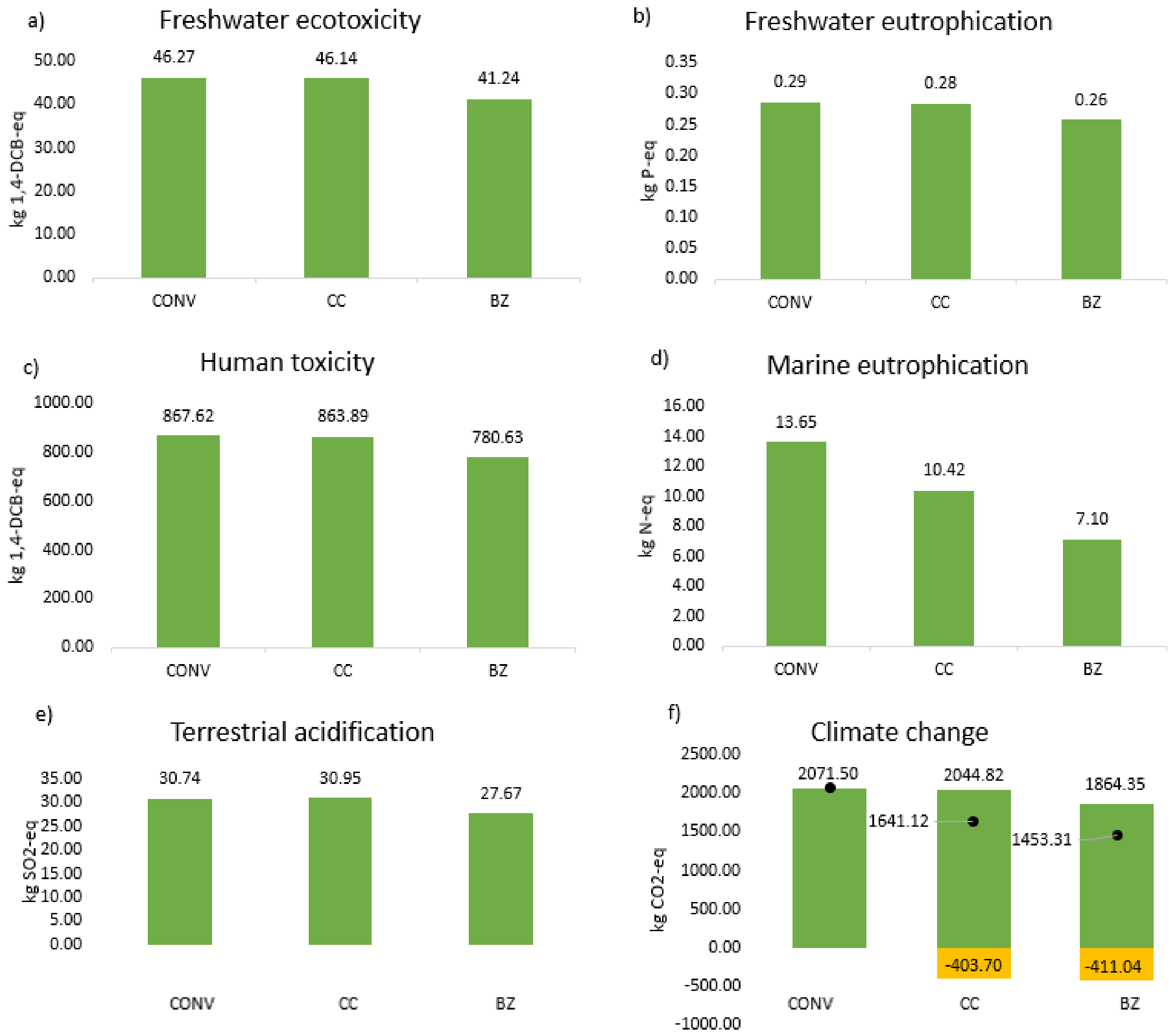


Figure 7 LCA results for FU: 1 ha for the six impact categories. CONV performs the worst for all impact categories expect for terrestrial acidification. All impact categories are better the lower the impact the practice has.

Freshwater ecotoxicity is measured in 1,4-DCB-eq. BZ performs 10% better than CONV, while the difference between CONV and CC is insignificant. The contributors to freshwater ecotoxicity are mainly harvesting (11.2%) and fertilizer production. As BZ has 10% less inputs than CONV, this explains the difference.

Freshwater eutrophication is measured kg phosphorus(P)-eq. The most prominent reference flows are the production of phosphate and P. The BZ inventory has 35.55 kg of P205 fertilizer, compared to 39.6 kg in both CONV and CC. Phosphate emissions to water are not included. Therefore, the results do not cover potential reduced impacts from CC and BZ. This is discussed in Chapter 3.4.3, General Uncertainties.

Human toxicity is measured in kg 1,4-DCB-eq emitted to urban air, freshwater, seawater, and soil. The most prominent reference flows are cadmium, manganese, and arsenic that comes from transportation on the field and fertilizer production. CC is performing only slightly better, with less than 1% less impact, than CONV, due to double the amount of transportation on the field, 60tkm compared to 30tkm in CONV. However, this impact could be decreased significantly if transportation on the fields was more efficient, combining several activities such as tillage, harrowing, and rolling with the same machine simultaneously. As with the other impact categories, BZ performs 10% better due to 10% less crop area. The three scenarios have between 780.63 and 867.62 kg 1,4-DCB eq., the second highest impact from the LCA analysis, after climate change. This suggests that reducing transportation and fertilization has a high potential for reduced impact of the practices on human toxicity.

Marine eutrophication is measured in kg N-eq. Both CC and BZ perform substantially better than CONV for this impact category. This is because the BZ filters 90% of surface run-off, preventing nutrients from reaching the waterways, while CC has 50% reduced run-off of N due to uptake in the CC. The eutrophication challenges in the Oslo fjord call for agri-environmental programs to decrease pollution (Aronsson et al., 2016). In 2020 agricultural land was responsible for 37% of P emissions and 34% of N emissions to the outer Oslo fjord (Walday et al., 2021), making any measures to reduce this load highly relevant in the region.

BZ has a 10% smaller impact on terrestrial acidification than CONV, while CC has a 0.68% higher impact than CONV. Terrestrial acidification is measured in kg SO_2-eq., and the impacts come from the production of fertilizer, mainly potassium, as K2O.

The climate change impact category shows kg CO_2-eq ha^{-1} yr^{-1} both with and without carbon sequestration (CS) in BZ and CC. Both CC and BZ perform better in both cases but substantially better when including CS, with 20.78% and 29.4% less impact for CC and BZ, respectively. Table 5 shows the relative impacts of CC and BZ compared to CONV, including CS in CC and BZ.

Table 5 Relative LCA results with FU: 1 ha for all three scenarios and the corresponding six impact categories. The base of comparison is CONV, and the lower the score, the lesser the negative impact.

	Freshwater ecotoxicity	Freshwater eutrophication	Human toxicity	Marine eutrophication	Terrestrial acidification	Climate change
CONV	100.00 %	100.00 %	100.00 %	100.00 %	100.00 %	100.00 %
CC	99.72 %	98.90 %	99.57 %	76.32 %	100.68 %	79.22 %
BZ	89.14 %	90.00 %	89.97 %	51.99 %	90.00 %	70.16 %

On average, the BZ performs 19.79% better, and the CC 7.6% better than the CONV. However, there is a decrease in yields for the two alternative scenarios. The following section examines how the three scenarios perform when the FU is 1 kg of barley rather than 1 ha.

3.2.2 Functional unit 1 kg

To account for yield reduction, the LCA is also done with FU 1 kg, dividing all inventory by the corresponding yield for that scenario. Yields are 4200 kg barley ha^{-1} yr^{-1} for CONV, 4074 kg barley ha^{-1} yr^{-1} for CC, and 3780 kg barley ha^{-1} yr^{-1} for BZ. Doing so alters the result, as illustrated in Figure 8 and Table 6.

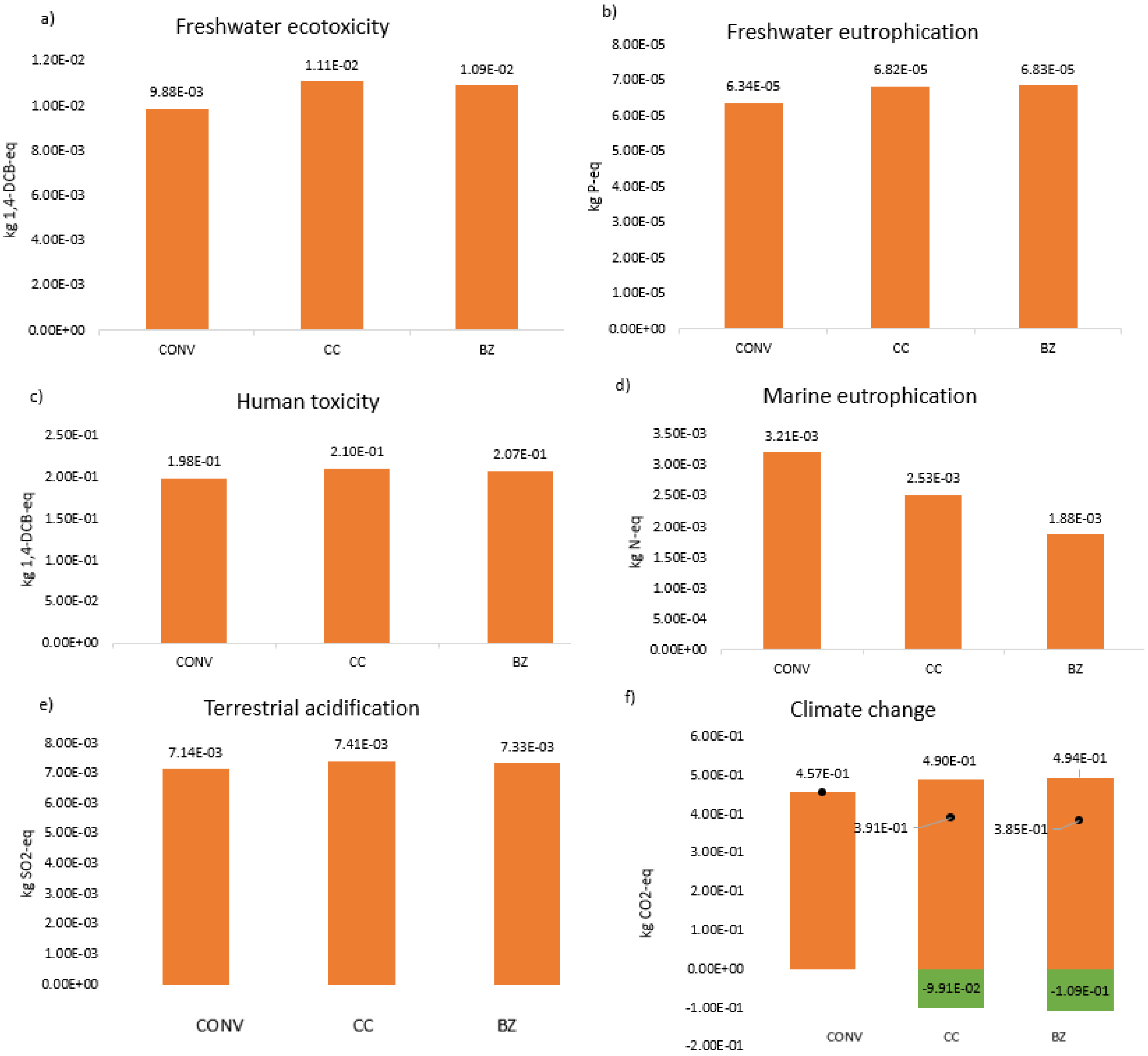


Figure 8 LCA results for FU: 1 kg showing that changing the FU from 1 ha to 1 kg alters the results significantly.

The CONV now performs better than the alternative practices on four out of six impact categories: Freshwater ecotoxicity, freshwater eutrophication, human toxicity, and terrestrial acidification. The most noticeable change is for freshwater ecotoxicity, where CC and BZ performs 12% and 10% worse, respectively, with FU 1kg, compared to 1% better and 10% better with FU 1ha. Both CC and BZ still perform significantly better than CONV for marine eutrophication and climate change, Table 6.

Table 6 Relative LCA results with FU: 1 kg favors CONV more than FU 1 ha.

	Freshwater ecotoxicity	Freshwater eutrophication	Human toxicity	Marine eutrophication	Terrestrial acidification	Climate change
CONV	100.00 %	100.00 %	100.00 %	100.00 %	100.00 %	100.00 %
CC	112.06 %	107.50 %	106.19 %	78.66 %	103.70 %	85.57 %
BZ	110.45 %	107.69 %	104.23 %	58.42 %	102.62 %	84.17 %

Changing the FU from 1 ha to 1 kg alters the results by making CONV appear more appealing than before. The BZ performed on average 5.41% better than the CONV scenario, while CC performed on average 1.05% better than the CONV scenario. These are interesting results because even with very conservative changes to the inventory and considering yield reductions, CC and BZ both perform better, despite significant inputs of glyphosate in the CC scenario and considerable yield reduction in the BZ scenario. However, it is difficult to argue for the implementation of CC and BZ due to the reduction in yields of 3% and 10%, respectively. Therefore, CONV appears as the most appealing practice when using 1 kg as the FU, while CC and BZ appear more appealing when using 1 ha as the FU.

3.3 ES

Effects on ES, such as soil erosion and habitat quality, are not possible to capture in conventional LCA today. However, they are very positively affected by CSA measures such as CC and BZ (Blankenberg et al., 2017; Bøe et al., 2019, 2020; Garland et al., 2021; Syversen, 2005).

Below is a representation of how the different scenarios performs concerning the four ES, assessed outside the LCA but with LCA principles, Figure 9. The unit for HQ is the HQ score, meaning the higher the score, the better the performance. SE is expressed in ton ha^{-1} yr^{-1}, meaning the lower the result, the better the performance. CS expresses how much carbon the scenarios sequester in kg C ha^{-1} yr^{-1}, meaning the lower the result, the better performance. CP, or yields, is expressed in kg ha^{-1} yr^{-1}, meaning the higher the yield, the better the performance.

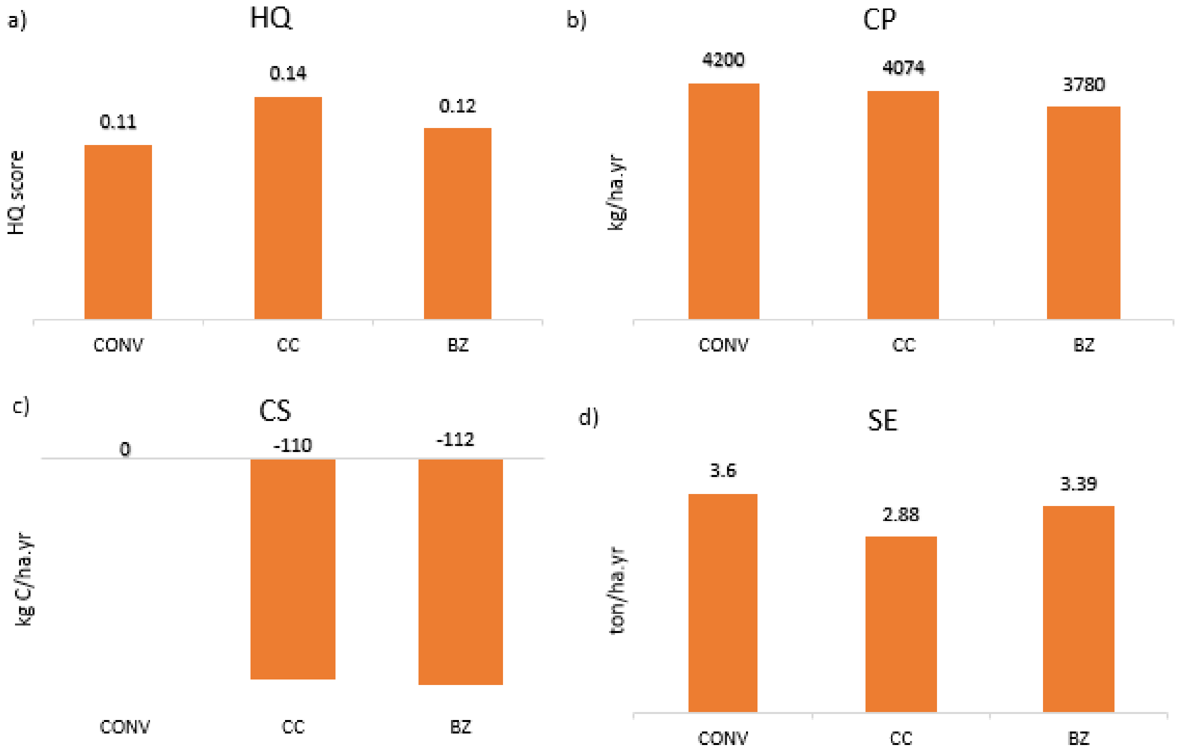


Figure 9 Results from the ES assessment of habitat quality, crop production, carbon sequestration, and soil erosion.

CC scored 27% and BZ 9% better in HQ than CONV. CC provide a diverse and dense vegetation cover during periods when the main cash crop is not growing (Bøe et al., 2019). This creates a suitable habitat and refuge for various beneficial organisms, such as insects, birds, and small mammals (Blanco-Canqui et al., 2015). These organisms can find shelter, food, and nesting sites in the cover crop, contributing to increased biodiversity on the farm.

Secondly, CC help to improve soil quality, indirectly supporting biodiversity (Dabney et al., 2001). The root systems of CC penetrate and stabilize the soil, promoting soil structure and aeration. Improved soil health provides a favorable environment for soil organisms, including earthworms, bacteria, and fungi, which play critical roles in nutrient cycling and ecosystem functioning. Dabney et al. (2001) found that CC help maintain the mycorrhizal population, assist plants in water and nutrient uptake, and improve drought toleration (Schipanski et al., 2014).

The BZ scores 0.12 for HQ, compared to 0.11 for the CONV. The relatively small increase of 9% is due to only 10% of the field experiencing increase HQ. As Gundersen et al. (2010) pointed out, BZ are essential for terrestrial and aquatic biodiversity. Low-laying areas are especially prone to floods, depositing small particles which enrich the soil, leading to a diverse range of species thriving in these BZ (Blankenberg et al., 2017). The BZ is vital for terrestrial species because it acts as a corridor and provides drinking water for amphibians, small mammals, and large mammals such as deer, moose, and lynx (Cole et al., 2020; Direktoratet for naturforvaltning, 2007; Lind et al., 2019). Up to 3000 bird pairs exist per square kilometer, a rate close to that of tropical forests (Direktoratet for naturforvaltning, 2007). The high humidity in the BZ makes it an excellent habitat for moss, lichen, and mushrooms (Blankenberg et al., 2017). The forest shades the waterways and moderates the temperature in the water, benefiting aquatic life (Gundersen et al., 2010). The roots reduce soil erosion and stabilize the stream banks, which is particularly important for spawning salmon, and litter from the trees is an essential feed for the aquatic species (Blankenberg et al., 2017). If the BZ is continuous along the river, it is reasonable to argue that the HQ for the BZ scenario could be higher.

CC has a 20% smaller SE rate than CONV, while BZ has a 10% smaller SE rate. The SE rate is lower for CC because the roots and plant material stabilize the soil, slow down the surface run-off and increase infiltration (Bøe et al., 2019). For the BZ the overall SE rate is reduced compared to CONV because trees, their roots, and other plants in the BZ significantly reduce SE, reducing the overall SE rate in the BZ scenario (Blankenberg et al., 2017; Syversen, 2005; Zhou et al., 2021a). The SE rates change when using FU 1 kg and is for CONV 0.857 kg/ kg barley, 0.701 kg/ kg barley for CC, and 0.89 kg/ kg barley for BZ, corresponding with a 17.5% SE rate reduction for CC, and a 4.6% increase in the SE rate for the BZ, compared to 20% and 10% with FU 1ha.

The CONV scenario has no CS, while CC sequesters 110 kg C ha^{-1} yr^{-1} and BZ 112 kg C ha^{-1} yr^{-1}. The CC sequesters CO_2 through the perennial ryegrass and transfers it to the ground where it is stored as SOC (Bøe et al., 2019). The BZ sequesters CO_2 from the atmosphere and store it mainly in above ground biomass as the trees grow (Lindroos et al., 2022).

CC has yield reductions of 3% compared to the CONV scenario, while BZ has yield reductions of 10% compared to CONV (Bøe et al., 2019; Fischer et al., 2021). The reduction in yield in the CC is due to competition for nutrients between the main crop, barley, and the CC, perennial ryegrass. The BZ has lower yields due to a smaller area available for barley production.

The aspect of flood protection from BZ is not quantified but considered important. The BZ's ability to reduce floods, and the damage from them, is much stronger for BZ consisting of trees than grass (Blankenberg et al., 2017). By retaining rainwater, the tree crowns allow for water to evaporate back into the atmosphere rather than reaching the water (European Environment Agency, 2015). The forest soil and roots around the river works like a sponge and prevents water on the surface from reaching the water, and floodwater is delayed as it flows between tree trunks, in contrast to when water is allowed to flow freely (Rusch, 2012).

3.4 Uncertainties

This chapter examines and discusses the uncertainties surrounding the study's findings, revealing opportunities for future investigation and improvement.

3.4.1 The CC Scenario

3.4.1.1 Nitrogen

CC mainly affects N on the field in four different ways: N scavenging, fixation, release, and immobilization.

CC with its extensive root systems can scavenge and absorb residual N from the soil profile, reducing the risk of leaching and run-off. This helps to prevent N losses and improves nutrient use efficiency. In the CC scenario the grass reduced N run-off by 50%. In the CC inventory, no changes are made to the input of fertilizer. However, if the CC scavenges N to prevent nutrient run-off and releases this later, the farmer may reduce the amount of N in his fertilizer. The availability of N from the CC for next year's crop depends on species, tillage practices, weather conditions, and the C:N ratio (Bøe et al., 2019). Bøe et al. (2019) conclude that there are significant variations, but that the N in the soil increases after termination of CC and tillage in the spring. Assuming CC become part of the crop cycling, it is reasonable to assume that N requirements from fertilizer could reduce over time. Several studies discuss the effect of N in CC (Abdalla et al., 2019; Behnke & Villamil, 2019; Blanco-Canqui et al., 2015; Jensen et al., 2021; Koudahe et al., 2022; Qin et al., 2023; Sainju & Singh, 2008).

While the evidence for reduced N run-off due to grass CC is strong (Bøe et al., 2019; Koudahe et al., 2022), the scientific evidence supporting the impact of grass CC on N availability in the soil is not currently robust (Bøe et al., 2019, 2020), differently from legume CC, that provides substantial amounts of N fixation in nutrient-deficient soils and serve as a valuable N source for subsequent crops (Blanco-Canqui et al., 2015).

When CC decompose, they release nutrients, including N, back into the soil. This slow release of N can provide a long-term nutrient supply for subsequent cash crops but is not accounted for in the inventory due to lack of evidence on N availability. Compared to grass CC, legume CC has a more rapid residue composition because it has a lower C/N ratio than grass CC (Dabney et al., 2001).

In certain situations, cover crop residues can immobilize N temporarily (Bøe et al., 2019). During decomposition, microorganisms break down the CC residues, and in the process, they temporarily immobilize N as they use it for their own growth. This can lead to a temporary reduction in available N for the subsequent crop.

Additionally, CC can reduce N_2O-emissions, but reductions in N_2O emissions are not included in the CC scenario due to lack of Norwegian data. If Norwegian conditions are similar to Denmark's, CC could reduce N_2O emissions (Bøe et al., 2019). A Danish study finds that the average annual N_2O fluxes for straw without CC are 801g N_2O-N ha^{-1} and 509g N_2O-N ha^{-1} for perennial ryegrass CC (Li et al., 2015), meaning a 27% reduction in these emissions. A German study also concludes on reduced N_2O emissions using ryegrass CC (Wang et al., 2021).

After reviewing the results, a different levels of N fertilizer is assessed with FU 1 ha to assess the possibility of reduced needs of N fertilizer if the CC releases it back into the soil for the barley to use, Figure 10. The inventory is the same, except for 30% less ammonium nitrate and organic N fertilizer and 30% less emissions to air, namely ammonia, dinitrogen monoxide, and nitrogen oxides. The results are presented relative to the CONV scenario (Figure 7 & Table 5).

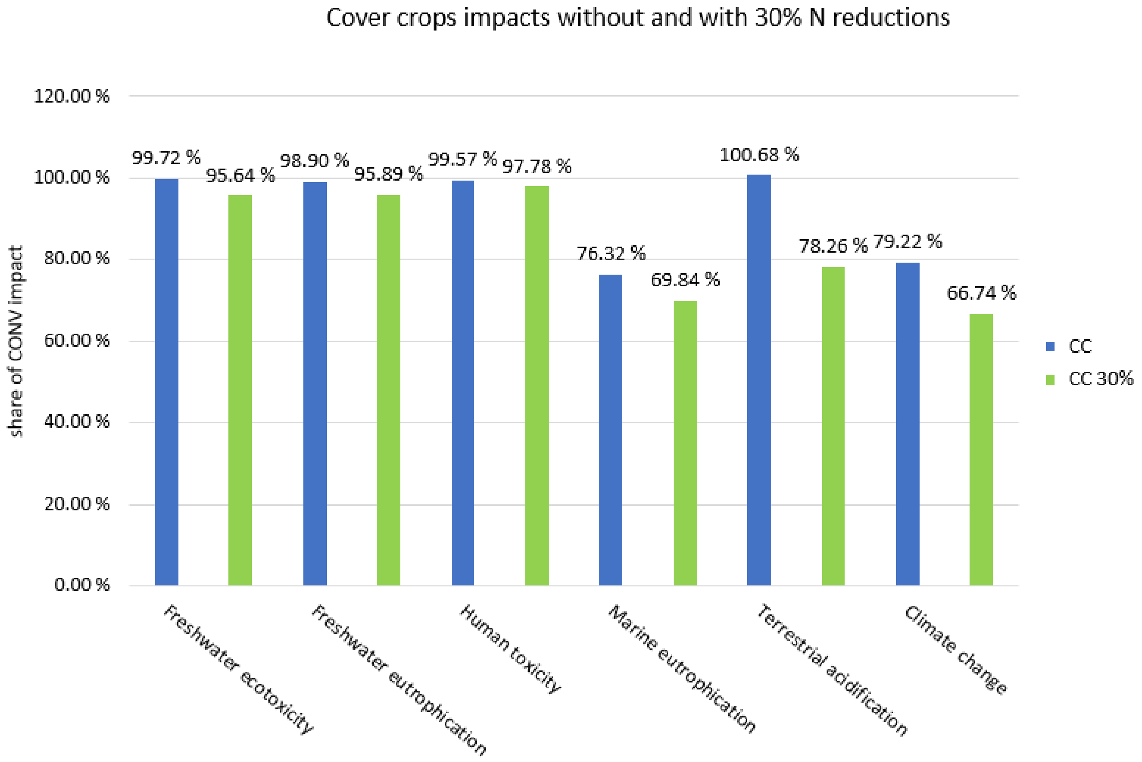


Figure 10 Illustration of CC impacts without and with reduction in N fertilizer relative to CONV (100%). CC=no changes in N inputs, CC 30%= 30% reduction in N inputs. All impacts reduce when fertilizer amounts reduce.

Overall, the CC scenario now performs 15.98% better, compared to 7.60% with no reduction in N fertilizer and associated emissions. The most notable change occurs for terrestrial acidification, with 78.26% in the CC 30% scenario, compared to 100.68% in the CC scenario. This highlights the importance of fertilization production and application and calls for future research on the N availability in the soil when using CC.

3.4.1.2 Glyphosate

The CC scenario has an additional 5.1 kg of glyphosate added to the inventory to terminate the CC in spring. A sensitivity analysis is performed to see how the CC performs if no additional glyphosate is necessary. Surprisingly, changing the glyphosate in CC to the same level of the CONV scenario does not alter the results, Table 7. Freshwater ecotoxicity and human toxicity are slightly affected, with>1% reduced impact, while the remaining categories are unaffected. This suggests that the increased use of glyphosate has little to no effect on the overall environmental impact of the CC scenario. However, it will still be an economic expense for the farmer. Although human toxicity and freshwater ecotoxicity account for glyphosate impacts, the input amounts are small and do therefore not impact the results significantly.

Table 7 Relative impacts of the three scenarios with no additional glyphosate in CC. Results indicate that the amount of glyphosate has insignificant effects on the environmental impacts of CC.

	CONV	CC		BZ
Scenario	**0.93 kg glyphosate**	**6.03 kg glyphosate**	**0.93 kg glyphosate**	**0.84 kg glyphosate**
Freshwater ecotoxicity	100.00 %	99.72 %	99.62 %	89.14 %
Freshwater eutrophication	100.00 %	98.90 %	98.90 %	90.00 %
Human toxicity	100.00 %	99.57 %	99.57 %	89.97 %
Marine eutrophication	100.00 %	76.32 %	76.32 %	51.99 %
Terrestrial acidification	100.00 %	100.68 %	100.68 %	90.00 %
Climate change	100.00 %	79.22 %	79.22 %	70.16 %

3.4.1.3 Snow cover

Norway is located to the far north, with snow cover in periods during the winter. This is not accounted for in the HQ assessment, where land cover is an important parameter. However, climate change is expected to affect winters in Norway from much snow cover to frequent thaw and freeze cycles with less snow, especially in the south and at low altitudes, which is where the agricultural land is (Wiréhn, 2018). Hence, including this aspect is not likely to have altered the results significantly.

3.4.1.4 Tillage

In the CC scenario, tillage happens in the spring rather than in the fall, as in the CONV scenario. On the one hand, there might be additional benefits of not plowing in the fall in the CC scenario that are not included in the inventory. On the other hand, not plowing in the fall may be the main reason for reductions in impacts, rather than the CC itself (Bøe et al., 2019).

3.4.2 The BZ Scenario

3.4.2.1 Agrochemicals

Some research suggests that BZs consisting of trees and shrubs may lead to increased use of agrochemicals due to more favorable habitat for insects and pests in the BZ (Blankenberg et al., 2017; Skarbøvik & Blankenberg, 2019). This is not included in the inventory as it is unknown which agrochemicals would increase, and how much.

3.4.2.2 Soil erosion

In addition, for this analysis, BZ altered the SE rate only in the BZ itself. If, however, the zone affects the SE rate on the remaining 90% of the field, the practice would appear more favorable, as discussed in Chapter 3.3.

3.4.3 Phosphorus

Emissions of phosphate run-off to water from fertilizer application are not included in the LCA for either scenario because CC has shown to not significantly affect P run-off, as opposed to N (Bøe et al., 2019; Øgaard & Bechmann, 2021). Managing to incorporate emissions of phosphate would, however, have altered the results for the BZ, as the zone filters 20-100% of the nutrients in surface run-off (Christen & Dalgaard, 2013). Since emissions from phosphate to water are not included, BZ appears less appealing than it might actually be. This aspect is thus a limitation of the study, and further studies should attempt to include this.

3.5 The choice of functional unit

When conducting an LCA, the choice of the FU should be carefully considered. As discussed throughout the thesis, the choice of FU for agricultural outputs has traditionally been per unit of food. However, in the work against more sustainable land management, this thesis argues that a FU of 1 ha better captures the overall effects of the land, in addition to adding more value to ES. The results for CC emphasize this point. With FU 1 ha, CC performs slightly worse on some impact categories, but the improvement is substantial for the ones it performs better, such as marine eutrophication and climate change. 1 ha is also a good choice of FU as agricultural land is very constrained in Norway, with less than 4% of the total area being arable (SSB, 2017), making agricultural land a very limited resource. As populations grow, so does demand; therefore, combining systems to provide food, biomass such as CC or trees from the BZ, and ES will be crucial in the years to come and much likely take a bigger part in policies. Because land is a limited resource, using 1 kg as the FU hides parts of the challenge, while using 1 ha allows for more effortless incorporation to policies on sustainable land management and integrated systems. The ES approach has garnered significant interest from policymakers, planners, and various interdisciplinary fields in recent years (Bernués et al., 2022; Kühne & Duttmann, 2020; Lipper et al., 2014; Steenwerth et al., 2014). Despite its broad acknowledgment worldwide, several well-known conceptual and methodological limitations limits its use and practical operationalization (van der Werf et al., 2020). This discussion is relevant for farmers, policymakers, and academic research to provide quantified levels of impact and indicate the potential to minimize the environmental impacts from food production in Norway.

3.6 Potential under large-scale implementation, barriers and solutions

3.6.1 Cover crops

Bøe et al. (2019) assess national emissions to water and air when implementing CC on 60%, 1760 km^2, of the grain area in Norway, an estimation made by Aronsson et al. (2016). They find the following reductions in emissions, Table 8, consistent with the carbon sequestration in CC in this thesis of 330 kg CO_2 ha^{-1} yr^{-1}:

Table 8 Potential for reduced emissions annually using CC.

Emissions to air and water	
Effect	**Estimated reduced emissions with CC on 60% of grain area**
Carbon binding	-200 689 t CO_2-eq.
Direct N_2O emissions from areas with CC compared to straw without CC	-23 447 t CO_2eq.
Indirect N_2O emissions due to reduced run-off	-12 000 t CO_2 eq.
Sum of the effect:	-236 136 t CO_2 eq.
N-loss in run-off	-3420 t N

Source: Adapted from Bøe et al. (2019)

For comparison, in 2021 the agricultural sector in Norway was responsible for 4.6 million ton CO_2-eq., with a share of 9.4% of the total Norwegian GHG (Miljødirektoratet, 2022). Consequently, CC could offset 5% of the GHG emissions stemming from the agricultural sector in Norway. The effect on eutrophication is higher, CC could reduce the total N-loss to water due to agriculture by 12% annually (Bye et al., 2020).

In their report Cover Crops as a Climate Change Mitigation Measure (Fangvekster som klimatiltak), Bøe et al. (2020) extensively investigate possible barriers to implementing CC in Norway. They performed a workshop on CCs with both internal (NIBIO) and external participants, such as interest organizations and grain farmers. They discussed and concluded on the following barriers and solutions, presented in Table 9.

Table 9 Barriers and solutions for the implementation of CC in Norway.

Barrier	Solution
The CC reduces yields because of competition for nutrients, leading to lower income for the farmer.	Subsidies to compensate for the farmer's economic loss. In the period 2002-2003 10% of the grain area in Norway had CC, this period had high subsidies and extensive information campaigns, suggesting that this would work again.
There is a risk of the CC returning as weeds the following year.	
Marked barrier: Not enough seeds available.	Subsidies could solve this by sparking the industry.
Knowledge on the use and effects of CC among the farmers and producers.	Information campaigns, demonstrations, open farm days. More research on the long-term effects on carbon binding, soil structure, nutrient leaching and availability is also needed.
Status quo-bias	Behavioral barriers: farmers tend to favor the current way of doing things, in addition to many farmers in Norway only working part-time as farmers. This may lead to them prioritizing the most necessary actions, and not embracing alternative practices.
Climate conditions. A short growing season with limited sunlight in fall and winter.	Further climate change may increase the growing season.

Source: Adapted from Bøe et al. (2020)

Aronsson et al. (2016) also point out that the lack of subsidies is one of the main reasons for the declining interest in under-sown grass CCs. They point out four main reasons: 1. Implementation barriers, 2. Low subsidy levels, 3. Fear of adverse effects, and 4. Lack of information. Today, Norwegian farmers get paid 1200NOK ha^{-1} of under-sown CCs (Statsforvalteren i Innlandet, n.d.), which may be too low. In addition, the CCs are not harvested due too economic factors, but terminated in spring and tilled into the soil. The short growing season in Norway limits the time available for cover crop growth. Harvesting CC would require additional resources, such as machinery and labor, which may not be economically viable or practical within the limited timeframe. If they are harvested in spring, the farmer would get an economic benefit from the CCs, but this would likely not outweigh the operational costs. The SE and HQ effects during fall and winter would still be present. However, the potential of increased N availability would no longer be present if the grass is removed rather than decomposed in the ground. This could, however, help lower the barriers to implementation. An ES credit for providing ESs could also make farmers more willing to adapt to CSA practices, including CC and BZ, especially when the society receives more benefits from the practices than the farmer himself.

It is important to portray to farmers that as climate change proceeds, the climate will become more unstable, with periods of both drought and heavy precipitation. A more climate-resilient production system can lead to better yields and less loss of nutrients, which means less economic loss for the farmer (Norwegian Ministry of Climate and Environment, 2012). This goes for both CC and BZ.

3.6.2 Buffer zone

Large-scale deployments of BZ would enhance several of its positive effects. Gundersen et al. (2010) emphasize that how well the BZ functions as a refuge depends on the continuity of the BZ in the landscape. Considering its relatively high yield loss, BZ can be a good strategy for local areas with a high risk of eutrophication as it stops run-off, or areas prone to floods and soil erosion. In other words, a local context might be required to motivate BZ implementation.

Areas experiencing SE more significant than 10t ha^{-1} year $^{-1}$ are affected by severe SE rates, as erosion of this extent severely affects the area's productivity (Prăvălie et al., 2021). As emphasized by the same authors, SE rates between 1 and 2t ha^{-1} year $^{-1}$ should also be addressed, as they are unsustainable in the long term. This study's area has SE rate of 3.6t ha^{-1} yr^{-1}. Soil erosion rates in Norway are expected to increase in the future due to climate change (Kvalvik et al., 2011), making measures that can reduce the SE rate highly relevant. Hence, both CC and BZ could play a big part in reducing SE and nutrient run-off, as agriculture is one of the main contributors to marine and freshwater eutrophication (Walday et al., 2021). In 2022, Norway had 286 241m of BZ near waterways (Landbruksdirektoratet, 2023). Assuming a 10m width of the BZ (Krzeminska et al., 2020), this area is 286,24ha. Using the CS rate for BZ of 405 kg CO_2-eq. ha^{-1}yr^{-1} national emissions could be reduced by 142,83t CO_2-eq. annually. The potential for increased use of BZ are high, thus there lies great potential for CS in large scale deployment of BZ.

Examining barriers to implementation in agriculture is crucial due to farmers' pivotal role and willingness to adapt. By understanding these barriers, valuable insights into farmers' challenges can be gained, leading to the successful implementation of practices such as CC and BZ. Barriers for implementation exists also for BZ. In the BZ scenario, the farmers use 10% of their field for natural revegetation. This means that yields reduce by 10%, but so do agrochemicals, fertilizer, and fuel inputs. If the BZ reduces soil erosion on the remaining part of the field, discussed briefly in Chapter 3.4.2, some yield reduction could be offset. Nevertheless, for the practice to appear appealing to the farmers, they should receive subsidies or an ES credit for providing ES and preventing nutrient run-off and emissions to waterways. Subsidies for improved HQ in the BZ could also provide incentives for implementing BZ. The BZ can also be used for agroforestry, as explored by Christen & Dalgaard (2013), which could lower the barriers for implementation, but would affect some of the interactions with ES.

3.7 Recommendations for future research

Conduct field experiments with reduced fertilization in CC: Evaluate the effects of reduced N fertilization combined with CC on crop yields. Design field experiments to assess the performance of CC in different nutrient management scenarios, including reduced fertilization levels. Analyze the interactions between CC and reduced fertilization to understand their combined effects on soil fertility, crop productivity, and nutrient cycling.

Investigate the effectiveness of combined grass and legume CC: Explore the potential benefits of integrating both grass and legume CC in agricultural systems. Assess the N contribution of legumes to subsequent crop yields and study the optimal combination ratios of grasses and legumes. Consider previous research by Abdalla et al. (2019) which suggests that a mix of legumes and grasses can enhance both yields and N content in the grain.

Examine the interaction of P with CC: Explore the role of P in the context of CC. Investigate how different cover crop species and management practices influence P dynamics, availability, and subsequent impacts on crop productivity. Assess the potential for CC to enhance P use efficiency and minimize losses through leaching or runoff.

Study soil erosion effects from BZ: Investigate the impact of BZ on soil erosion within agricultural fields. Assess the effectiveness of BZ in reducing erosion rates and evaluate the subsequent effects on the remaining areas of the field. Consider factors such as BZ width, vegetation composition, and management practices to determine the optimal design for mitigating soil erosion.

Evaluate water use efficiency of different practices: Given the potential for climate change to induce periods of drought, assess the water use efficiency of CC, BZ, and CONV practices. Investigate how these practices affect water retention and availability in agricultural systems. Explore the potential of CSA measures to retain water more effectively than CONV practices during periods of drought.

Conduct an economic analysis and assess farm profitability: Evaluate the economic viability of implementing CC or BZ. Consider factors such as the potential revenue streams from selling timber from agroforestry in the BZ and biomass harvested from CCs. Analyze the overall farm profitability and compare the economic performance of different practices to provide insights for farmers and policymakers.

Examine policy and institutional frameworks: Investigate the existing policy and institutional frameworks related to CC and BZ. Analyze the barriers and incentives for implementing these practices at different scales, from local to national levels. Explore policy options and institutional arrangements that can facilitate the adoption of sustainable farming practices and promote the integration of CC and BZ into agricultural landscapes.

4 Conclusion

Climate change challenges food security due to more frequent extreme weather events. By incorporating cover crops (CC) and buffer zones (BZ), the Norwegian agricultural sector can enhance its resilience to climate change while simultaneously contributing to carbon sequestration in biomass and soil.

The thesis assesses the two practices' environmental impacts and interaction with ecosystem services (ES) using life cycle assessment (LCA) methodology. Addressing the research question, CC and BZ demonstrate lower environmental impacts compared to conventional farming, with an average decrease of 7.6% and 19.79%, respectively, with 1 ha as the functional unit (FU). CC exhibit favorable ES interactions with minimal yield reductions of 3%. BZ display even lower environmental impacts, however with a larger decline in crop yields of 10%. This establishes CC as a win-win scenario, while BZ necessitate motivation stemming from localized issues such as runoff, erosion, flooding, and biodiversity scarcity to offset the substantial decline in yields. It is important to acknowledge the existence of trade-offs in this context and their relevance to the discussion.

CC and BZ improve marine eutrophication, soil erosion, habitat quality and carbon sequestration. Eutrophication is a considerable issue in the Oslo fjord. Hence, as soil erosion and heavy rain will increase surface run-off any measure to reduce this is important. In this study, the effects of CC and BZ on nitrogen (N) run-off include the BZ filtering the surface run-off, preventing N from reaching the waters, and the CC taking up N and storing it in the biomass, which reduces N loss over the winter by 50%. The relevance of N fertilizer is assessed to unravel potential benefits of reduced N fertilization in CC. This proves to be valuable, with an average reduced environmental impact of 15.98%, compared to 7.6%.

Furthermore, the thesis highlights the significance of selecting an appropriate FU for LCA, revealing that using 1 kg as the FU yields lower environmental impacts for conventional farming, while implementing 1 ha as the FU leads to reduced impacts for CC and BZ. These findings hold crucial implications for advancing sustainable land management practices.

Interventions from governments are required for successful implementation of the practices, as the farmers require economic compensation for yields losses and for providing ES. Information campaigns are crucial in guiding the farmers, conveying the message of reduced nutrient loss leading to reduced economic loss. Further research on both practices is required, especially on N availability to reduce fertilizer in cover crops, and interactions with phosphorus.

Although ES carry uncertainties, their results are valuable in guiding agricultural systems towards a more ES-based approach. Focusing on ES may lead to reduced yields in the short term. However, this may be offset by more climate-resilient farms in the future. Conserving ES is becoming increasingly important and should thus be included in LCA methodology.

References

Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., Truu, J., Rees, R. M., & Smith, P. (2019). A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. *Global Change Biology*, *25*(8), 2530–2543. https://doi.org/10.1111/gcb.14644

Aronsson, H., Hansen, E. M., Thomsen, I. K., Liu, J., Øgaard, A. F., Känkänen, H., & Ulén, B. (2016). The ability of cover crops to reduce nitrogen and phosphorus losses from arable land in southern Scandinavia and Finland. *Journal of Soil and Water Conservation*, *71*(1), 41–55. https://doi.org/10.2489/jswc.71.1.41

Behnke, G. D., & Villamil, M. B. (2019). Cover crop rotations affect greenhouse gas emissions and crop production in Illinois, USA. *Field Crops Research*, *241*, 107580. https://doi.org/10.1016/j.fcr.2019.107580

Bernués, A., Tenza-Peral, A., Gómez-Baggethun, E., Clemetsen, M., Eik, L. O., & Martín-Collado, D. (2022). Targeting best agricultural practices to enhance ecosystem services in European mountains. *Journal of Environmental Management*, *316*, 115255. https://doi.org/10.1016/j.jenvman.2022.115255

Blanco-Canqui, H., Shaver, T. M., Lindquist, J. L., Shapiro, C. A., Elmore, R. W., Francis, C. A., & Hergert, G. W. (2015). Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils. *Agronomy Journal*, *107*(6), 2449–2474. https://doi.org/10.2134/agronj15.0086

Blandford, D., & Hassapoyannes, K. (2018). *The role of agriculture in global GHG mitigation* (No. 112; OECD Food, Agriculture and Fisheries Papers). OECD Publishing. https://doi.org/10.1787/da017ae2-en

Blankenberg, A.-G. B., Skarbøvik, E., & Kværnø, S. (2017). *Effekt av buffersoner—På vannmiljø og andre økosystemtjenester* (No. 3/14/2017; p. 72).

Bøe, F., Bechmann, M., Øgaard, A. F., Sturite, I., & Brandsæter, L. O. (2019). *Fangvekstenes økosystemtjenester* (No. 5/9/2019; p. 53).

Bøe, F., Sturite, I., Lågbu, R., Hegrenes, A., & Ring, P. H. (2020). *Fangvekst som klimatiltak i Norge* (No. 6/4/2020; p. 50).

Bommarco, R., Kleijn, D., & Potts, S. G. (2013). Ecological intensification: Harnessing ecosystem services for food security. *Trends in Ecology & Evolution*, *28*(4), 230–238. https://doi.org/10.1016/j.tree.2012.10.012

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., Bagarello, V., Oost, K. V., Montanarella, L., & Panagos, P. (2017). An assessment of the global impact of 21st century land use change on soil erosion. *Nature Communications*, *8*(1), Article 1. https://doi.org/10.1038/s41467-017-02142-7

Bye, A. S., Aarstad, P. A., Løvberget, A. I., Rognstad, O., & Storbråten, B. (2020). *Jordbruk og miljø 2019. Tilstand og utvikling*. Statistics Norway.

Chaplin-Kramer, R., Sim, S., Hamel, P., Bryant, B., Noe, R., Mueller, C., Rigarlsford, G., Kulak, M., Kowal, V., Sharp, R., Clavreul, J., Price, E., Polasky, S., Ruckelshaus, M., & Daily, G. (2017). Life cycle assessment needs predictive spatial modelling for biodiversity and ecosystem services. *Nature Communications*, *8*(1), Article 1. https://doi.org/10.1038/ncomms15065

Chen, L., Rejesus, R. M., Aglasan, S., Hagen, S. C., & Salas, W. (2022). The impact of cover crops on soil erosion in the US Midwest. *Journal of Environmental Management*, *324*, 116168. https://doi.org/10.1016/j.jenvman.2022.116168

Christen, B., & Dalgaard, T. (2013). Buffers for biomass production in temperate European agriculture: A review and synthesis on function, ecosystem services and implementation. *Biomass and Bioenergy*, *55*, 53–67. Scopus. https://doi.org/10.1016/j.biombioe.2012.09.053

Clark, A. (2015). *Cover Crops at Work: Covering the Soil to Prevent Erosion*. SARE. https://www.sare.org/publications/cover-crops/ecosystem-services/cover-crops-at-work-covering-the-soil-to-prevent-erosion/

Clark, M., & Tilman, D. (2017). Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environmental Research Letters*, *12*(6), 064016. https://doi.org/10.1088/1748-9326/aa6cd5

Cole, L. J., Stockan, J., & Helliwell, R. (2020). Managing riparian buffer strips to optimise ecosystem services: A review. *Agriculture, Ecosystems & Environment*, *296*, 106891. https://doi.org/10.1016/j.agee.2020.106891

Cook-Patton, S. C., Leavitt, S. M., Gibbs, D., Harris, N. L., Lister, K., Anderson-Teixeira, K. J., Briggs, R. D., Chazdon, R. L., Crowther, T. W., Ellis, P. W., Griscom, H. P., Herrmann, V., Holl, K. D., Houghton, R. A., Larrosa, C., Lomax, G., Lucas, R., Madsen, P., Malhi, Y., … Griscom, B. W. (2020). Mapping carbon accumulation potential from global natural forest regrowth. *Nature*, *585*(7826), Article 7826. https://doi.org/10.1038/s41586-020-2686-x

Dabney, S. M., Delgado, J., & Reeves, D. W. (2001). Using Winter Cover Crops to Improve Soil and Water Quality. *Communications in Soil Science and Plant*, *32*. https://doi.org/10.1081/CSS-100104110

de Pinto, A., Cenacchi, N., Kwon, H.-Y., Koo, J., & Dunston, S. (2020). Climate smart agriculture and global food-crop production. *PLoS ONE*, *15*(4). Scopus. https://doi.org/10.1371/journal.pone.0231764

Dick, M., Abreu da Silva, M., & Dewes, H. (2015). Life cycle assessment of beef cattle production in two typical grassland systems of southern Brazil. *Journal of Cleaner Production*, *96*, 426–434. https://doi.org/10.1016/j.jclepro.2014.01.080

Direktoratet for naturforvaltning. (2007). *Kartlegging av naturtyper—Verdisetting av biologisk mangfold*. https://www.miljodirektoratet.no/globalassets/publikasjoner/dirnat2/attachment/54/handbok-13-080408_low.pdf

ESA. (2013). *Land cover CCI*. https://scholar.google.com/scholar_lookup?title=Land%20Cover%20CCI%3A%20Product%20User%20Guide%20Version%202.0&publication_year=2017&author=ESA

European Environment Agency. (2015). *Water-retention potential of Europe's forests* (No. 13). doi:10.2800/790618

FAO. (n.d.-a). *FAO.STAT. License: CC BY-NC-SA 3.0 IGO.* Retrieved 28 April 2023, from https://www.fao.org/faostat/en/#data/QCL

FAO. (n.d.-b). *GAEZ v4 Data Portal*. FAO. Retrieved 26 April 2023, from https://gaez.fao.org/

FAO. (2020). *Land use in agriculture by the numbers*. Food and Agriculture Organization of the United Nations. http://www.fao.org/sustainability/news/detail/en/c/1274219/

Fendrich, A. N., Matthews, F., Van Eynde, E., Carozzi, M., Li, Z., d'Andrimont, R., Lugato, E., Martin, P., Ciais, P., & Panagos, P. (2023). From regional to parcel scale: A high-resolution map of cover crops across Europe combining satellite data with statistical surveys. *Science of The Total Environment*, *873*, 162300. https://doi.org/10.1016/j.scitotenv.2023.162300

Fischer, G., van Velthuizen, & Nachtergaele, F. O. (2021). *GAEZ*.

Frank, S., Havlík, P., Soussana, J.-F., Levesque, A., Valin, H., Wollenberg, E., Kleinwechter, U., Fricko, O., Gusti, M., Herrero, M., Smith, P., Hasegawa, T., Kraxner, F., & Obersteiner, M. (2017). Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters*, *12*(10), 105004. https://doi.org/10.1088/1748-9326/aa8c83

Garland, G., Edlinger, A., Banerjee, S., Degrune, F., García-Palacios, P., Pescador, D. S., Herzog, C., Romdhane, S., Saghai, A., Spor, A., Wagg, C., Hallin, S., Maestre, F. T., Philippot, L., Rillig, M. C., & van der Heijden, M. G. A. (2021). Crop cover is more important than rotational diversity for soil multifunctionality and cereal yields in European cropping systems. *Nature Food*, *2*(1), Article 1. https://doi.org/10.1038/s43016-020-00210-8

González-García, S., Esteve-Llorens, X., Moreira, M. T., & Feijoo, G. (2018). Carbon footprint and nutritional quality of different human dietary choices. *Science of The Total Environment*, *644*, 77–94. https://doi.org/10.1016/j.scitotenv.2018.06.339

Gundersen, P., Laurén, A., Finér, L., Ring, E., Koivusalo, H., Sætersdal, M., Weslien, J.-O., Sigurdsson, B. D., Högbom, L., Laine, J., & Hansen, K. (2010). Environmental Services Provided from Riparian Forests in the Nordic Countries. *AMBIO*, *39*(8), 555–566. https://doi.org/10.1007/s13280-010-0073-9

Hall, L. S., Krausman, P. R., & Morrison, M. L. (1997). The habitat concept and a plea for standard terminology. *Wildlife Society Bulletin*, *25*(1), 173–182. Scopus.

Heller, M. C., Keoleian, G. A., & Willett, W. C. (2013). Toward a Life Cycle-Based, Diet-level Framework for Food Environmental Impact and Nutritional Quality Assessment: A Critical Review. *Environmental Science & Technology*, *47*(22), 12632–12647. https://doi.org/10.1021/es4025113

Henriksen, T. M., & Korsaeth, A. (2013). *Inventory of Norwegian grain production* (69 2013; Bioforsk Report). Bioforsk Øst Apelsvoll.

Holland, J., Brown, J. L., MacKenzie, K., Neilson, R., Piras, S., & McKenzie, B. M. (2021). Over winter cover crops provide yield benefits for spring barley and maintain soil health in northern Europe. *European Journal of Agronomy*, *130*, 126363. https://doi.org/10.1016/j.eja.2021.126363

Holmen, B. I. (2020). *Økt karbonbinding ved bruk av fangvekster på kornarealet* (No. 5–2020; p. 37). AgriAnalyse. https://www.agrianalyse.no/getfile.php/135416-1584531803/Dokumenter/Dokumenter%202020/Rapport_5_2020_%C3%98kt%20karbonbinding%20ved%20bruk%20av%20fangvekster%20p%C3%A5%20kornarealet_web.pdf

Hu, X., Hou, Y., Li, D., Hua, T., Marchi, M., Paola Forero Urrego, J., Huang, B., Zhao, W., & Cherubini, F. (2023). Changes in multiple ecosystem services and their influencing factors in Nordic countries. *Ecological Indicators*, *146*, 109847. https://doi.org/10.1016/j.ecolind.2022.109847

Hu, X., Næss, J. S., Iordan, C. M., Huang, B., Zhao, W., & Cherubini, F. (2021). Recent global land cover dynamics and implications for soil erosion and carbon losses from deforestation. *Anthropocene*, *34*, 100291. https://doi.org/10.1016/j.ancene.2021.100291

International Organization for Standardization. (2006). *ISO 14044:2006*. ISO. https://www.iso.org/standard/38498.html

Jensen, J. L., Thomsen, I. K., Eriksen, J., & Christensen, B. T. (2021). Spring barley grown for decades with straw incorporation and cover crops: Effects on crop yields and N uptake. *Field Crops Research*, *270*, 108228. https://doi.org/10.1016/j.fcr.2021.108228

Jwaideh, M. A. A., Sutanudjaja, E. H., & Dalin, C. (2022). Global impacts of nitrogen and phosphorus fertiliser use for major crops on aquatic biodiversity. *The International Journal of Life Cycle Assessment*, *27*(8), 1058–1080. https://doi.org/10.1007/s11367-022-02078-1

Koudahe, K., Allen, S. C., & Djaman, K. (2022). Critical review of the impact of cover crops on soil properties. *International Soil and Water Conservation Research*, *10*(3), 343–354. https://doi.org/10.1016/j.iswcr.2022.03.003

Krzeminska, D., Blankenberg, A.-G., Bøe, F., Nemes, A., & Skarbøvik, E. (2020). *Renseeffekt og kanterosjon i kantsoner med forskjellig vegetasjonstype*. *6/30/2020*, 32. https://nibio.brage.unit.no/nibio-xmlui/handle/11250/2645890

Kühne, O., & Duttmann, R. (2020). Recent Challenges of the Ecosystems Services Approach from an Interdisciplinary Point of View. *Raumforschung Und Raumordnung | Spatial Research and Planning*, *78*(2), 171–184. https://doi.org/10.2478/rara-2019-0055

Kvalvik, I., Dalmannsdottir, S., Dannevig, H., Hovelsrud, G., Rønning, L., & Uleberg, E. (2011). Climate change vulnerability and adaptive capacity in the agricultural sector in Northern Norway. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science*, *61*(sup1), 27–37. https://doi.org/10.1080/09064710.2011.627376

Landbruksdirektoratet. (2023). *Avrenning til vann*. Landbruksdirektoratet. https://www.landbruksdirektoratet.no/nb/statistikk-og-utviklingstrekk/miljostatistikk/avrenning

Li, X., Petersen, S. O., Sørensen, P., & Olesen, J. E. (2015). Effects of contrasting catch crops on nitrogen availability and nitrous oxide emissions in an organic cropping system. *Agriculture, Ecosystems & Environment*, *199*, 382–393. https://doi.org/10.1016/j.agee.2014.10.016

Lind, L., Hasselquist, E. M., & Laudon, H. (2019). Towards ecologically functional riparian zones: A meta-analysis to develop guidelines for protecting ecosystem functions and biodiversity in agricultural landscapes. *Journal of Environmental Management*, *249*, 109391. https://doi.org/10.1016/j.jenvman.2019.109391

Lindroos, A.-J., Mäkipää, R., & Merilä, P. (2022). Soil carbon stock changes over 21 years in intensively monitored boreal forest stands in Finland. *Ecological Indicators*, *144*. Scopus. https://doi.org/10.1016/j.ecolind.2022.109551

Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D., Henry, K., Hottle, R., Jackson, L., Jarvis, A., Kossam, F., Mann, W., McCarthy, N., Meybeck, A., Neufeldt, H., Remington, T., … Torquebiau, E. F. (2014). Climate-smart agriculture for food security. *Nature Climate Change*, *4*(12), Article 12. https://doi.org/10.1038/nclimate2437

Lobell, D. B., Burke, M. B., Tebaldi, C., Mastrandrea, M. D., Falcon, W. P., & Naylor, R. L. (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science*, *319*(5863), 607–610. Scopus. https://doi.org/10.1126/science.1152339

Miljødirektoratet. (2022, November 7). *Klimagassutslipp fra jordbruk i Norge*. Miljøstatus. https://miljostatus.miljodirektoratet.no/tema/klima/norske-utslipp-av-klimagasser/klimagassutslipp-fra-jordbruk/

Næss, J. S., Hu, X., Gvein, M. H., Iordan, C.-M., Cavalett, O., Dorber, M., Giroux, B., & Cherubini, F. (2023). Climate change mitigation potentials of biofuels produced from perennial crops and natural regrowth on abandoned and degraded cropland in Nordic countries. *Journal of Environmental Management*, *325*, 116474. https://doi.org/10.1016/j.jenvman.2022.116474

NIBIO. (n.d.). *Kantsoner*. Nibio. Retrieved 9 December 2022, from https://nibio.no/tema/miljo/tiltaksveileder-for-landbruket/vannmilljotiltak/kantsoner

Norwegian Ministry of Climate and Environment. (2012). *Climate change adaptation in Norway. (Meld. St. 33 (2012-2013) Report to the Storting (white paper))*. https://www.regjeringen.no/contentassets/e5e7872303544ae38bdbdc82aa0446d8/en-gb/pdfs/stm201220130033000engpdfs.pdf

Øgaard, A. F., & Bechmann, M. (2021). *Fangvekster i vårkorn. Effekt på fosfortap.* (No. 7/29/2021; p. 28). NIBIO.

Poeplau, C., & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. *Agriculture, Ecosystems & Environment*, *200*, 33–41. https://doi.org/10.1016/j.agee.2014.10.024

Prăvălie, R., Patriche, C., Borrelli, P., Panagos, P., Roșca, B., Dumitraşcu, M., Nita, I.-A., Săvulescu, I., Birsan, M.-V., & Bandoc, G. (2021). Arable lands under the pressure of multiple land degradation processes. A global perspective. *Environmental Research*, *194*. Scopus. https://doi.org/10.1016/j.envres.2020.110697

Qin, Z., Guan, K., Zhou, W., Peng, B., Tang, J., Jin, Z., Grant, R., Hu, T., Villamil, M. B., DeLucia, E., Margenot, A. J., Mishra, U., Chen, Z., & Coppess, J. (2023). Assessing long-term impacts of cover crops on soil organic carbon in the central U.S. Midwestern agroecosystems. *Global Change Biology*, *29*(9). https://doi.org/10.1111/gcb.16632

Rautiainen, A., Lintunen, J., & Uusivuori, J. (2018). How harmful is burning logging residues? Adding economics to the emission factors for Nordic tree species. *Biomass and Bioenergy*, *108*, 167–177. https://doi.org/10.1016/j.biombioe.2017.11.010

Ritchie, H., & Roser, M. (2020). Environmental Impacts of Food Production. *Our World in Data*. https://ourworldindata.org/environmental-impacts-of-food

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., van Vuuren, D. P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., … Tavoni, M. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, *8*(4), Article 4. https://doi.org/10.1038/s41558-018-0091-3

Rusch, G. (2012). Klima og økosystemtjenester. Norske økosystemers potensial for avbøting av og tilpasning til klimaendringer. In *43 s.* Norsk institutt for naturforskning. https://brage.nina.no/nina-xmlui/handle/11250/2379885

Sainju, U. M., & Singh, B. P. (2008). Nitrogen Storage with Cover Crops and Nitrogen Fertilization in Tilled and Nontilled Soils. *Agronomy Journal*, *100*(3), AGJ2AGRONJ20070236. https://doi.org/10.2134/agronj2007.0236

Schau, E. M., & Fet, A. M. (2008). LCA studies of food products as background for environmental product declarations. *The International Journal of Life Cycle Assessment*, *13*(3), 255–264. https://doi.org/10.1065/lca2007.12.372

Schipanski, M. E., Barbercheck, M., Douglas, M. R., Finney, D. M., Haider, K., Kaye, J. P., Kemanian, A. R., Mortensen, D. A., Ryan, M. R., Tooker, J., & White, C. (2014). A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agricultural Systems*, *125*, 12–22. https://doi.org/10.1016/j.agsy.2013.11.004

Sharma, P., Singh, A., Kahlon, C. S., Brar, A. S., Grover, K. K., Dia, M., & Steiner, R. L. (2018). The Role of Cover Crops towards Sustainable Soil Health and Agriculture—A Review Paper. *American Journal of Plant Sciences*, *9*(9), Article 9. https://doi.org/10.4236/ajps.2018.99140

Shukla P.R., Skea J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H-O., Roberts, D.C., Zhai, P., Slade, R., Connors S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J., (eds.). IPCC, 2019: Summary for Policymakers. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. In press.

Skarbøvik, E., & Blankenberg, A.-G. B. (2019). *Trær langs jordbruksvassdrag: Fordeler og ulemper* (Vol.5 Nr. 3). NIBIO. https://nibio.brage.unit.no/nibio-xmlui/handle/11250/2585762

Solberg, M. M. (2022). *Assessing Agricultural Management Practices for More Sustainable Agriculture in Norway* [Project thesis]. Norwegian University of Science and Technology.

SSB. (2017). *Nedbygging av jordbruksareal. En kartbasert undersøkelse av nedbygging og bruksendringer av jordbruksareal* (Statistics Norway).

SSB. (2022a). *Fakta om jordbruk—Statistisk sentralbyrå*. SSB. https://www.ssb.no/jord-skog-jakt-og-fiskeri/faktaside/jordbruk

SSB. (2022b). *Korn og oljevekster, areal og avlinger*. SSB. https://www.ssb.no/jord-skog-jakt-og-fiskeri/jordbruk/statistikk/korn-og-oljevekster-areal-og-avlinger

Statsforvalteren i Innlandet. (n.d.). *Fangvekster som miljø- og klimatiltak*. Statsforvalteren i Innlandet. Retrieved 16 April 2023, from https://www.statsforvalteren.no/nb/innlandet/landbruk-og-mat/miljotiltak-i-jordbruket/regional-miljoprogram-for-jordbruket/fangvekster/

Staubo, I., Carm, K., Høegh, B. Å., L'Abée-Lund, J. H., & Solheim, S. Å. (2019). *Kantvegetasjon langs vassdrag* (No. 2). Norges vassdrags- og energidirektorat.

Steenwerth, K. L., Hodson, A. K., Bloom, A. J., Carter, M. R., Cattaneo, A., Chartres, C. J., Hatfield, J. L., Henry, K., Hopmans, J. W., Horwath, W. R., Jenkins, B. M., Kebreab, E., Leemans, R., Lipper, L., Lubell, M. N., Msangi, S., Prabhu, R., Reynolds, M. P., Sandoval Solis, S., … Jackson, L. E. (2014). Climate-smart agriculture global research agenda: Scientific basis for action. *Agriculture & Food Security*, *3*(1), 11. https://doi.org/10.1186/2048-7010-3-11

Stewart, W. M., & Roberts, T. L. (2012). Food Security and the Role of Fertilizer in Supporting it. *Procedia Engineering*, *46*, 76–82. https://doi.org/10.1016/j.proeng.2012.09.448

Sumberg, J., & Giller, K. E. (2022). What is 'conventional' agriculture? *Global Food Security*, *32*, 100617. https://doi.org/10.1016/j.gfs.2022.100617

Syversen, N. (2005). Effect and design of buffer zones in the Nordic climate: The influence of width, amount of surface runoff, seasonal variation and vegetation type on retention efficiency for nutrient and particle runoff. *Ecological Engineering*, *24*(5), 483–490. https://doi.org/10.1016/j.ecoleng.2005.01.016

Tisserant, A., Morales, M., Cavalett, O., O'Toole, A., Weldon, S., Rasse, D. P., & Cherubini, F. (2022). Life-cycle assessment to unravel co-benefits and trade-offs of large-scale biochar deployment in Norwegian agriculture. *Resources, Conservation and Recycling*, *179*, 106030. https://doi.org/10.1016/j.resconrec.2021.106030

van der Werf, H. M. G., Knudsen, M. T., & Cederberg, C. (2020). Towards better representation of organic agriculture in life cycle assessment. *Nature Sustainability*, *3*(6), 419–425. Scopus. https://doi.org/10.1038/s41893-020-0489-6

Vermeulen, S. J., Campbell, B. M., & Ingram, J. S. I. (2012). Climate Change and Food Systems. *Annual Review of Environment and Resources*, *37*(1), 195–222. https://doi.org/10.1146/annurev-environ-020411-130608

Walday, M., Engesmo, A., Fagerli, C. W., Gitmark, J. K., Gran, S., Kaste, Ø., Kile, M. R., Moy, S., Borgersen, G., Brkljacic, M., & Staalstrøm, A. (2021). *Overvåking av Ytre Oslofjord 2019-2023—Årsrapport 2021*.

Wang, H., Beule, L., Zang, H., Pfeiffer, B., Ma, S., Karlovsky, P., & Dittert, K. (2021). The potential of ryegrass as cover crop to reduce soil N2O emissions and increase the population size of denitrifying bacteria. *European Journal of Soil Science*, *72*(3), 1447–1461. https://doi.org/10.1111/ejss.13047

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., Vries, W. D., Sibanda, L. M., … Murray, C. J. L. (2019). Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, *393*(10170), 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4

Wilson, M. H., & Lovell, S. T. (2016). Agroforestry-The next step in sustainable and resilient agriculture. *Sustainability (Switzerland)*, *8*(6). Scopus. https://doi.org/10.3390/su8060574

Wiréhn, L. (2018). Nordic agriculture under climate change: A systematic review of challenges, opportunities and adaptation strategies for crop production. *Land Use Policy*, *77*, 63–74. https://doi.org/10.1016/j.landusepol.2018.04.059

Zhou, N., Hu, X., Byskov, I., Næss, J. S., Wu, Q., Zhao, W., & Cherubini, F. (2021a). Overview of recent land cover changes, forest harvest areas, and soil erosion trends in Nordic countries. *Geography and Sustainability*, *2*(3), 163–174. https://doi.org/10.1016/j.geosus.2021.07.001

Zhou, N., Hu, X., Byskov, I., Næss, J. S., Wu, Q., Zhao, W., & Cherubini, F. (2021b). Overview of recent land cover changes, forest harvest areas, and soil erosion trends in Nordic countries. *Geography and Sustainability*, *2*(3), 163–174. https://doi.org/10.1016/j.geosus.2021.07.001

Appendices

Appendix 1: Inventory for the CONV scenario
Appendix 2: Translation of cover crop interaction with ecosystem services from Bøe et al. (2019)
Appendix 3: Inventory for the CC scenario
Appendix 4: Inventory for the BZ scenario

Appendix 5: Normalized synthesized results for the extended LCA with FU 1 ha

Appendix 1

Conventional barley cultivation in Norway, ha yr^{-1}	***Amount***	***Unit***	***Source inventory***
Output to technosphere	1	ha yr^{-1}	Tisserant et al. (2022)
Inputs from technosphere			
Soil			
tillage, ploughing	1	ha yr^{-1}	Tisserant et al. (2022)
sowing	1	ha yr^{-1}	Tisserant et al. (2022)
tillage, harrowing, by rotary harrow	2	ha yr^{-1}	Tisserant et al. (2022)
liming (lime+fertilising by broadcaster)	447	kg yr^{-1}	Tisserant et al. (2022)
tillage, rolling	1	ha yr^{-1}	Tisserant et al. (2022)
combine harvesting	1	ha yr^{-1}	Tisserant et al. (2022)
Agrochemicals			
application of plant protection product, by field sprayer	2.333	ha yr^{-1}	Tisserant et al. (2022)
triazine compound	0.011	kg yr^{-1}	Tisserant et al. (2022)
pyretroid compound	0.017	kg yr^{-1}	Tisserant et al. (2022)
benzoic compound	0.088	kg yr^{-1}	Tisserant et al. (2022)
organophosphorus-compound	0.98	kg yr^{-1}	Tisserant et al. (2022)
packaging, for pesticides	1.181	kg yr^{-1}	Tisserant et al. (2022)
Emissions to soil (due to agrochemicals)			
Fludioxonil	0.01	kg yr^{-1}	Tisserant et al. (2022)
Tribenuron-methyl	0.011	kg yr^{-1}	Tisserant et al. (2022)
Alpha-cypermethrin	0.017	kg yr^{-1}	Tisserant et al. (2022)
Trifloxystrobin	0.088	kg yr^{-1}	Tisserant et al. (2022)
Prothioconazol	0.075	kg yr^{-1}	Tisserant et al. (2022)
Glyphosate	0.93	kg yr^{-1}	Tisserant et al. (2022), Bøe et al. (2020)
Other			
barley seed, for sowing	160	kg yr^{-1}	Tisserant et al. (2022)
transport, tractor and trailer, agricultural	30	tkm yr^{-1}	Tisserant et al. (2022)
grass seed, organic, for sowing		kg yr^{-1}	Bøe et al. (2020)
Carbon sequestration aboveground	0	kg CO$_2$ yr^{-1}	
Carbon sequestration belowground	0	kg CO$_2$ yr^{-1}	
Fertilizer			
fertilizing, by broadcaster	1	ha yr^{-1}	Tisserant et al. (2022)
organic nitrogen fertilizer, as N, from cattle, liquid, manure	0.075	kg yr^{-1}	Tisserant et al. (2022)
Ammonium nitrate, as N	112	kg yr^{-1}	Tisserant et al. (2022)
Ammonium nitrate, as N	15.5	kg yr^{-1}	Tisserant et al. (2022)
inorganic phosphorus fertilizer, as P2O5	39.5	kg yr^{-1}	Tisserant et al. (2022)
inorganic potassium fertilizer, as K2O	75.9	kg yr^{-1}	Tisserant et al. (2022)
packaging, for fertilizers	426.3	kg yr^{-1}	Tisserant et al. (2022)
Emissions to air (due to fertilizer)			

Ammonia	7.75	kg yr^{-1}	Tisserant et al. (2022)
Dinitrogen monoxide	2.43	kg yr^{-1}	Tisserant et al. (2022)
Nitrogen oxides	5.1	kg yr^{-1}	Tisserant et al. (2022)
Emissions to soil (due to fertilizer in some way)			
Cadmium	4.83E-03	kg yr^{-1}	Tisserant et al. (2022)
Chromium	3.79E-03	kg yr^{-1}	Tisserant et al. (2022)
Lead	9.85E-04	kg yr^{-1}	Tisserant et al. (2022)
Nickel	4.14E-03	kg yr^{-1}	Tisserant et al. (2022)
Emissions to water (due to fertilizer)			
Cadmium, ion, groundwater	4.39E-05	kg yr^{-1}	Tisserant et al. (2022)
Cadmium, ion, river	2.81E-05	kg yr^{-1}	Tisserant et al. (2022)
Chromium, ion, groundwater	1.86E-02	kg yr^{-1}	Tisserant et al. (2022)
Chromium, ion, river	2.81E-03	kg yr^{-1}	Tisserant et al. (2022)
Copper, ion, groundwater	2.60E-03	kg yr^{-1}	Tisserant et al. (2022)
Copper, ion, river	1.93E-03	kg yr^{-1}	Tisserant et al. (2022)
Lead, groundwater	1.65E-04	kg yr^{-1}	Tisserant et al. (2022)
Lead, river	3.82E-05	kg yr^{-1}	Tisserant et al. (2022)
Nickel, ion, river	1.61E-03	kg yr^{-1}	Tisserant et al. (2022)
Nitrate	28.7	kg yr^{-1}	Tisserant et al. (2022)
Zinc, ion, groundwater	2.27E-03	kg yr^{-1}	Tisserant et al. (2022)
Zinc, ion, river	1.13E-02	kg yr^{-1}	Tisserant et al. (2022)

Appendix 2

Variable	Effect	Description	Cause of variation
Yield effect on main crop	-	<3% reduction in yields when sowing 7 – 10 kg/ha with perennial ryegrass	Choice of species, sort, and quantity sowed. Perennial ryegrass decreases yield in grains less than Italian ryegrass.
	+	Legumes can increase yields	
Nitrogen runoff	+	Perennial ryegrass reduces nitrogen loss with about 50%	Choice of species, weather and climate. The cover crops germination and growth vary from year to year. Also, loss from cover crops of grass during freezing of plant material in the winter.
	-	Legumes can increase nitrogen loss.	
Phosphorus runoff	+/-	Cover crops can both increase and reduce the risk of phosphorus runoff	Phosphorus loss dependent from freeze-thaw cycles, snow cover and first temperature. Harvesting catch crops can help reduce phosphorus loss. Catch crops decrease the loss of particulate-bound phosphorus.
Soil loss	+	Reduced erosion. The roots stabilize the soil, while above ground plant slow down the rate of the runoff and increase infiltration.	The CC' ability to reduce erosion depends on plant cover and root development.
Carbon bonding	+	Binds carbon (potentially 320 kg/ha/year with perennial ryegrass)	Depends on species and biomass. Grass takes up more than legumes due to slower decomposition of the plant material.
Soil structure	+	Improves aggregate stability, pore volume and reduce the density	Choice of plant species. Deep roots can loosen soil compaction.
N2O emissions	-/+	Direct N2O emissions vary. More loss with legumes than with grass.	Winter conditions, uptake in the plants, mineral nitrogen in the soil.
CO2 emissions	+	Reduced net CO2 emissions by binding carbon	Depends on species and biomass of the CC.
Weeds	+	Cover crops will in various degree reduce growth of weeds	Reduced weeds due to competition from CC but may also be caused by allelopathic effects. Grass reduced weeds more than legumes, but the best effect comes when you combine the two.

Source: Bøe et al. (2019)

Appendix 3

Barley with cover crops	***Amount***	***Unit***	***Source changes in CC***
Output to technosphere	1	ha yr^{-1}	
Inputs from technosphere			
Soil			
tillage, ploughing	1	ha yr^{-1}	(Statsforvalteren i Innlandet, n.d.)
sowing	1	ha yr^{-1}	(Bøe et al., 2020)
tillage, harrowing, by rotary harrow	1	ha yr^{-1}	(Statsforvalteren i Innlandet, n.d.)
liming (lime+fertilising by broadcaster)	447	kg yr^{-1}	Assuming no change
tillage, rolling	1	ha yr^{-1}	Assuming no change
combine harvesting	1	ha yr^{-1}	Assuming no change
Agrochemicals			20% less input for all
application of plant protection product, by field sprayer	2.33	ha yr^{-1}	Bøe et al. (2020)
triazine compound	0.0088	kg yr^{-1}	Bøe et al. (2019
pyretroid compound	0.0136	kg yr^{-1}	Bøe et al. (2019)
benzoic compound	0.0704	kg yr^{-1}	Bøe et al. (2019)
organophosphorus-compound	0.784	kg yr^{-1}	Bøe et al. (2019)
packaging, for pesticides	0.9448	kg yr^{-1}	Bøe et al. (2019)
Emissions to soil (due to agrochemicals)			Bøe et al. (2019)
Fludioxonil	0.008	kg yr^{-1}	Bøe et al. (2019)
Tribenuron-methyl	0.0088	kg yr^{-1}	Bøe et al. (2019)
Alpha-cypermethrin	0.0136	kg yr^{-1}	Bøe et al. (2019
Trifloxystrobin	0.0704	kg yr^{-1}	Bøe et al. (2019
Prothioconazol	0.06	kg yr^{-1}	Bøe et al. (2019
Glyphosate	6.03	kg yr^{-1}	Bøe et al. (2020)
Other			
barley seed, for sowing	160	kg yr^{-1}	
transport, tractor and trailer, agricultural	60	tkm yr^{-1}	Bøe et al. (2020)
grass seed, organic, for sowing	8	kg yr^{-1}	Bøe et al. (2020)
Carbon sequestration aboveground	0	kg CO_2 yr^{-1}	
Carbon sequestration belowground	403.7	kg CO_2 yr^{-1}	Bøe et al. (2020), Qin et al. (2023)
Fertilizer			
fertilising, by broadcaster	1	ha yr^{-1}	Assuming no change

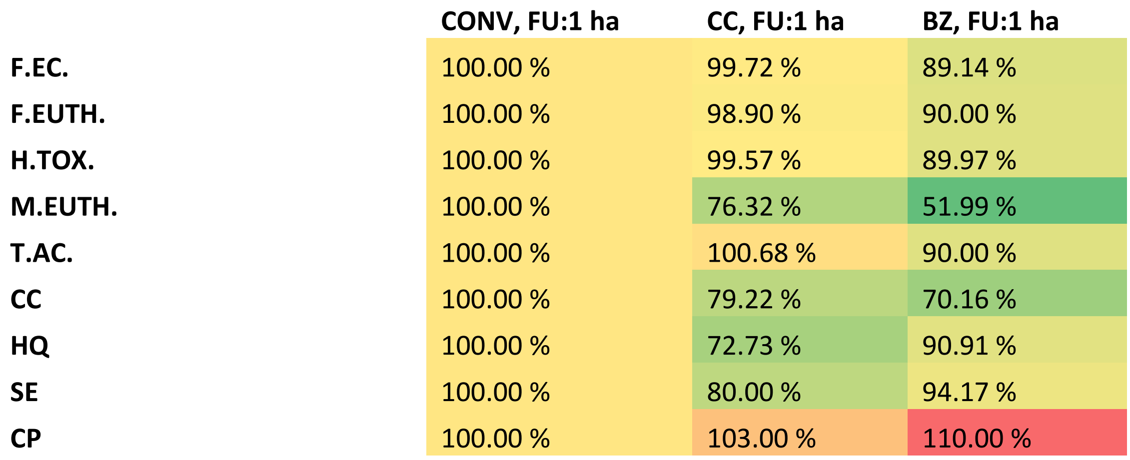
organic nitrogen fertiliser, as N, from cattle, liquid, manure	0.075	kg yr^{-1}	assuming no change
Ammonium nitrate, as N	112	kg yr^{-1}	assuming no change
Ammonium nitrate, as N	15.5	kg yr^{-1}	assuming no change
inorganic phosphorus fertiliser, as P2O5	39.5	kg yr^{-1}	assuming no change
inorganic potassium fertiliser, as K2O	75.9	kg yr^{-1}	assuming no change
packaging, for fertilisers	426.3	kg yr^{-1}	assuming no change
Emissions to air (due to fertilizer)			
Ammonia	7.75	kg yr^{-1}	assuming no change
Dinitrogen monoxide	2.43	kg yr^{-1}	assuming no change
Nitrogen oxides	5.1	kg yr^{-1}	assuming no change
Emissions to soil (due to fertilizer in some way)			
Cadmium	4.83E-03	kg yr^{-1}	assuming no change
Chromium	3.79E-03	kg yr^{-1}	assuming no change
Lead	9.85E-04	kg yr^{-1}	assuming no change
Nickel	4.14E-03	kg yr^{-1}	assuming no change
Emissions to water (due to fertilizer)			
Cadmium, ion, groundwater	4.39E-05	kg yr^{-1}	assuming no change
Cadmium, ion, river	2.81E-05	kg yr^{-1}	assuming no change
Chromium, ion, groundwater	1.86E-02	kg yr^{-1}	assuming no change
Chromium, ion, river	2.81E-03	kg yr^{-1}	assuming no change
Copper, ion, groundwater	2.60E-03	kg yr^{-1}	assuming no change
Copper, ion, river	1.93E-03	kg yr^{-1}	assuming no change
Lead, groundwater	1.65E-04	kg yr^{-1}	assuming no change
Lead, river	3.82E-05	kg yr^{-1}	assuming no change
Nickel, ion, river	1.61E-03	kg yr^{-1}	assuming no change
Nitrate	14.35	kg yr^{-1}	50% reduction in N runoff, Bøe et al. (2019)
Zinc, ion, groundwater	2.27E-03	kg yr^{-1}	assuming no change
Zinc, ion, river	1.13E-02	kg yr^{-1}	assuming no change

Appendix 4

Barley with buffer zone	***Amount***	***Unit***	***Source changes in BZ***
Output to technosphere	1	ha yr^{-1}	
Inputs from technosphere			
Soil			
tillage, ploughing	0.9	ha yr^{-1}	Blankenberg et al. (2017)
sowing	0.9	ha yr^{-1}	Blankenberg et al. (2017)
tillage, harrowing, by rotary harrow	1.8	ha yr^{-1}	Blankenberg et al. (2017)
liming (lime+fertilising by broadcaster)	402.3	kg	Blankenberg et al. (2017)
tillage, rolling	0.9	ha yr^{-1}	Blankenberg et al. (2017)
combine harvesting	0.9	ha yr^{-1}	Blankenberg et al. (2017)
Agrochemicals			
application of plant protection product, by field sprayer	2.0997	ha yr^{-1}	Blankenberg et al. (2017)
triazine compound	0.0099	kg yr^{-1}	Blankenberg et al. (2017)
pyretroid compound	0.0153	kg yr^{-1}	Blankenberg et al. (2017)
benzoic compound	0.0792	kg yr^{-1}	Blankenberg et al. (2017)
organophosphorus-compound	0.882	kg yr^{-1}	Blankenberg et al. (2017)
packaging, for pesticides	1.0629	kg yr^{-1}	Blankenberg et al. (2017)
Emissions to soil (due to agrochemicals)			Blankenberg et al. (2017)
Fludioxonil	0.009	kg yr^{-1}	Blankenberg et al. (2017)
Tribenuron-methyl	0.0099	kg yr^{-1}	Blankenberg et al. (2017)
Alpha-cypermethrin	0.0153	kg yr^{-1}	Blankenberg et al. (2017)
Trifloxystrobin	0.0792	kg yr^{-1}	Blankenberg et al. (2017)
Prothioconazol	0.0675	kg yr^{-1}	Blankenberg et al. (2017)
Glyphosate	0.837	kg yr^{-1}	Blankenberg et al. (2017)
Other			
barley seed, for sowing	144	kg yr^{-1}	Blankenberg et al. (2017)
transport, tractor and trailer, agricultural	27	tkm yr^{-1}	Blankenberg et al. (2017)
grass seed, organic, for sowing		kg yr^{-1}	
Carbon sequestration aboveground (Cook-pattern)	367	kg CO_2 yr^{-1}	(Cook-Patton et al., 2020)
Carbon sequestration belowground	132.12	kg CO_2 yr^{-1}	(Lindroos et al., 2022)
Fertilizer			
fertilising, by broadcaster	0.9	ha yr^{-1}	Blankenberg et al. (2017)
organic nitrogen fertiliser, as N, from cattle, liquid, manure	0.0675	kg yr^{-1}	Blankenberg et al. (2017)
Ammonium nitrate, as N	100.8	kg yr^{-1}	Blankenberg et al. (2017)
Ammonium nitrate, as N	13.95	kg yr^{-1}	Blankenberg et al. (2017)
inorganic phosphorus fertiliser, as P2O5	35.55	kg yr^{-1}	Blankenberg et al. (2017)

inorganic potassium fertiliser, as K2O	68.31	kg yr^{-1}	Blankenberg et al. (2017)
packaging, for fertilisers	383.67	kg yr^{-1}	Blankenberg et al. (2017)
Emissions to air (due to fertilizer)			
Ammonia	6.975	kg yr^{-1}	Blankenberg et al. (2017)
Dinitrogen monoxide	2.187	kg yr^{-1}	Blankenberg et al. (2017)
Nitrogen oxides	4.59	kg yr^{-1}	Blankenberg et al. (2017)
Emissions to soil (due to fertilizer in some way)			
Cadmium	0.004347	kg yr^{-1}	Blankenberg et al. (2017)
Chromium	0.003411	kg yr^{-1}	Blankenberg et al. (2017)
Lead	0.0008865	kg yr^{-1}	Blankenberg et al. (2017)
Nickel	0.003726	kg yr^{-1}	Blankenberg et al. (2017)
Emissions to water (due to fertilizer)			
Cadmium, ion, groundwater	4.39E-06	kg yr^{-1}	(Krzeminska et al., 2020
Cadmium, ion, river	2.81E-06	kg yr^{-1}	(Krzeminska et al., 2020
Chromium, ion, groundwater	1.86E-03	kg yr^{-1}	(Krzeminska et al., 2020
Chromium, ion, river	2.81E-04	kg yr^{-1}	(Krzeminska et al., 2020
Copper, ion, groundwater	2.60E-04	kg yr^{-1}	(Krzeminska et al., 2020
Copper, ion, river	1.93E-04	kg yr^{-1}	(Krzeminska et al., 2020
Lead, groundwater	1.65E-05	kg yr^{-1}	(Krzeminska et al., 2020
Lead, river	3.82E-06	kg yr^{-1}	(Krzeminska et al., 2020
Nickel, ion, river	1.61E-04	kg yr^{-1}	(Krzeminska et al., 2020
Nitrate	2.87E+00	kg yr^{-1}	(Krzeminska et al., 2020
Zinc, ion, groundwater	2.27E-04	kg yr^{-1}	(Krzeminska et al., 2020
Zinc, ion, river	1.13E-03	kg yr^{-1}	(Krzeminska et al., 2020

Appendix 5



	CONV, FU:1 ha	CC, FU:1 ha	BZ, FU:1 ha
F.EC.	100.00 %	99.72 %	89.14 %
F.EUTH.	100.00 %	98.90 %	90.00 %
H.TOX.	100.00 %	99.57 %	89.97 %
M.EUTH.	100.00 %	76.32 %	51.99 %
T.AC.	100.00 %	100.68 %	90.00 %
CC	100.00 %	79.22 %	70.16 %
HQ	100.00 %	72.73 %	90.91 %
SE	100.00 %	80.00 %	94.17 %
CP	100.00 %	103.00 %	110.00 %

F.EC.=freshwater ecotoxicity, F.EUTH.= freshwater eutrophication, H.TOX.= human toxicity, M.EUTH.= marine eutrophication, T.AC.= terrestrial acidification, CC= climate change, HQ= habitat quality, SE= soil erosion, CP= crop production

The table visualizes the three scenarios' impact and interactions with impact categories and ES. The greener the color, the lesser the impact, and the redder the color, the worse impact.

NTNU

Norwegian University of
Science and Technology