

Research article

Environmental benefits and changes in ecosystem services of climate-smart agriculture relative to conventional agriculture in Norway

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ABSTRACT

Climate-smart agriculture (CSA) practices aim to reduce land degradation and enhance climate resilience through sustainable land use. The environmental benefits of CSA often go undetected and appear negative in life cycle assessment (LCA), which typically focuses on product-based outputs, overlooking ecosystem services and resilience. Integrating ecosystem services within LCA of agricultural systems can help provide evidence of the environmental benefits of CSA and favor its consideration by farmers and decision makers. Here, we explore how CSA can be better represented in LCA by investigating barley production on cropland at risk of soil erosion in Norway under three management scenarios: conventional agriculture, integration of winter cover crops, and establishment of trees as buffer zones. The assessed environmental impacts combine ecosystem services (reduction of soil erosion, habitat quality, carbon sequestration) with traditional life-cycle impact categories (eutrophication, climate change, etc.). Relative to the conventional system, buffer zones improve all environmental indicators, while cover crops show an improvement in all indicators but terrestrial acidification and freshwater ecotoxicity. Buffer zones and cover crops increase habitat quality, terrestrial carbon storage, and reduce nutrient and soil-particle runoff, thereby supporting long-term yields, despite a small short-term reduction in barley yields. Overall, concerns about additional costs and management practices, limited know-how by farmers, and poor policy schemes limit the widespread CSA adoption. Engagement of farmers, local authorities and stakeholders is instrumental to overcome these barriers. Incorporating ecosystem services into LCA provides scientific evidence to support the shift toward sustainable agriculture while capturing environmental benefits of CSA.

1. Introduction

In developed countries, conventional agriculture is characterized by high inputs of synthetic fertilizers, agrochemicals, and intensive tillage to optimize yields and profits (Alejandre et al., 2019). Its implementation contributed to more stable and predictable agriculture systems, but also led to adverse environmental impacts such as soil erosion and degradation (Sumberg and Giller, 2022), water pollution and unsustainable levels of water resource extraction (Gu et al., 2023; Liu et al., 2021), high GHG emissions (Crippa et al., 2021), and biodiversity loss (Chaudhary et al., 2016; Willett et al., 2019; Wittwer et al., 2021). Under the projected climatic changes, agriculture in Northern Europe is expected to benefit from milder temperatures and longer growing seasons, but changes in precipitation patterns, droughts and higher temperatures will lead to increased soil erosion, surface runoff, floods, and increased

risk of pests and diseases (Wiréhn, 2018; Hu et al., 2023; Zhou et al., 2021). In Norway, 17% of the agriculture land is under soil erosion rates higher than 1 tonne per hectare per year ($t\ ha^{-1}yr^{-1}$), which requires some form of mitigation measures to prevent adverse losses in soil quality and productivity in the long term (Zhou et al., 2021). The Oslo Fjord region, a major player for Norwegian grain production, is facing high agriculture-related eutrophication of marine and freshwater ecosystems. Around 37% of total phosphorous emissions and 34% of nitrogen emissions are emitted by the agricultural sector (Waldy et al., 2021), leading to calls for actions to reduce nutrients runoff (Aronsson et al., 2016).

Climate-smart agriculture (CSA) has emerged as an overarching concept embracing a variety of practices aiming at stimulating more sustainable and resilient agri-food systems where crop productivity is maintained, if not increased, while enhancing ecosystem services, and

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climate change mitigation and adaptation (FAO, 2023; de Pinto et al., 2020). Common CSA practices are agroforestry, sustainable livestock management, and conservation agriculture, such as integration of cover crops and buffer zones into agri-food systems (FAO, 2022). Cover crops provide soil cover in periods where the soil would otherwise be bare and can induce several benefits to the land. There is growing interests in these practices in colder regions where milder winters, as a result of ongoing climate change, can now favor year-round vegetation growth (Unc et al., 2021; Wiréhn, 2018). Although there are regional variations, evidence shows that cover crops can actively reduce soil erosion (Kaye and Quemada, 2017), increase soil microbial abundance (Wang et al., 2021), improve soil moisture retention (Kaye and Quemada, 2017), reduce nitrogen oxides emissions (Wang et al., 2021), reduce weeds and pests (Wittwer et al., 2017), and increase crop yields (Vendig et al., 2023). Some studies also find that cover crops can increase soil carbon sequestration (Qin et al., 2023; Jian et al., 2020), but others find that the outcomes are more uncertain and can be affected by experimental bias (Chaplot and Smith, 2023). Riparian buffer zones are vegetated strips along waterways and, thanks to above ground structure and root systems, can reduce soil erosion by water and wind (Dindaroğlu et al., 2015), reduce surface nutrient runoff loss (Aguar et al., 2015), provide flood protection (Blankenberg et al., 2017), and increase biodiversity and habitat quality (Hanle et al., 2021; Skarbøvik and Blankenberg, 2019). In addition, buffer zones can contribute to climate change mitigation by storing carbon above and below ground (Chapman et al., 2020). Buffer zones can also include agroforestry, alley cropping, windbreaks, and forest farming practices (Wilson and Lovell, 2016).

Despite the potential environmental benefits of CSA, these practices still face significant barriers for broader implementation. From a farmer perspective, typical barriers include potential short-term crop yield reduction in farmed areas, and increases in crop production costs (Fuglie et al., 2023; Lobell and Villoria et al., 2023). These challenges could be alleviated by providing robust scientific evidence for the environmental benefits of CSA e.g., longer soil fertility, reduced soil erosion and nutrient runoff, and increased carbon sequestration. These benefits can secure the main crop yield in the long term (Bergtold et al., 2019), thereby contributing to climate change mitigation and adaptation in the agricultural sector. The environmental benefits of CSA can be assessed via life cycle assessment (LCA), a methodology commonly applied to assess the sustainability of agri-food systems (van der Werf et al., 2020). However, under the current focus of LCA on agriculture productivity, importance is almost entirely attributed to the amount of food produced, while potential benefits to ecosystem services and securing yields in the long-term remain largely undetected (Wittwer et al., 2021; Taelman et al., 2023; De Luca Peña et al., 2022; Hardaker et al., 2022). More sustainable practices are often penalized despite being associated with lower emissions per hectare of land or year of farming operations. This penalization happens because of potential short-term yield losses due to practices such as reduced synthetic inputs or tillage or reduced cultivation areas to accommodate trees or shrub (Tuomisto et al., 2012; Meier et al., 2015). These potential benefits better emerge if ecosystem services are incorporated within the indicators used in LCA of agricultural products, as well as considering a functional unit that does not mainly focus on crop productivity.

Previous studies explored the incorporation of ecosystem services into LCA (Alejandro et al., 2019; Chaplin-Kramer et al., 2017; van der Werf et al., 2020). Key gaps identified include a lack of indicators for measuring land degradation, soil quality, biodiversity, and toxicity impacts on ecosystems and human health (van der Werf et al., 2020). Additionally, there is a lack of a broad perspective on agricultural systems, including their co-benefits (Chen et al., 2021; Liu et al., 2020), site-specific conditions (Taelman et al., 2023), and multi-functionality (van der Werf et al., 2020). In general, assessments that integrate ecosystem services into LCA are more complex and require a specific local context (Chaplin-Kramer et al., 2017), as well as a shift from a process-based to a systems perspective (Pavan and Ometto, 2018). The

integration requires adjustments to system boundaries, functional units and life-cycle inventories. For example, the whole agricultural area can be considered as a multifunctional landscape that co-delivers crops, buffer trees and ecosystem services, rather than focusing only on the crop-producing area (Boone et al., 2019; van der Werf et al., 2020). Inventory data should be updated to represent natural flows of carbon, water and nutrients to account for ecosystem services, performing a shift from product-based environmental assessments towards land-based system-wide assessments. Also, the use of land-based functional unit is the preferred choice as the basis for comparing the multiple benefits that agricultural systems provide (of which crop production is one of them).

This study performs an environmental assessment of conventional and CSA farming options of barley production in an area affected by severe erosion rates and high levels of eutrophication in Norway. This area, close to Oslo Fjord, produces 87% of Norwegian grain production (SSB, 2022a), and has annual erosion rates around 4 tonne ha⁻¹ yr⁻¹ (Borrelli et al., 2017; Zhou et al., 2021). These variety of effects are here integrated in a LCA where different ecosystem services, including habitat quality, soil erosion, carbon sequestration, and crop production, are added to conventional LCA indicators, such as climate change and eutrophication impacts, for a more thorough evaluation of the different practices. Barriers to the implementation of CSA in Norwegian agriculture are finally identified, and the possible solutions reviewed and discussed.

2. Methodology

The environmental impacts of conventional and CSA practices are assessed by conducting an LCA of barley production (at farm gate) in Norway. Barley is the most widely grown grain crop in Norway (SSB, 2022b). The assessment is carried out by integrating LCA impact categories with ecosystem services. The integration is performed at three levels: I) by adjusting system boundaries, i.e., considering the management of a same hectare of land under different agricultural practices involving either pure cropland or a mix of cropland and trees; II) by adjusting life-cycle inventories incorporating relevant flows to the ecosystem services provided, e.g., reduction of nutrients runoff to watersheds (detailed in section 2.3); III) by choosing 1 ha of land as functional unit, to capture a broader perspective that includes all the land area of interest (Section 2.3.6).

2.1. Study location

The study area is located in Gjerdrum, 25 km north of Oslo. This region plays a significant role in national grain production, contributing approximately 87% of the Norwegian output. The study area is affected by severe erosion rates, around 4 tonne ha⁻¹ yr⁻¹ (Borrelli et al., 2017; Zhou et al., 2021), and high levels of eutrophication (Waldy et al., 2021; Aronsson et al., 2016), requiring implementation of mitigation measures. Cover crops and buffer zones are among the most common strategies considered to reduce high soil erosion and nutrients runoff. These practices provide physical barriers to wind and water runoff and erosion, by building up below and above ground carbon stocks, but they can reduce the amount of land dedicated to crop production and/or influence crop yields.

2.2. Scenarios and life-cycle inventories

Three scenarios are considered (Fig. 1) and their foreground inventories are detailed in Table S1. The background inventory relies on the Ecoinvent database 3.9.1 cut-off version (FitzGerald and Sonderegger, 2022). The conventional (CONV) scenario (Fig. 1a) considers a common barley production system in Norway (Tisserant et al., 2022). This case includes synthetic fertilizers and pesticides, and intensive tillage practices (i.e., turning the soil to prepare for seeding, and to control pests) typical of monoculture cropping systems (Sumberg and

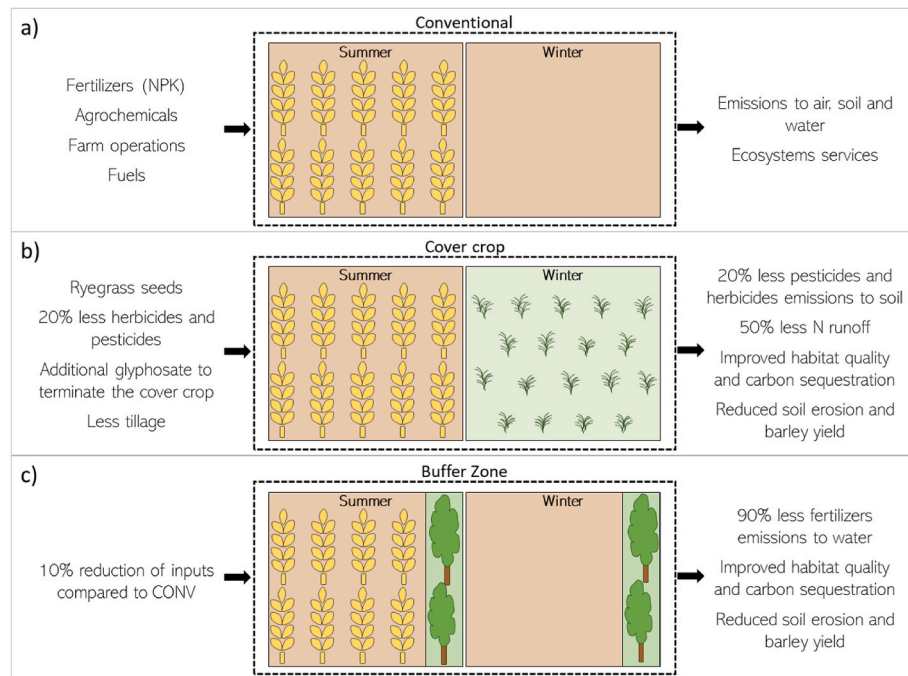


Fig. 1. Schematic representation of the investigated systems. Barley production under conventional system (CONV) (a), integrated with cover crops (CC) (b), and with 10% of area used as buffer zone (BZ) (c).

Giller, 2022). Barley yield is 4200 kg per hectare per year ($\text{kg ha}^{-1}\text{yr}^{-1}$), which is a 10-year average of yields of barley in Norway from 2013 to 2022 (SSB, 2023).

The cover crop (CC) scenario (Fig. 1b) considers barley production integrated with ryegrass in winter; ryegrass is both a cover crop providing green cover to the soil, and a catch crop reducing surface runoff and soil erosion (Bøe et al., 2019). This scenario differs from CONV in terms of agricultural operations, agrochemical inputs, fertilizers emissions, and barley yield. Ryegrass is sown simultaneously as barley during spring and eight kg per hectare of ryegrass seeds are required (Bøe et al., 2020). Tillage happens in spring rather than the fall, and harrowing (i.e., breaking up clods of soil) happens once in spring instead of both on fall and spring. There are no changes to the inventory for sowing, liming, rolling (i.e., level the ground), and combined harvesting, compared to CONV. The perennial ryegrass is not harvested, but terminated in spring, before tillage and harrowing. The termination requires additional $5.1 \text{ kg ha}^{-1}\text{yr}^{-1}$ of glyphosate (Bøe et al., 2020) and doubles the agricultural operations (Bøe et al., 2020). We consider 20% less agrochemicals inputs and their associated emissions to the soil compared to CONV scenario, since cover crops reduce weeds (Blanco-Canqui et al., 2015) and break pest insect life cycles (Bøe et al., 2019). Barley yields are reduced by 3% when integrated with ryegrass (Bøe et al., 2019) due to competition for nutrients between the two crops. Thus, the barley yield in the CC scenario is $4074 \text{ kg ha}^{-1}\text{yr}^{-1}$. Cover crops can reduce nutrient runoff by up to 50% (Bøe et al., 2019) and prevents nitrogen runoff during winter (Aronsson et al., 2016). The extensive root systems of ryegrass can scavenge and absorb residual nitrogen from the soil, reducing the risk of leaching and runoff (Bøe et al., 2019; Koudahe et al., 2022). This helps to prevent nitrogen losses and improves nutrient use efficiency, and a 50% reduction in nitrate emissions to water is applied compared to CONV.

The buffer zone (BZ) scenario (Fig. 1c) considers that 10% of the area used in CONV for barley production is left to natural revegetation (primarily deciduous birch species) as riparian buffer zone (Blankenberg et al., 2017). The inventory for BZ considers 90% of the values from CONV scenario, including 10% lower barley yield (e.g., $3780 \text{ kg ha}^{-1}\text{yr}^{-1}$), with an equivalent reduction of emissions to water due to

lower fertilizer use on the cropland. Although buffer zone trees can completely reduce surface runoff (Blankenberg et al., 2017; Krzeminska et al., 2020), there are some uncertainties associated to the share of the infiltrated water transported to the river via pore systems (Krzeminska et al., 2020). A conservative approach is taken considering 90% reduction of fertilizer emissions to water compared to CONV.

2.3. Environmental indicators

Environmental indicators referring to both life cycle impact categories and ecosystem services assessment are considered and grouped as follows: soil erosion rates and terrestrial acidification potentials, marine and freshwater eutrophication, toxicity (human toxicity, carcinogenic and freshwater ecotoxicity), climate change (in terms of life-cycle GHG emissions and ecosystem carbon storage), habitat quality, and crop production. Characterization factors for terrestrial acidification, eutrophication and toxicity from the Environmental Footprint (EF) method v3.1 (EC, 2022) and climate change impacts are taken from the latest IPCC report (IPCC, 2021). The ecosystem services are selected based on their reported interactions with cover crops and buffer zones (Table S2). They are a mix of provisioning, regulating, and supporting services, including reduction in nutrient runoff and soil erosion, improvement in soil and habitat quality, and crop production (Table S3). They are estimated using site-specific datasets and literature sources. Although cover crops and buffer zones can also provide cultural ecosystem services (e.g., knowledge and learning, tourism in the tree areas, etc.), this is not included in our study.

2.3.1. Soil erosion rates and terrestrial acidification potentials

The soil erosion rate for each one of the three scenarios (CONV, CC and BZ) is calculated applying data from Equation (1) with the site-specific parameters from Table S4.

$$SE = SE_{CONV} * (1 - x_{CSA}) \quad \text{Eq. 1}$$

Where SE is the total soil erosion per scenario, in $\text{t ha}^{-1}\text{yr}^{-1}$, SE_{CONV} is the soil erosion rate of CONV, in $\text{t ha}^{-1}\text{yr}^{-1}$; x_{CSA} is the rate of reduction in soil erosion, in %, provided by cover crops or buffer zone. The soil

erosion rate for CONV is equal to $3.6 \text{ t ha}^{-1}\text{yr}^{-1}$, and it is one of the highest in south-eastern Norway according to site-specific soil erosion data (Borrelli et al., 2017; Zhou et al., 2021). Cover crops reduce soil erosion (Chen et al., 2022; Holland et al., 2021), because the ryegrass roots and plant material stabilize the soil, slow down the surface runoff and increase infiltration (Bøe et al., 2019), and a typical reduction rate of 20% can be considered (Panagos et al., 2021; EC, 2018). In the BZ scenario, a 61.5% reduction in soil erosion of the agriculture area is considered based on average reduction of soil particles runoff in Norway after implementation of buffer zones (Blankenberg et al., 2017). Terrestrial acidification impact category uses characterization factors from EF v3.1 method (EC, 2022).

2.3.2. Eutrophication

Freshwater and marine eutrophication impact categories are assessed using characterization factors from EF v3.1 method (EC, 2022). The integration with ecosystem service (reduction of nutrient runoff) happens at the inventory level by adjusting the emissions of nutrients to soil and water flows, as explained in Section 2.2. The reference selected for barley production in Norway (Tisserant et al., 2022) provide inventory data for the main agricultural activities and related soil emissions, except for phosphate emissions. Thus, these are estimated here applying Equation (2) with the parameter values from Table S4 that are specific to each agricultural practice considered (CONV, CC or BZ).

$$P_{\text{emis}} = (P_{\text{fert}} - (P_{\text{fert}} - P_{\text{above}} + P_{\text{fert}} * P_{\text{roots}})) * P_{\text{loss}} * (1 - Y_{\text{CSA}}) \quad \text{Eq. 2}$$

P_{emis} is the phosphate emission to the water, in $\text{kg ha}^{-1}\text{yr}^{-1}$; P_{fert} is the input of phosphate fertilizer, in $\text{kg ha}^{-1}\text{yr}^{-1}$; P_{above} is how much the plant above ground recovers of applied phosphate as fertilizer, in %; P_{roots} is how much the plant roots recover of applied phosphate as fertilizer, in %; P_{loss} is how much of phosphorous available in the soil is emitted to freshwater, in %; and Y_{CSA} is how much the emissions are reduced by the CSA. For CC, no reduction in phosphorous runoff is considered, as cover crops do not impact phosphorous emissions (Aronsson et al., 2016). The phosphate emissions to water consider only the applied phosphate, without accounting for previous phosphorous available in the soil.

2.3.3. Toxicity

We selected human toxicity (carcinogenic) and freshwater ecotoxicity from EF v3.1 method (EC, 2022) to assess toxicity impacts. The integration with ecosystem service (i.e., nutrients recycling and natural pest control) happens at the inventory level by adjusting the inputs of fertilizers and agrochemicals and the emissions of nutrients to soil and water flows (Section 2.2).

2.3.4. Climate change

Life-cycle GHG emissions are aggregated using the global warming potential 100 years (GWP100) (IPCC, 2021). In addition, we estimate the carbon sequestration potential (i.e., regulating ecosystem service) on the investigated CSA practices relative to conventional agriculture. In this case, system boundaries are adjusted to account for the potential carbon sequestration in the whole area (i.e., including the buffer zone), and not only the area where barley is produced. The CONV scenario is the base for comparison and no changes are considered in above or below carbon sequestration. The carbon sequestration for CC and BZ scenarios is calculated applying Equation (3) and using the local parameter data from Table S4.

$$CS = SOC * a + AG * b \quad \text{Eq. 3}$$

Where CS is the total carbon sequestered, in kilogram of carbon per hectare per year ($\text{kg C ha}^{-1}\text{yr}^{-1}$), SOC is the soil organic carbon sequestration rate, in $\text{kg C ha}^{-1}\text{yr}^{-1}$, y is the share of area under cover crop or buffer zone, and AG is the above ground carbon sequestration rate, in $\text{kg C ha}^{-1}\text{yr}^{-1}$. An average rate of $320 \text{ kg C ha}^{-1}\text{yr}^{-1}$, over a

period of 20 years, has been reported for the carbon sequestration rate in the soil in Norwegian agricultural land under cover crops (Bøe et al., 2019). No above-ground carbon sequestration is considered for CC. For the BZ scenario, both above and below ground carbon sequestration are considered for the 10% of area with buffer zone, since natural revegetation leads to changes in carbon uptake (Næss et al., 2023). The above-ground carbon sequestration rate is $1166 \text{ kg C ha}^{-1}\text{yr}^{-1}$, according to a spatially-explicit dataset based on observations of natural vegetation regrowth that represents a 30-year average annual carbon sequestration rate (Cook-Patton et al., 2020). The SOC sequestration rate is $360 \text{ kg C ha}^{-1}\text{yr}^{-1}$ (Lindroos et al., 2022), assumed over a saturation period of carbon sequestration of 20 years.

2.3.5. Habitat quality

Habitat quality is a proxy for biodiversity and refers to the ability of ecosystems to provide suitable conditions for individual and population (i.e., animals or plants) survival (Hall et al., 1997). The habitat quality is calculated for the three scenarios applying Equation (4), with the parameters shown in Table S4. This equation is based on the INVEST habitat quality model (Sharp et al., 2014), adapted to Norwegian conditions (Hu et al., 2023).

$$HQ = (S_{\text{CONV}} * z_{\text{CONV}} + S_{\text{CSA}} * z_{\text{CSA}}) * c \quad \text{Eq. 4}$$

HQ is the habitat quality per each scenario; the S score (i.e., S_{CONV} and S_{CSA}) represents the habitat suitability score from 0 to 1, with 0 being the lowest suitability; y_{CONV} and y_{CSA} represent the factor of area that the S score applies; and c is the threat level and scaling, equal for all scenarios. For CONV scenario, S_{CONV} considers habitat suitability for rainfed cropland (Hu et al., 2023). The CC scenario has ryegrass cover 50% of the time, from fall until termination in spring, and the S_{CSA} considers the habitat suitability for fields with continuous cover (Hu et al., 2023). For BZ, the S_{CSA} represents the habitat suitability for tree-covered land (Hu et al., 2023).

2.3.6. Crop production

Here, we assess how the three scenarios impact on the provisioning ecosystem service for food production, and how changing the functional unit from 1 ha of land to one kg of barley produced influence the environmental performances of the scenarios. The barley production is $4200 \text{ kg ha}^{-1}\text{yr}^{-1}$ in the CONV scenario, $4074 \text{ kg ha}^{-1}\text{yr}^{-1}$ in the CC scenario and $3780 \text{ kg ha}^{-1}\text{yr}^{-1}$ in the BZ scenario. The potential challenges to sustain the current yields of CONV at present soil erosion rates is a main driver for implementing CSA and considered in the interpretation of the results, but yield declines are not simulated because of a lack of data and the inherent uncertainties in such estimates.

To understand how the two different functional units influence the environmental performance of the scenarios, we compare the results using both an area-based and a product-based functional unit for all the environmental indicators. It is important to note that the product-based functional unit accounts for the 3% and 10% lower barley yields in the CC and BZ scenarios, respectively. Therefore, the use of the production-based functional unit penalizes the environmental performance of CSA to the extent of the yield reduction of the main crop when compared to conventional agriculture, in addition to changes in system inputs.

2.3.7. Sensitivity analysis

A sensitivity analysis is performed to account for variations in the environmental performance of CC and BZ scenarios that depend on management practices (i.e., fertilizer inputs, field operations), weather conditions (i.e., snow cover) and plant and soil characteristics (i.e., nutrient runoff, soil erosion). We consider variability in some factors representing low and high-performance efficiencies in the benefits that can be expected from CC and BZ practices. For CC scenario, low performance (CC_{low}) is a combination of high nitrogen fertilizer inputs and high soil nitrogen emissions, high glyphosate application rates to terminate the crop, increased tillage practices, reduced crop yields,

reduced carbon sequestration rates, and reduced habitat quality because of snow cover during winter months. The opposite applies for the high performance (CC_high) of CC scenario that is a combination of low fertilizer inputs and emissions, reduced tillage practices, increased crop yields and increased carbon sequestration rates. For BZ scenario, low performance (BZ_low) is a combination of high inputs of agrochemicals, increased runoff of nutrients and pollutants, low reduction of soil erosion rates, and reduction of habitat quality because of snow cover. The high performance of BZ scenario (BZ_high) combines low inputs of agrochemicals, reduced runoff, and lower soil erosion. A full list of all parameters, including those used to simulate low and high performances, is available in [Supplementary Table S5](#).

These parameters represent possible variations on the reported effects of introducing cover crop and buffer zones into agricultural land in Norway. For example, there are uncertainties around the nitrogen response to cover crops, which depends on species, tillage practices, weather conditions, and the carbon/nitrogen ratio of the soil (Bøe et al., 2019). Cover crop residues can immobilize nitrogen temporarily due to microorganisms' activity (Bøe et al., 2019), leading to a temporary reduction in available nitrogen for the subsequent crop, requiring more nitrogen fertilization. We assume 30% lower inputs of nitrogen fertilizers in CC_high and 30% higher inputs of nitrogen fertilizer CC_low (Abdalla et al., 2019; Wang et al., 2021). Different tillage and plowing practices can be implemented in the CC scenario (Bøe et al., 2019). More tillage operations might be needed to fully incorporate the terminated cover crop into the soil and 30% more tillage operation is considered in CC_low (Bøe et al., 2019). If, however, the cover crop is harvested, we assumed 30% less tillage is needed in CC_high (Bøe et al., 2019). The termination of ryegrass, commonly practiced in Norway, typically involves glyphosate application (Bøe et al., 2020). The cover crop can be fully or partially harvested for feed and energy purposes, potentially reducing the need for glyphosate inputs. A 30% higher glyphosate inputs in considered in CC_low and 30% less in CC_high, based on Bøe et al. (2020). Management practices, site-specific conditions and cover crop species can impact positively or negatively the main crop yields. Reported main crop yields can be an increase by 7.8% (Vendig et al., 2023) or a reduction by 7% (Bøe et al., 2019), and these values are considered in the CC_high and CC_low sensitivities, respectively. The potential carbon sequestration is also affected by management practices, site specific conditions and crop species (Jian et al., 2020; Chaplot and Smith, 2023). SOC under cover crops management is reported as high as $480 \text{ kg C ha}^{-1}\text{yr}^{-1}$ (Qin et al., 2023), applied in CC_high, or as low as $210 \text{ kg C ha}^{-1}\text{yr}^{-1}$, considered in CC_low sensitivity (McClelland et al., 2020). Finally, the habitat quality considers habitat suitability for fields with continuous agriculture cover but does not account for effects of snow cover (Hu et al., 2023), which might negatively affect the habitat quality. We consider three months of snow cover, resulting in a 25% penalization of habitat quality in CC_low.

In the BZ scenario, trees and shrubs can provide biological competition for common plagues, resulting in 30% less input of agrochemicals in BZ_high (Blankenberg et al., 2017; Skarbøvik and Blankenberg, 2019), but they also may lead to increased use of agrochemicals due to more favorable habitat for insects and pests, leading to a 30% higher input of agrochemicals in BZ_low. Varying nutrient runoff rates are also considered, as the physical barrier that buffer zones offer reduce runoff, but it depends on tree species, root depth, aspect of the terrain and continuity. The default reduction of runoff considered for BZ is 90%, and a 30% higher runoff reduction benefit is considered in BZ_high and 30% lower in BZ_low (Cole et al., 2020). Different tree species and management impact on particles runoff and the reduction in soil erosion rates can vary from 32% (BZ_low) to 91% (BZ_high) (Blankenberg et al., 2017). The reduction in soil erosion and nutrient runoff, and increased carbon sequestration provided by the conservative management provides a more resilient crop production, securing or even increasing the yield in the long term (Du et al., 2022). A conservative 10% yield increase is considered in BZ_high, and we apply a 25% reduction of habitat

quality in BZ_low, consequence of 3-month snow cover during winter season.

3. Results and discussion

3.1. Environmental impacts

In general, the BZ scenario performs better than the CONV scenario across all environmental indicators except crop production, while CC delivers better indicators than CONV in all the cases but terrestrial acidification and crop production (Table S6). The better environmental advantages of CC relative to CONV are in carbon sequestration and habitat quality.

3.1.1. Soil erosion and terrestrial acidification

CC and especially BZ have the potential to reduce soil erosion rates compared to CONV (Fig. 2a). Soil erosion for CONV is $3.6 \text{ t ha}^{-1}\text{yr}^{-1}$ compared to $1.4 \text{ t ha}^{-1}\text{yr}^{-1}$ in BZ. Considering high and low efficiency sensitivities of particles runoff, the soil erosion ranges from $0.3 \text{ t ha}^{-1}\text{yr}^{-1}$ (BZ_high) to $2.4 \text{ t ha}^{-1}\text{yr}^{-1}$ (BZ_low). In CC, soil erosion is reduced by 20%, from $3.6 \text{ t ha}^{-1}\text{yr}^{-1}$ to $2.9 \text{ t ha}^{-1}\text{yr}^{-1}$. The variations for terrestrial acidification are less pronounced, with the BZ scenario that shows a 10% lower impact compared to CONV (Fig. 2b). Terrestrial acidification is reduced by 24% in CC_high compared to CC, primarily due to reduced tillage practices and reduced nitrogen fertilizer inputs.

3.1.2. Eutrophication

Relative to conventional agriculture, both CC and BZ reduce eutrophication impacts. BZ reduces marine eutrophication by 49% (Fig. 3a) and freshwater eutrophication by 48% (Fig. 3b). The trees in BZ can filter surface runoff, preventing nitrate, soil particles and phosphate leaching through waterways. These results are sensitive to the key uncertainties considered in the analysis. Varying runoff rates reduced marine eutrophication by 3% in BZ_high and increased by 3% in BZ_low compared to BZ scenario; although the runoff of nitrate is reduced, the fertilizer inputs remain the same as in BZ. The 48% reduction of freshwater eutrophication in BZ compared to CONV is explained by a reduced runoff of phosphate compared to CONV. The variations of freshwater eutrophication ranges from 4% reduction (BZ_high) to 4% increase (BZ_low), compared to BZ scenario, as there is no variation of phosphate fertilizer inputs. Comparing CC with CONV, marine eutrophication is reduced by 24%, mainly due to a reduction of nitrate runoff coming from ryegrass nitrogen uptake, and freshwater eutrophication by 1.5%, as cover crops does not affect phosphate runoff.

3.1.3. Toxicity

For human toxicity, BZ and CC resulted in 4.5% and 2.8% lower impacts than CONV, respectively (Fig. 4a). Variations in agrochemicals input led to a 11% increase in human toxicity impacts in BZ_low and a 11% reduction in BZ_high compared to the default BZ scenario. Human toxicity varies by 6% in both CC_high (reduction) and CC_low (increase) compared to CC scenario, due to changes in tillage practices.

The BZ scenario shows 10% lower impacts in freshwater ecotoxicity (Fig. 4b) compared to CONV. These reductions are essentially a consequence of the lower crop area due to the establishment of the buffer trees (10% of the original agricultural land), which result in fewer agrochemical inputs. These impacts are relatively similar for CC and CONV (variations are smaller than 1%) because these scenarios still share similar harvesting area, agricultural operations, and fertilizer application. Freshwater ecotoxicity is reduced by 3% in CC_high compared to CC scenario due to lower glyphosate inputs, and 4% in BZ_high compared to BZ scenario, due to a 30% reduction in all agrochemical's inputs.

3.1.4. Climate change

BZ shows 10% lower impacts than CONV, explained by the lower

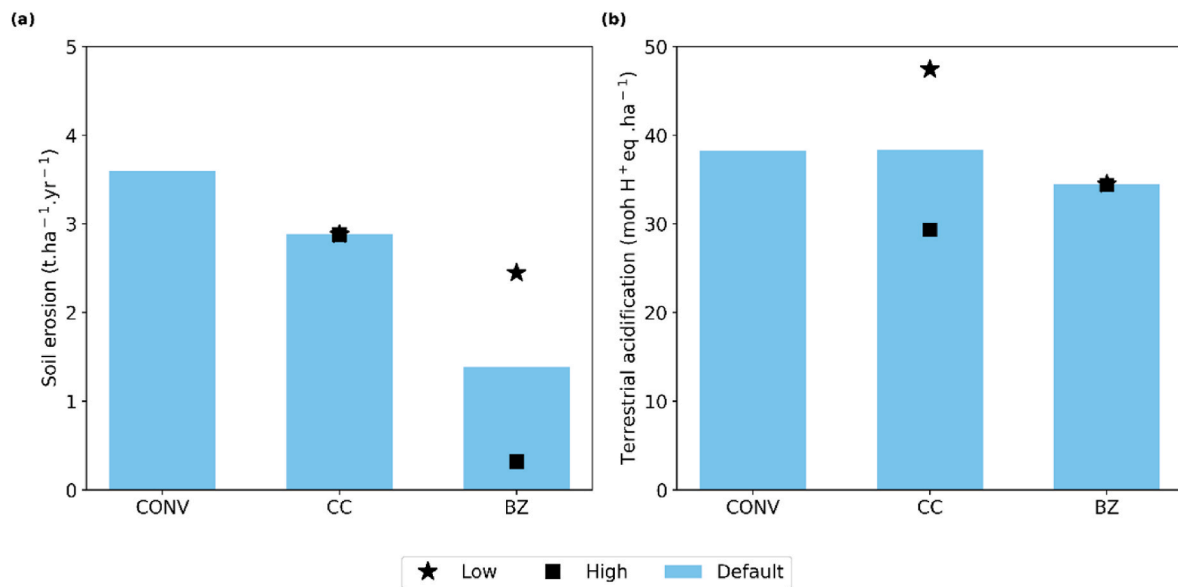


Fig. 2. Comparison of changes in a) soil erosion and b) terrestrial acidification for CONV, CC and BZ scenarios. Blue bars represent the default CONV, CC and BZ scenarios, which refer to average effects. The stars (low performance) and square (high performance) represent possible variations in key parameters of the effects induced by BZ or CC. Low performance indicates relatively lower benefits than those considered in the default case, e.g., lower reduction in soil erosion, higher inputs of fertilizers, agrochemicals, and tillage practices, reduced runoff benefits. High performance indicates higher reduction in soil erosion, lower inputs of fertilizers, agrochemicals, and tillage practices, and reduced runoff. Absolute values are shown in [Table S6](#).

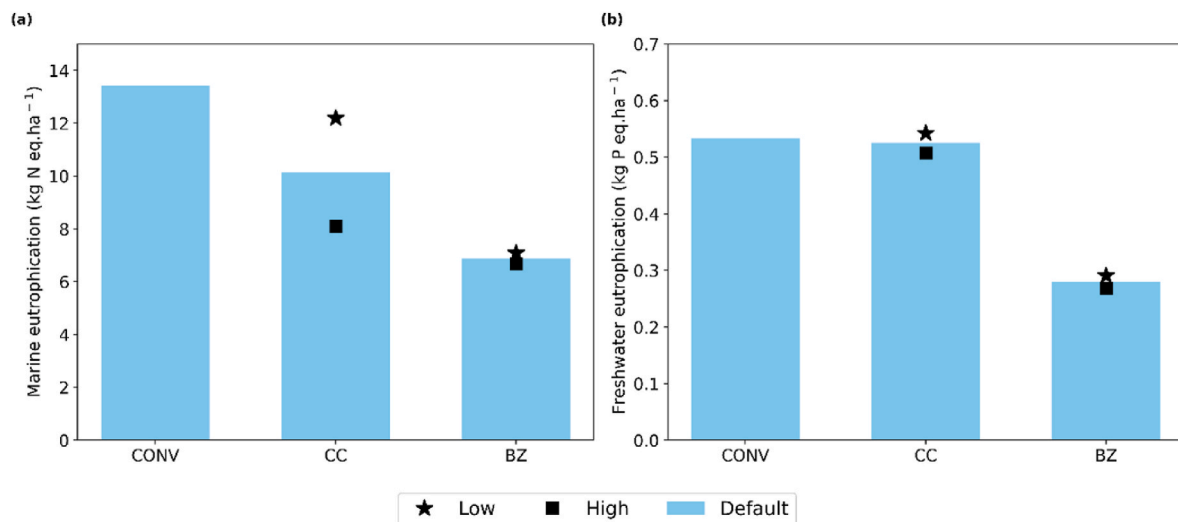


Fig. 3. Comparison of eutrophication impacts of CONV, CC and BZ scenarios for a) marine eutrophication and b) freshwater eutrophication. Blue bars represent the default CONV, CC and BZ scenarios, which refer to average effects. The stars (low performance) and square (high performance) represent possible variations in key parameters of the effects induced by BZ or CC. Low performance indicates relatively lower benefits than those considered in the default case, e.g., higher inputs of fertilizers, agrochemicals, and tillage practices, and reduced runoff benefits. High performance indicates lower inputs of fertilizers, agrochemicals, and tillage practices, and reduced runoff. Absolute values are shown in [Table S6](#).

area, while CC shows 2% lower impacts than CONV. In this case, some reductions in fertilizer inputs are compensated by additional seed inputs and increased glyphosate requirements, for example ([Fig. 5a](#)). Climate change increases by 16% in CC_{low} compared to CC, a result of combined increases of nitrogen fertilizers and tillage practices. The CC scenario sequesters the highest amount of carbon from the atmosphere ([Fig. 5b](#)), about $-320 \text{ kg C ha}^{-1}\text{yr}^{-1}$ thanks to the ryegrass that transfers carbon to the ground as SOC once terminated. Although trees have a higher potential to sequester carbon than cover crops, only 10% of the total area is used as a buffer zone, so BZ scenario sequesters $-153 \text{ kg C ha}^{-1}\text{yr}^{-1}$ of which 76% are from above ground biomass (trees growth) and 24% from SOC. In CC_{high}, carbon sequestration increases 50%

compared to CC, reaching $-480 \text{ kg C ha}^{-1}\text{yr}^{-1}$, but it is reduced by 34% ($-210 \text{ kg C ha}^{-1}\text{yr}^{-1}$) in CC_{low}.

3.1.5. Habitat quality

CC provides the best habitat quality ([Fig. 6](#)) with a score of 0.14, against 0.12 and 0.11 for BZ and CONV, respectively. The ryegrass provides a diverse and dense vegetation cover that creates a suitable habitat and refuge for insects, birds, and small mammals, which is an advantage relative to the bare ground in winter times of conventional farming ([Blanco-Canqui et al., 2015](#)). The cover crop root system also improves soil health and quality, by promoting soil structure and aeration that indirectly support biodiversity by providing a favorable

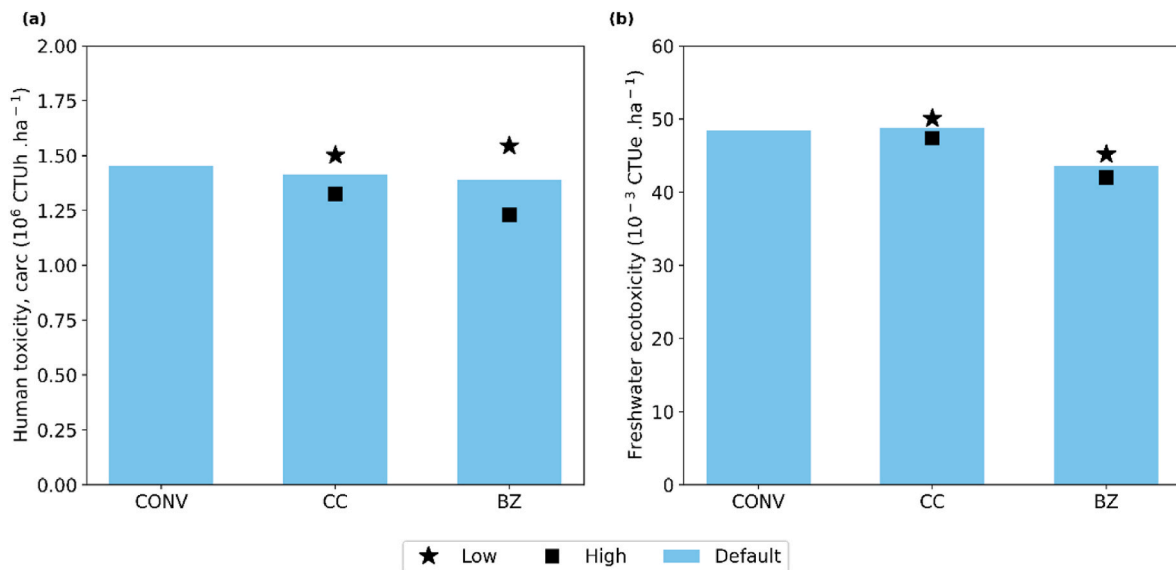


Fig. 4. Comparison of the toxicity impacts of CONV, CC and BZ scenarios for a) human toxicity, carcinogenic and b) freshwater ecotoxicity. Blue bars represent the default CONV, CC and BZ scenarios, which refer to average effects. The stars (low performance) and square (high performance) represent possible variations in key parameters of the effects induced by BZ or CC. Low performance indicates relatively lower benefits than those considered in the default case, e.g., higher inputs of fertilizers, agrochemicals, and tillage practices, reduced runoff benefits. High performance indicates lower inputs of fertilizers, agrochemicals, and tillage practices, reduced runoff. Absolute values are shown in Table S6.

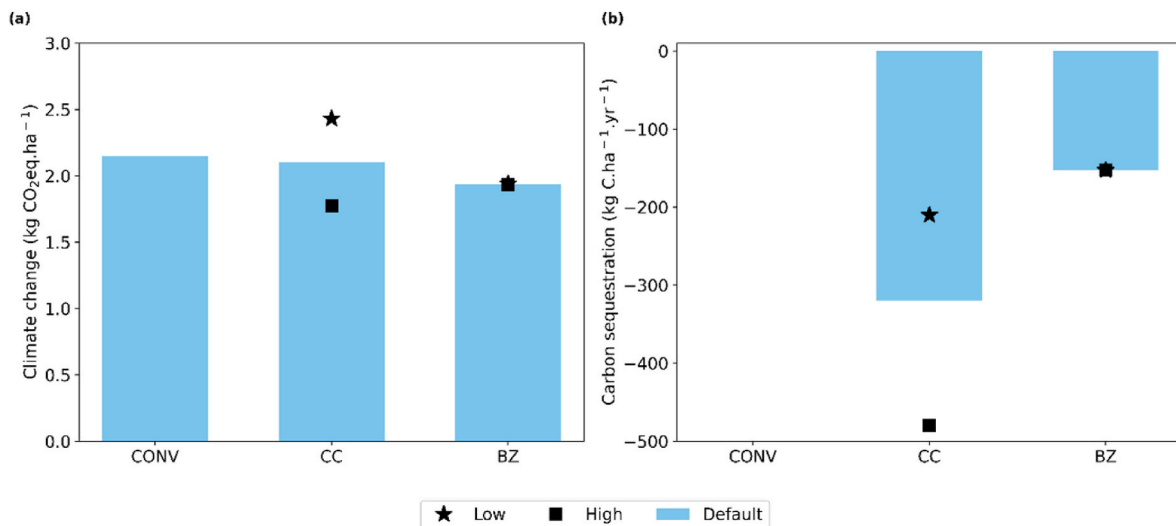


Fig. 5. Comparison of CONV, CC and BZ scenarios for a) global warming potential indicator and b) carbon sequestration potentials. Blue bars represent the default CONV, CC and BZ scenarios, which refer to average effects. The stars (low performance) and square (high performance) represent possible variations in key parameters of the effects induced by BZ or CC. Low performance indicates relatively lower benefits than those considered in the default case, e.g., higher inputs of fertilizers, agrochemicals, and tillage practices, and lower benefits in terms of carbon sequestration. High performance indicates lower inputs of fertilizers, agrochemicals, and tillage practices, and increased carbon sequestration rates. Absolute values are shown in Table S6.

environment for soil organisms (e.g., worms, bacteria, and fungi) (Wang et al., 2021). The latter also play critical roles in water and nutrient uptake, nutrient cycling, and ecosystem functioning (Schipanski et al., 2014). In BZ, trees can potentially improve biodiversity (Cole et al., 2020), as they can act as a vegetation corridor for amphibians and small and large mammals (Lind et al., 2019), reduce fragmentation, and improve humidity, and directly favor habitat conditions for moss, lichens, and mushrooms (Blankenberg et al., 2017). Tree leaves are essential feed for aquatic species and provide shades that moderate the temperature in the waterways, benefiting aquatic life and the microclimate (Cole et al., 2020). Accounting for snow cover reduces habitat quality by 25% in CC_{low} and BZ_{low} compared to the default CC and BZ scenarios; however, winters are expected to be milder in the Nordics

under global warming, thus lesser snow cover is expected in the long-term.

3.1.6. Crop production

The CONV scenario only performs better than CSA practices for crop production, with barley yields at 4.2 t ha⁻¹yr⁻¹. The CC and BZ scenarios result in 3% and 10% lower production, respectively. In CC_{high}, cover crops increase barley yield by 8%, reaching 4.5 t ha⁻¹ yr⁻¹, outperforming CONV yields. Conversely, in CC_{low}, barley yield declines to 3.9 t ha⁻¹ yr⁻¹. The introduction of BZ in cropland can provide long-term yield benefits, e.g., thanks to reduced nutrient runoff and soil erosion. In BZ_{high}, barley yields reach 4.0 t ha⁻¹ yr⁻¹, compared to 3.8 t ha⁻¹ yr⁻¹ in BZ scenario.

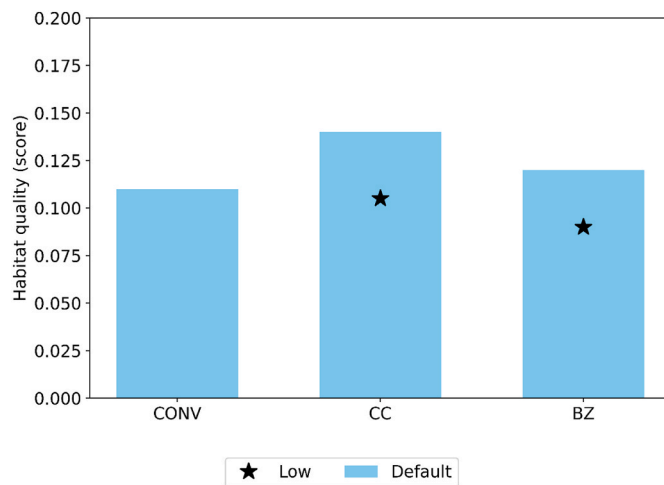


Fig. 6. Comparison of habitat quality of CONV, CC and BZ scenarios. Blue bars represent the default CONV, CC and BZ scenarios, which refer to average effects. The stars (low performance) represent snow cover during winter, that can potentially reduce habitat quality. Absolute values are shown in Table S6.

The use of a functional unit based on food production instead of hectare of land usually shows lower benefits of CSA practices relative to the conventional farming scenario, which has the highest yield (Table 1, where a positive value of the Gap index indicates that the environmental impacts of the given scenario, relative to CONV, are higher with a production-based functional unit). The difference for CC (Gap_{CC}) is around 3% for freshwater ecotoxicity, freshwater eutrophication, human toxicity, terrestrial acidification and climate change, reflecting the yield reduction in CC scenario compared to CONV. Similarly, the Gap_{BZ} for freshwater ecotoxicity, human toxicity, terrestrial acidification, and climate change is close to 10%, which reflects the yield reduction in BZ scenario.

However, for marine eutrophication, habitat quality and soil erosion, the Gap_{CC} ranges from −3.9% to 2.5%, and for freshwater eutrophication, marine eutrophication, habitat quality and soil erosion Gap_{BZ} ranges from −12.1% to 5.8%. This means that in these cases there are more parameters that influence the impacts, and not only the yield reduction. These environmental impacts are integrated with ecosystem services directly associated with land. For example, reduced runoff, which is linked to the area rather than production, directly impacts marine and freshwater eutrophication; similarly, soil erosion reduction is directly associated with the area.

Although the environmental performance of BZ scenario is better than CONV scenario for both FUs, the benefits of BZ are on average 25% better than CONV when using area-based functional unit but decrease to 20% when a product-based functional unit is used. For CC,

improvements compared to CONV are on average 10% better for the area-based functional unit and 8% for product-based functional unit. The choice of functional unit significantly impacts the environmental performance of CC compared to CONV. When using area-based functional unit, only terrestrial acidification and freshwater ecotoxicity impacts of BZ scenario are higher than CONV (−0.3% and −0.5%, respectively). However, with the product-based functional unit, three more categories are negatively impacted for BZ scenario, including freshwater eutrophication (−1.6%), human toxicity (−0.2%) and climate change (−0.8%). These results align with other findings from previous studies. Meier et al. (2015) found that organic products have up to 67% lower environmental impacts than conventional agriculture when considering an area-based functional unit, but this difference ranged from 38% lower impact to 53% higher impact compared to conventional agriculture when using a product-based functional unit. Similarly, Tuomiso et al. (2012) reported environmental impacts that were 18%–34% lower than conventional agriculture when using area-based functional unit but 8%–11% higher with a product-based functional unit.

3.2. Barriers to implementation

Buffer zones and cover crops are effective CSA strategies for providing ecosystem services and enhancing climate adaptation in the Nordic countries. However, their implementation faces significant challenges. The main barriers and potential solutions are summarized in Table 2. Barriers include concerns about reduced main crop yields, the need for additional field operations and management, and a lack of economic incentives. Potential solutions include better CSA management practices, payments for ecosystem services, and government incentives.

Policies that jointly target climate change mitigation and adaptation, securing ecosystem services and area-unit management can achieve larger environmental benefits. However, most agricultural policies are today oriented towards productivity as they typically target national food security and incomes of rural areas, with little or no consideration of environmental benefits. Alternative incentive mechanisms should be explored to support a transition towards multifunctional landscapes that reduce environmental impacts of agriculture and increase the delivery of multiple ecosystem services. There are approaches aiming at stimulating new financial frameworks centered on ecosystems services for the governance of agricultural land that have been proposed (Gawith and Hodge, 2019; Pe'er et al., 2020), including methods for monetization of the natural capital and ecosystem services (Brander et al., 2024). Implementing these solutions requires establishment of robust methods to account for effects at a landscape level (cropland plus trees) and to characterize the different services (crop, climate resilience, biodiversity, carbon sequestration, etc.) that are delivered by different management strategies. Coordinated efforts are needed to meet multiple objectives in

Table 1

Comparison of environmental impacts of climate-smart agriculture (cover crops (CC), and buffer zones (BZ)) relative to conventional production (CONV) when using area-based (FU: 1 ha) or product-based (FU: 1 kg) functional units. Negative values mean an increase of impacts compared to CONV scenario. For habitat quality, the higher the better, so 27.3% and 31.2% are positive. The indices Gap_{CC} or Gap_{BZ} refer to the difference of CC and BZ relative impacts compared to CONV when using the two different functional units (Eqs. S1 and S2). A positive value means that the production-based functional unit resulted in higher relative impact than when using area-based functional unit. CONV has no carbon sequestration, thus not possible to present CC and BZ relative impacts.

Environmental Indicator	Soil Erosion	Terrestrial acidification	Marine eutrophication	Freshwater eutrophication	Freshwater ecotoxicity	Human toxicity	Climate change	Habitat Quality
Comparison of CC and CONV scenario								
FU: 1 ha	20.0%	−0.3%	24.3%	1.5%	−0.5%	2.8%	2.3%	27.3%
FU: 1 kg	17.5%	−3.4%	22.0%	−1.6%	−3.7%	−0.2%	−0.8%	31.2%
GapCC	2.5%	3.1%	2.3%	3.0%	3.1%	3.0%	3.0%	−3.9%
Comparison of BZ and CONV scenario								
FU: 1 ha	61.5%	10.0%	48.7%	47.5%	10.1%	4.5%	10.0%	−9.1%
FU: 1 kg	57.2%	0.0%	43.0%	41.6%	0.1%	−6.2%	0.0%	−21.2%
GapBZ	4.3%	10.0%	5.7%	5.8%	10.0%	10.6%	10.0%	12.1%

Table 2

Potential barriers of a wider implementation of CSA in Norway and possible solutions.

Indicator	Barrier	Solution
Cover crops		
Economic	•The low risks of yield reductions of main crop can lower the farmer income (Fuglie et al., 2023; Lobell and Villoria, 2023). •Cover crops add costs to the farmer but do not provide immediate economic returns (e.g., additional machinery and labor) (Daryanto et al., 2019; Lee and McCann, 2019).	•Subsidies to compensate the economic losses (Daryanto et al., 2019). •Payment of ecosystem services (Daryanto et al., 2019; Cook et al., 2016). •Harvesting the cover crop for animal feed or bioenergy purposes (Roesch-McNally et al., 2017). However, Norway has a limited timeframe for cover crop harvesting, and this requires feasibility assessments.
Management	•Cover crops can return as weed on the following year (Bøe et al., 2020). •Additional labor and operations on the field (Lee and McCann, 2019; Roesch-McNally et al., 2017). Part time farmers are less likely to adopt cover crops, due to less available time for this additional labor and field operations (Lee and McCann, 2019).	•Improved termination practices and/or cover crop harvesting (Thompson et al., 2021). •Adoption of CSA can be easier for farms already applying other conservative practices (e.g., no tillage, different crops) as they probably already have the necessary equipment (Lee and McCann, 2019).
Know-how	•Lack of knowledge of cover crop implementation, management and impacts among the farmers and producers (Daryanto et al., 2019). •Fear of adverse effects due to lack of information.	•Government and non-governmental organizations providing information campaigns and education (Thompson et al., 2021). •More research and dissemination on the long-term ecosystem services provided by cover crops (Daryanto et al., 2019; Thompson et al., 2021).
Climate	•Norway has a short growing season with limited sunlight in fall and winter (Bøe et al., 2020). •Competition for water (Lee and McCann, 2019).	•Selection of cover crops that are more adapted to Norwegian climate (Bøe et al., 2020).
Buffer zones		
Economic	•Reduction on main crop yields, due to reduction in the production area. •No economic gains from buffer zones (e.g., extraction and harvest of biomass) (Blankenberg et al., 2017).	•Long term yield benefits (Du et al., 2022). •Payment of ecosystem services (Cook et al., 2016). •Implementation of agroforestry (fruit trees) as buffer zones that can provide economic returns (Riis et al., 2020).
Know-how	•Lack of knowledge of buffer zone implementation, management and impacts among the farmers and producers (Skarbøvik and Blankenberg, 2019).	•Government and NGOs can provide information campaigns, and education. More research on the long-term ecosystem services provided by buffer zones (Blankenberg et al., 2017).
Management	•Natural regrowth and non-managed buffer zones might not be enough to provide ecosystem service, as buffer zone length, size and density influence on ecosystem services (Kumwimba et al., 2023; Lind et al., 2019).	•Planted and managed trees (Fortier et al., 2015). •Integrate buffer zones with other agriculture practices that can address the specific issues of the cropland (Zomer et al., 2016).
Climate	•Low temperatures can reduce tree growth rates and the effectiveness of buffer zones to provide ecosystem services (Kumwimba et al., 2023).	• Natural regrowth will result in native and adapted tree species. If managed, selection of trees over crops that are adapted to Norwegian

Table 2 (continued)

Indicator	Barrier	Solution
		climate is key, and fertilization can stimulate growth (Skarbøvik and Blankenberg, 2019).

agriculture, such as securing crop yield, sustainable water use, flood management, wildlife conservation and increase carbon storage above and below ground, by balancing marketed and non-marketed products. Integrating ecosystem services into a carbon pricing scheme can promote more sustainable agriculture, for instance by making carbon sequestration into agricultural landscapes a core asset of farmer incentives. In general, increasing carbon in vegetation and soils is a driver for inducing co-benefits to multiple ecosystem services, such as nutrient/water retention, biodiversity and climate regulation. Financial support can be given to farmers embracing strategies that increase the carbon stored in soils and vegetation (e.g., via buffer zones and cover crops), prioritizing those in areas where ecosystem services are declining and securing long-term yields is challenging. The funds can be taken from re-investing profits from global GHG emission pricing.

A clear and transparent accounting and reporting system for ecosystem services is necessary, which can be developed in similarity with the current mechanisms that are used by countries to report their GHG emissions to the United Nations Framework Convention on Climate Change. Overall, each transition brings risks of conflicts between (and among) sustainability challenges and society if poorly planned. Because the adoption of more sustainable agricultural practices can induce short-term trade-offs, as shown in this study, the long-term benefits should be clearly communicated to farmers and be inclusive. Norway had an incentive program that included widespread information of CSA benefits to farmers and some economic incentives, which has brought to the adoption of cover crops on approximately 4% of agricultural land (Aronsson et al., 2016). Further stimulating these initiatives is key to support the deployment of more sustainable practices in agriculture.

3.3. Study limitations

Future studies should better explore the implications of specific plant species and management practices of CSA in the Norwegian context. Harvesting the cover crop and establishing tree fruits as buffer zones have the potential to generate additional economic gains from biomass residues from tilling operations and fruit selling. Different plant species for cover crops and buffer zones can expand the range of environmental benefits provided beyond those considered in this analysis. Legume cover crops can fix nitrogen and are a valuable nitrogen source for subsequent crops (Blanco-Canqui et al., 2015), improving grain yields (Abdalla et al., 2019). A managed buffer zone with selected trees species and fertilization instead of natural regrowth can improve ecosystem carbon storage (Fortier et al., 2015), as trees species impact the efficiency of carbon sequestration and plant growth, which in turn affects nutrient runoff and habitat quality (Chapman et al., 2020; Zomer et al., 2016).

Our analysis is subject to multiple uncertainties, of which the most relevant have been explored in a sensitivity analysis. Other limitations exist, such as the simplified phosphorous balance that does not consider the phosphorous available in the soil or the potential reduced phosphorus losses associated with the reduction in soil erosion (Carver et al., 2022).

Beyond the ones considered in this study, other benefits of CSA over conventional systems can be explored. Cover crops and buffer zones can improve water quality by reducing runoff and associated eutrophication (Hanrahan et al., 2021), improve water retention in the soil and increase the water availability for the crop (Kaye and Quemada, 2017). Buffer zones can provide flood protection. The forest soil and roots around the

river works like a sponge and prevents water on the surface from reaching the waterways, and floodwater is delayed as it flows between tree trunks, in contrast to when water is allowed to flow freely (Rusch, 2012; Daryanto et al., 2018).

4. Conclusion

This study assessed the environmental benefits of climate-smart agriculture practices (such as cover crops and buffer zones) in Norway by incorporating ecosystem services into life cycle assessment and comparing the environmental outcomes against conventional agriculture using two alternative functional units, one based on crop production and the other on land area. The implementation of buffer zones is a measure to retain soil nutrient and water content, provide flood protection, and increase carbon sequestration below and aboveground. Its deployment shows better environmental performance compared to conventional farming under both functional units, with the only exception being crop production, where conventional scenario performs better. In particular, major benefits occur for marine eutrophication, soil erosion and freshwater eutrophication (up to 64% lower) due to high reduction of nutrients and soil particle runoff, thereby helping to alleviate a local environmental aspect of growing concern such as the eutrophication of the Oslo Fjord and the soil degradation of the region. The integration of cover crops into the annual growing cycle is a main solution to habitat quality, which can improve by more than 31% compared to conventional agriculture, due to a dense and diverse vegetation as opposed to the bare soil typically found in conventional farming practices.

For a fair comparison of climate-smart agriculture against conventional agriculture, it is important to assess both area and product units. In general, assessing environmental performances only normalized to production volumes disfavors climate-smart agriculture, since the multiple benefits of this practice better emerge when looking at impacts per area.

Although the incorporation of buffer zone results in a 10% reduction in barley production, the increased environmental benefits can be used as arguments to support a transition to more sustainable agricultural systems where crop yields, despite potential short-term declines, are more secure and climate resilient in the medium-to long-term.

The broad implementation of cover crops and buffer zones in the Norwegian agricultural sector can enhance its resilience to climate change while simultaneously contributing to ecosystem services. While climate-smart agriculture offers significant environmental advantages, concerns about reduced main crop yields, additional management practices, lack of know-how by farmers, and poor policy supporting schemes pose barriers to its widespread adoption. However, these barriers can be overcome with clear governance and engagement of stakeholders at different levels (from farmers to local authorities and society in general). Incorporating ecosystem services into life cycle assessment studies of agricultural systems is a way by which the scientific community can contribute to bring scientific evidence in support of the shift to sustainable land use systems that contribute to climate change mitigation and adaptation.

CRedit authorship contribution statement

Narié Rinke Dias de Souza: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Marte Kristiane Mohn Solberg:** Writing – original draft, Investigation, Formal analysis, Data curation. **Xiangping Hu:** Methodology, Investigation. **Francesco Cherubini:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2025.124633>.

Data availability

Data is provided as supporting information.

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