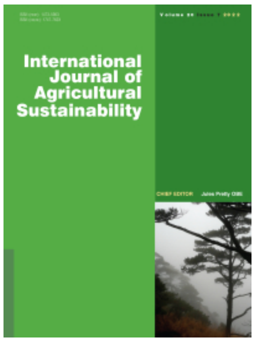
The carbon footprint of Conservation Agriculture



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The carbon footprint of Conservation Agriculture

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ABSTRACT

Proponents of Conservation Agriculture (CA) believe that by not tilling the soil, climate-friendly agriculture is achieved by reducing greenhouse gas emissions from agriculture and by storing atmospheric carbon in the soil. However, some scientists question climate benefits of CA. Literature shows that carbon storage through soil organic carbon (SOC) accumulation of up to 1 t ha^{-1} y^{-1} is possible without increasing nitrous oxide (N_2O) emissions under a CA system. Opposing studies were flawed by analysing not complete CA systems and leaving out some of the principles. It is shown that each tillage operation releases up to 300 kg carbon dioxide equivalents (CO_2e) per hectare, and each of the average annual 10 t ha^{-1} of eroded topsoil can emit additional 300 kg CO_2e ha^{-1}. A case study in Germany confirms these findings that with full application of CA the carbon footprint of agricultural food production can be significantly decreased, helping to mitigate climate change. It is concluded that net soil carbon storage is possible if all the principles of CA are consistently implemented. It is also concluded that together with other complementary production measures, CA has the potential to make agriculture carbon neutral.

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KEYWORDS
No-till; soil erosion emissions; tillage emissions; soil organic carbon accumulation; climate change mitigation

1. Introduction

'How we treat land, how we treat the soil, is fundamental to the health and survival of modern civilization', writes David Montgomery in his book *Dirt* (Montgomery, 2010).

More clearly: Humanity's existence is based on an average of 20 centimetres of fertile topsoil on which to live and grow food. But every year, more than 24 billion tons of soil are lost worldwide through erosion. This corresponds to an area of 12 million hectares (0.8% of available agricultural land) where deserts form because the fertile topsoil is completely eroded (Pimentel et al., 1995; UNCCD, 2011). Soil removal by water and wind, which the word erosion describes, results in a global average erosion loss of 16 t·ha^{-1} y^{-1} (Biggelaar et al., 2004). Estimates for erosion losses in Germany are somewhat lower at 1–10 t·ha^{-1} annually. In the same time, however, only a few kilograms to a maximum of 1 t ha^{-1} of soil are newly formed (Bundesverband Boden e.V., 2014; LRA Biberach, 2018). The balance is therefore clearly negative worldwide. With an average annual erosion loss of 10 t·ha^{-1} and a crumb depth of 20 cm, only about 200 years remain until the fertile topsoil of the currently used agricultural cropland in Germany will be completely eroded and become unsuitable for food production. On a global average, we have 125 years left if no more new land was added (UNCCD, 2011).

Agricultural practices in tillage are responsible for erosion: uncovered pulverized top soil from tillage makes the land surface vulnerable to wind and

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water erosion (UBA, 2020). Farming systems without tillage could fight the erosion and land degradation. Conservation Agriculture (CA) is such a sustainable farming system, which is defined by three principles (FAO, 2017):

1. **Continuous no or minimum mechanical soil disturbance** by no-tillage and direct seeding. Soil disturbance may be a maximum of 15 cm wide when opening the soil surface for seeding, or a maximum of up to 25% of the surface area disturbed.
2. **Permanent soil mulch cover** with plant biomass and cover crops on at least 30% of the surface area.
3. **Crop diversity** through crop rotations or associations, ideally with at least three crops.

These interlinked principles in CA systems, when applied together with locally adapted complementary practices of integrated crop, soil, nutrient, pest, water, energy and machinery management, offer a large range of productivity, economic, environmental and social benefits globally to farmers, their communities and society in general (Kassam, 2020; Lal, 2022; Reicosky & Kassam, 2022). CA systems are regenerative, resilient and self-protecting. In functionally degraded agricultural soils under use, they build soil organic matter and restore and sustain soil health and functions upon which soil productivity and ecosystem services depend (Corsi et al., 2012; González-Sánchez et al., 2017, 2019; Sá et al., 2020). For agricultural lands that have been abandoned for their use for cropping, CA systems can help to rehabilitate and restore them (Amado et al., 2020).

Globally, more than 200 million hectares of annual cropland are farmed according to these CA principles, with 50% of the area located in the North and 50% in the South. For example, in South America more than 60% of the annual cropland is under CA systems. In Europe, several countries such as Spain, Italy, France and the UK have transformed a significant cropland area into CA. However, in Germany CA is spread among only a few farmers (Kassam, 2015; Kassam et al., 2022).

Agriculture in Germany accounts for around 14% of the national greenhouse gas emissions (GHGE) and is therefore called upon to identify and exploit potential for reduction (Don, 2022). CA has the potential to reduce GHGE more than just the emissions reduced by avoiding tillage operations. CA can conserve carbon that is present in the soil by minimizing SOM oxidation resulting from minimum soil disturbance (no-till). CA can add to the soil carbon storage from crop biomass being retained on the ground as surface mulch cover to be incorporated into the soil by microorganisms, and from root and microbial biomass as well as from root exudates.

Thus, the ability of CA systems to increase SOC over time has been shown in several reviews and meta-analyses such as Corsi et al. (2012), González-Sánchez et al. (2017, 2019); Sá et al. (2020); Amado et al. (2020); Reicosky and Kassam (2022). Further, Alberta, Canada, has been running an agricultural carbon offset trading scheme based on CA land use that was initiated even before the COP 3 in Kyoto at which the target to limit temperature increase was agreed (Kassam et al., 2020).

However, there have been concerns expressed about the climate change mitigation benefits of no-till systems from a 'scientific' perspective. For example, a meta-study of no-till trials worldwide found no significant increase in SOC storage implying that there is no carbon removal from the atmosphere under no-till systems (Don & Jantz, 2013). Other meta-analyses conducted such as by Pittelkow et al. (2015) and Corbeels et al. (2020) have produced mixed results that cast doubts on the positive carbon storage potential reported in reviews and meta-analysis mentioned earlier. However, in these two meta-analyses, the authors admit that the data used covered a mixture of no-till systems which were not always based on the three principles of CA. In the case of the Pittelkow et al. (2015) study, data from conservation tillage studies were also used which meant that some of the data that was included was not from no-till systems. The study by Corbeels et al. (2020) did indicate that when the data was from CA systems, climate benefits were present. In addition, the meta-analysis conducted by Don and Jantz (2013) suggests that there is a risk that no-till systems cause N_2O emissions, making the carbon footprint of no-till cropping systems significantly worse than that of tillage-based cropping systems. However, this is not supported by studies on CA systems and N_2O emissions.

Given the existence of the above-described inconsistency in the analyses related to the climate mitigation impact of different soil management concepts, this paper thoroughly analyses the existing scientific evidence on the climate-relevant components of no-till systems, in particular CA systems. It attempts to answer the question, whether products originating from CA production systems have a smaller carbon footprint than products from tillage-based production systems.

The objectives of this work reported herein were to: (1) identify which climatic effects of no-till systems have been scientifically proven so far; (2) explain the cause for the existing ambiguity in the literature regarding the climate-relevant effects of tillage; and (3) verify the hypothesis with a model using data of a German farm, with the limitation that CA production systems in Germany are rare and very few farms have practiced CA long enough to permit drawing definite conclusions.

2. Methods

2.1. Literature research

The aim of the literature review was to find out the current state of knowledge about GHGE after tillage, SOC build-up and N_2O emissions under CA and prevention of soil erosion. The review data helped in the subsequent calculation of the CO_2 footprint. Information from books and professional journals from the university library was used. Also, Google was used for information from company websites and Google Scholar for scientific journals and papers. Particular attention was paid to the methodology used in the papers studied to allow an accurate differentiation of the results in terms of their validity for CA, no-till, and tillage systems. For the research on N_2O emissions in cropland under CA, 88 papers were reviewed. The review began with the 50 papers that had been examined by Don and Jantz (2013) and provided by Axel Don. Subsequently, the database was enlarged by additional 38 papers. For this, publications on the topic were searched on Google Scholar using the keywords N_2O, nitrous oxide, Conservation Agriculture and no-tillage. In selecting the papers, care was taken to ensure that the papers had investigated CA systems. Papers on grassland or on wetland rice systems did not correspond to the focus of the review and were not included in the review.

2.2. Calculation of the CO_2 footprints

The Cool Farm Tool (CFT) was used to calculate the carbon footprint of the Frese farm in Homburg (Efze), Germany. On 160 ha of cropland and 60 ha of grassland they are producing corn and silage as feed for 135 dairy cows and wheat and rapeseed as food crops. This farm was selected because the manager Mario Frese wants to become a pioneer in carbon neutral farming. To become carbon neutral the emissions from the dairy cows have to be reduced and as much as possible carbon has to be stored in his croplands to offset the rest of the emissions from the dairy branch of the farm. How his recent tillage-based cropping system has to be changed to achieve carbon storage was his task that led to this study.

The CFT is an online application for calculating the carbon footprint of agricultural products for farmers. Input masks are used to request information on crop and crop management, soil, fertilization and pest management, energy, fuel and water use, irrigation, soil carbon balance, and transportation routes, sorted by super-topic. The user or farmer must determine this information and figures on a farm-specific basis and enter it into the CFT. The programme calculates a value for the release of CO_2 equivalents (CO_2e) during production. In this work, the carbon footprints were calculated for three different crops of the Frese farm, each for an average farmed hectare. This was done by summing the inputs on all hectares of each crop in 2021 and dividing by the total hectares. The data was taken from the farm database.

As the CFT is a simplified application for practitioners, not all emissions relevant to this work could be calculated in sufficient detail. Therefore, the carbon footprints calculated by the CFT were exported to an Excel spreadsheet and manually completed with the missing values for emissions from tillage and erosion, and carbon storage from humus formation, as determined from the literature research. Based on the carbon footprint of the Frese farm, two scenarios were created to evaluate the impact of CA practices.

Microsoft Excel was then used to create the graphs. All carbon footprints are reported in units of $CO_2e\ ha^{-1}$. Typically, carbon equivalents emitted are reported per ton of finished product like litre of milk or kilo of meat. However, since the Frese farm is aiming to become CO_2-neutral on its cropland, or even to offset the emissions from the dairy business with a carbon sink on the cropland, it is more meaningful to present the emissions per hectare of each crop in this paper.

The question arose as to the limits of including indirect emissions that are not generated on the farm but are caused by the farm's actions. For example, the emissions caused by the production of

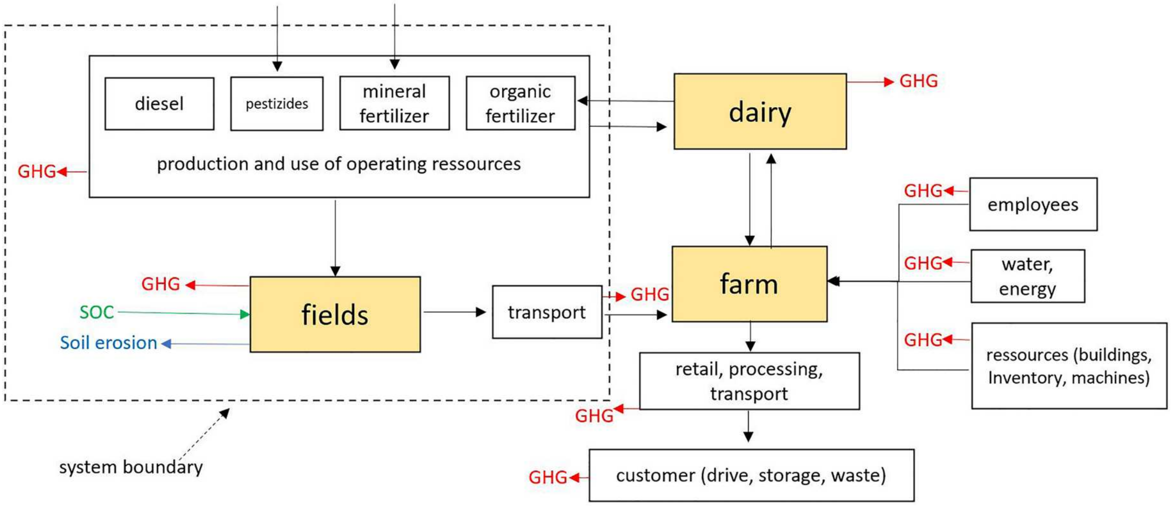

Figure 1. System boundary for the calculation of the CO_2 footprint.

mineral fertilizers and machinery. In this work, only direct emissions caused by field operations are considered. Data on indirect emissions, such as those from the manufacturing of fertilizers and pesticides, are partially included in the CFT, but they are not from the production of fuel and from the preparation and storage of organic fertilizers. The inclusion of these data would have exceeded the capacity of the actual research project and should be the subject to further studies.

Figure 1 illustrates that the actions of the company as a whole, but also of other actors within the product life cycle, cause further emissions that would have to be at least partially accounted for in carbon footprints of individual end products. The system boundary drawn there in the sketched product life cycle represents the observation framework of this work.

2.3. Farm data

Data for the calculation of the carbon footprints, such as machinery use, fertilizer types and amounts, pesticide use, and yields, were taken from the farm's database. Because the farm does not document fuel consumption, the consumption was estimated using the KTBL's field work calculator (KTBL, 2022). The data on the erosion hazard of the site comes from the erosion cadastre of the HLNUG (2022). The German general soil erosion equation (ABAG) was used to estimate the amount of soil eroded annually by precipitation water (Schwertmann et al., 1987).

For the 'CA after 20 years' scenario, data were taken from the literature and verified with experience from various practitioners in Germany.

3. Results

3.1. Synthesis of the literature

3.1.1. CO_2 emissions from soil tillage

Carbon stored in the soil is protected from oxidation and degradation by soil aggregates. Tillage destroys the soil aggregates and increases the number of air-filled pores in the soil. As a result of this increase in aeration, the unprotected carbon oxidizes and escapes in the form of CO_2 (La Scala et al., 2008). In a three-year field trial in Iowa, emissions were measured over 20 days after various tillage operations. The loamy soil had a SOC content of 2.9% and the crop rotation consisted of grain, corn and soybeans. In the third year of the experiment, a total of 300 kg CO_2 ha^{-1} was emitted from the soil after 20 days in the system without tillage and with crop biomass cover. In the systems involving cultivator and plough, emissions were 415 kg CO_2 ha^{-1} and 511 kg CO_2 ha^{-1} respectively (Mahdi & Xinhua, 2005). A similar trial was conducted over a five-year period at three experimental sites in Minnesota and Brazil on soils with 1.1% to 3.2% SOC. Soybean, corn, wheat, and sugarcane were grown. La Scala et al. (2008) obtained very similar results: For the Minnesota experiment, approximately 250 kg CO_2 ha^{-1} were found within 25 days in the no-till system. In the systems with power harrow and cultivator it was 430 and 530 kg CO_2 ha^{-1} respectively. Measurements on an area in Brazil showed that the emission values of plough and no-till only converge after 90 days. Consequently, no-till can be expected to save between 200 and 300 kg CO_2 ha^{-1} within 25 days. Over the entire year, it could be three to four times as much. Conversely, this means that tillage releases between 100 and 300 kg CO_2 ha^{-1} from the soil in 25 days, depending on depth and intensity, which should be considered in a carbon footprint but have been disregarded in previous carbon footprints.

3.1.2. SOC build-up under Conservation Agriculture

Many studies on the influences of reduced tillage and no-till on SOC build-up have been made. In the fall of 2021, two papers from Zinke (2021a, 2021b) on meta-studies by the University of Basel, Switzerland and the Thünen Institute in Braunschweig, Germany caused a great deal of interest and discussion among farmers and scientists in Germany (Don & Jantz, 2013; Xiao et al., 2021). Both meta-studies concluded that reduced tillage does not lead to significant SOC build-up compared to ploughing and that the positive climate effects of the reduction are therefore overestimated. Don and Jantz (2013) in their meta-study found an average increase of 40% in N_2O emissions under 'no-till' compared to tilled soils and therefore assumed that cropping systems without tillage are more climate damaging than those with tillage. However, both Xiao et al. (2021) and Don and Jantz (2013) emphasized that the retention of crop biomass on the field played a greater role in SOC build-up than the type of tillage.

With few exceptions, the papers have one characteristic in common and that is the studies analysed did not consistently implement the three principles of CA in the field trials: Either diverse crop rotation and no-tillage or permanent ground cover were missing (Don & Jantz, 2013; Xiao et al., 2021). However, according to Derpsch (2008) and Baker et al. (2007), the positive effects of no-till do not set in until at least no-till and permanent soil cover are implemented together. Govaerts et al. (2009) also summarized in a literature review that a diverse crop rotation and crop biomass soil cover have a positive effect on soil organic carbon storage. Of the 78 field trials studied, only 40 showed an increase in soil organic carbon levels when no-till was used compared to conventional tillage, 31 showed no change and 7 showed a decrease. (Govaerts et al., 2009) A meta-study by Ogle et al. (2005) investigated the influence of tillage and carbon input on SOC content under different climatic conditions. It was shown that the amount of SOC accumulation under reduced tillage and no-till is strongly dependent on precipitation and temperature or soil moisture and temperature. The wetter and warmer the climate, the greater the increase in SOC compared to conventionally tilled land. After 20 years, increases of 10–23% in SOC were found with no-till. In each climate region, the values for no-till were higher than those for conventional tillage (Figure 2) (Ogle et al., 2005). The intensity of carbon supply in the form of crop biomass, cover crops or optimized crop rotation is also clearly reflected in the results. While a low input strategy (e.g. straw removal, only SOC consuming crops, bare fallow) leads to decreasing carbon values compared to a balanced management (medium input), a high input strategy leads to increases of up to 11%. A crop rotation specifically optimized for carbon input (high input with balanced C/N ratio) was able to increase SOC levels by 38% after 20 years (Figure 3). Rainfall difference played only a minor role (Ogle et al., 2005). That climatic influences play an important role in SOC build-up under CA was also confirmed by Sun et al. (2020) who conducted a meta-study of the results of 138 studies in 21 countries worldwide. In this study, organic carbon levels and yields were compared between conventional tillage and no-till with crop biomass cover and cover crops over at least five years under the influence of temperature and precipitation. In contrast to Ogle et al. (2005), he found

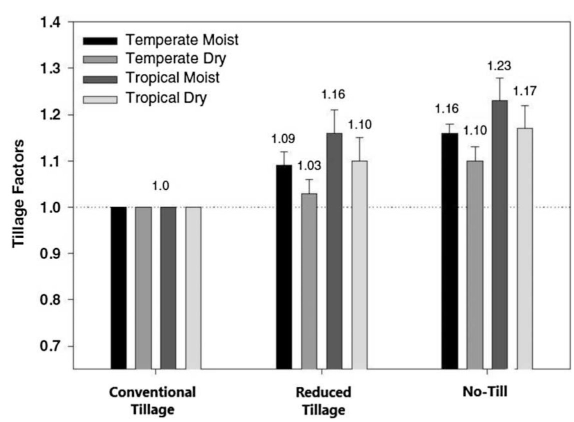

Figure 2. Soil organic carbon storage after 20 years without tillage compared to reduced and conventional tillage under different climatic conditions (Ogle et al., 2005).

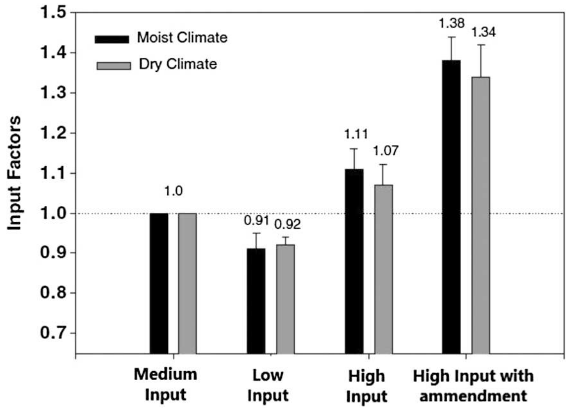

Figure 3. Soil organic carbon storage after 20 years under different carbon input strategies at different precipitation levels (Ogle et al., 2005).

the highest carbon increases under warm and dry conditions, while no SOC accumulation was found under cold and wet conditions.

According to Sun et al. (2020), SOC accumulation is expected for climatic conditions in Germany under constant yields, as illustrated by the map in Figure 4. It was also confirmed by Sun et al. (2020), that under all climatic conditions, no-till alone had no effect on SOC, but only the implementation of all CA principles did.

Similar results have been found by other authors in comparable meta-studies. Corsi et al. (2012) found between 0.25 and 1 t ha^{-1} y^{-1} of carbon sequestration for temperate humid climates in Germany and Western Europe, excluding Scandinavia and the Mediterranean region. Many studies found annual values of 0.4; 0.43; and 0.57 t·C ha^{-1}, respectively, which are within the range set by Corsi et al. (2012) (González-Sánchez et al., 2017, 2020; Sun et al., 2020; West & Post, 2002). As soil organic matter (SOM) is made of 60% carbon, the values correspond to a SOM build-up of 0.67–0.95 t ha^{-1} y^{-1} of humus (Stevenson, 1994). All samples were taken at a depth of at least 30 cm to avoid overestimating surface carbon accumulation under CA. However, SOM accumulation is not permanent but slows down after 5–10 years but under CA with optimized carbon addition, accumulation can continue for much longer, slowing down after 40–60 years. In order to maintain the SOM content at this new equilibrium level permanently, the management of carbon cycle must not change (West & Post, 2002).

Several authors have shown that an isolated consideration of the effects of different tillage practices on SOC levels does not allow conclusions to be drawn about SOC levels under correctly implemented CA principles. Rather, SOC accumulation appears to be realistic under many climatic conditions when all CA principles are implemented. For later calculations, the annual average SOC accumulation in Germany is assumed to be 0.625 t·ha^{-1}. Nevertheless, increased concomitant N_2O emissions could eliminate or even reverse the positive effect of SOC build-up on atmospheric CO_2 levels, as suggested by Don and Jantz (2013).

3.1.3. Nitrous oxide emissions under Conservation Agriculture

To verify the assumption of Don and Jantz (2013), 88 papers were analysed in a literature review (the full

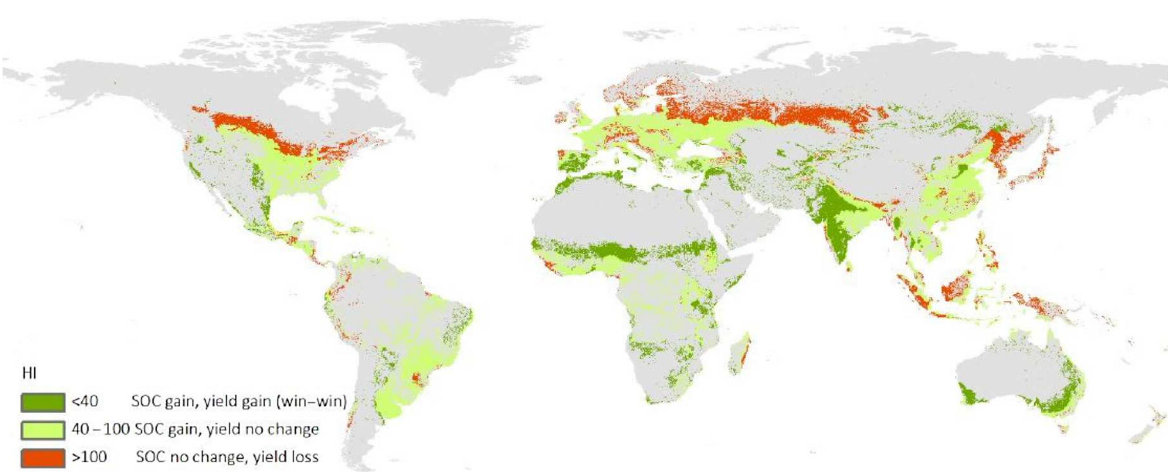

Figure 4. SOC balance and yield change under CA as a function of Humidity Index (HI) (Sun et al., 2020).

data set is available as supplementary material online), including the 50 papers evaluated by Don and Jantz (2013) (marked with 'x'). It was noted that eight of the papers reviewed by Don and Jantz (2013) did not include a no-till system and therefore should not have beeen included. A further eight studies cannot be used to draw conclusions on cropland because permanent grassland (6) and wet rice (2) were cultivated, which significantly increases N_2O emissions as well as methane emissions because of the anaerobic soil conditions. Of the remaining 34 studies, only 24% showed an increase in N_2O emissions compared to conventional tillage. Of the 72 papers included in the review, 22% showed increasing emissions, 39% decreasing emissions and 39% showed no change. In contrast, where emissions were unchanged, 43% studies showed non-significant trends towards decreasing emissions and 11% towards increasing emissions. It is possible that the duration of no-till practice has an influence on N_2O emissions, as only two studies found increasing emissions on plots that had not been under production for more than ten years. Unchanged or decreasing emissions were found in 19 other long-term trials.

It is also worth noting that, with the exception of the studies from Baggs et al. (2003) and Grageda-Cabrera et al. (2011), all the trials with increasing emissions had a tight rotation of one or two crops. Trials with diverse rotations or with cover cropping and under sowing had stable or decreasing emissions, with the exception of the two papers mentioned above. This suggests that extended crop rotations could avoid increased N_2O emissions when tillage is omitted. This assumption is supported by studies of crop rotations by Lehman et al. (2017) and Jantalia et al. (2008) which showed 24% lower emissions and the same emissions, respectively, with extended crop rotations (Bundesverband Boden e.V., 2014). Basche et al. (2014) confirm the conjectures regarding intercrops.

Several authors suggest that crop type, C/N ratio, soil moisture and drainage, and N fertilizer application have significant effects on N_2O formation, which may reduce the positive effects of crop rotation (Basche et al., 2014; Mitchell et al., 2013; Muhammad et al., 2019; Pimentel et al., 2015). In particular, Rochette (2008) assesses the influence of soil moisture as a key factor. Growing legumes in crop rotation, either as the main crop or as an intercrop, favours N_2O emissions (Ball et al., 2008; Peyrard et al., 2016; Pimentel et al., 2015). This is due to nitrogen fixation by bacteria living with legumes and the C/N ratio of legume plant residues. The more mineral nitrogen present in the soil, the greater the likelihood of denitrification, which produces N_2O. When the legumes die, the residues are microbially degraded. Because their C/N ratio is less than 25:1, this degradation is very rapid, and the nitrogen bound in the residues is mineralized. Above a C/N ratio of 25:1, degradation and mineralization take longer (Stahr et al., 2008). To reduce mineralization and thus the risk of denitrification and N_2O formation, crops with high C/N ratios should be grown. Because CA is designed to provide year-round mulch cover, crop biomass cover must not decompose quickly. Therefore, cover cropping is done at least in a mixture with crops that have a wide C/N ratio. In a broad rotation, pure legume crops occur only at multi-year intervals (Halde & Entz, 2016). N_2O emissions favoured by legumes are therefore already reduced in CA systems.

Anaerobic conditions, due to poor drainage, allow denitrification and thus N_2O emissions. They occur when there is no oxygen in the soil. This is the case when water fills the soil pores, or the total pore volume is very low. N_2O emissions increase sharply if >59% of soil pore space is waterfilled. The amount of waterfilled pore space depends on precipitation, total pore volume and soil drainage. Pore volume is reduced by compaction and increased by tillage (Hackmann, n.d.). In the absence of tillage, it is often assumed that the soil is compacted and thus the pore volume is reduced (Li et al., 2020). However, the opposite is observed, especially after many years of CA: The pore volume of the soil increases by up to 49% (Eze et al., 2020; He et al., 2011; Martínez et al., 2016). This is mainly due to the permanent root penetration and action of soil microorganisms, which loosen the soil and stabilizes the aggregates, improving the physical quality of the soil, which is no longer disturbed by mechanical intervention (Abdollahi et al., 2014; Baker et al., 2007; Panday & Nkongolo, 2021).

Overall, the claim by Don and Jantz (2013) of increased N_2O emissions under no-till is not confirmed by this literature review. On the contrary, it seems that the long-term absence of tillage, together with permanent soil biomass cover and diverse crop vegetation, can actually reduce N_2O emissions. However, due to the many different influencing factors, which depend on the exact location, initial soil drainage conditions, weather, and management, it is not possible to establish a generally valid average value. Therefore, this paper assumes constant N_2O emissions.

3.1.4. Soil erosion – emissions and prevention

Whether erosion is a net source or sink of greenhouse gases is controversial in the scientific community. van Oost et al. (2005) and others argue that carbon storage through complete humification at the erosion site and deposition of the humus-rich top layer on land outweighs CO_2 emissions from erosion (Liu et al., 2003; van Oost et al., 2005, 2007). However, Lal and Pimentel (2008) point out that, given methane and N_2O emissions and assuming actual humus formation rates, a net carbon sink from erosion is unrealistic. Dialynas et al. (2016) also found that the assumed carbon storage from SOC accumulation determines the net effect. Worrall et al. (2015) found annual net emissions of 0.3 t CO_2e per ton of eroded soil in a study in the UK, summarizing that carbon sinks can only be achieved if erosion rates are very low (<0.91 t ha^{-1}), all eroded carbon is replaced by humus accumulation, and less than half of the eroded carbon enters water bodies. However, since the average erosion rate worldwide and also in Germany is above 0.91 t ha^{-1} y^{-1} and not all carbon is replaced by SOC formation, Lal's assumption that an erosion-induced carbon sink is not realistic and that erosion causes GHGE seems to be confirmed (Biggelaar et al., 2004; Bundesverband Boden e.V., 2014; Lal & Pimentel, 2008).

In a study of 208 trials conducted in 13 European countries, annual average water erosion of 8.8 t ha^{-1} was found (Cerdan et al., 2006). In eastern England a study found between 0.1 and 2 t ha^{-1} y^{-1} of wind erosion (Chappell & Thomas, 2002). Both authors emphasize that during particularly severe weather events and on particularly exposed soils, the amounts are in many cases higher. This is consistent with the fact that Verheijen et al. (2009) in their review found between 10 and 20 t ha^{-1} y^{-1} total soil erosion for Europe.

There are other indirect greenhouse gas emissions from erosion, but these are difficult to quantify. For example, if water bodies become eutrophic due to nutrient inputs from eroded soil, the water body will emit more greenhouse gases than before (Dokulil & Teubner, 2011). Nutrient removal activities from drinking water further increase indirect erosion emissions (Racoviceanu et al., 2007). Fertilization in order to replace displaced nutrients at the erosion site causes emissions again (Walling & Vaneeckhaute, 2020).

In order to avoid direct and indirect emissions and other negative environmental impacts of erosion, several authors call for measures to reduce erosion (Lal, 2003; Worrall et al., 2015). An example of this is the implementation of the CA principles, because they successfully prevent soil erosion (Derpsch, n.d.; Kassam, 2020). Up to 98% less soil erosion was found when no-tillage was applied compared to tilled areas (Montgomery, 2007).

3.2. CO_2 footprints

3.2.1. Status quo

Initially, carbon footprints of the status quo at the Frese farm were calculated for silage corn, winter wheat and rapeseed, as these are the three main crops. The CFT results were manually supplemented with emissions from mineralization after tillage and erosion, and carbon storage through humus formation. Four tillage passes were made for corn and only three for winter wheat and rapeseed. Tillage-induced mineralization was assumed to result in emissions of approximately 150 kg CO_2e ha^{-1} per tillage pass over a period of 25 days (La Scala et al., 2008; Mahdi & Xinhua, 2005). Erosion at the Frese Farm site was calculated using the German ABAG equation and values from the Hessian State Office for Nature Conservation, Environment and Geology: Erosion $A = R*K*L*S*C*P$, where. R = erodibility factor (50), K = erodibility factor (0.35), L = slope length factor (2); S = slope factor (0.6) and C = cover factor (0.1 for WW and R; 0.35 for SM); P = erosion control measures (0) (HLNUG, 2022). Since the farm is located in a region characterized by slopes, the values for R, L and S are very high. Apart from the cultivation of cover crops, no erosion control measures are applied on the farm. Since these are incorporated, their erosion-reducing effect does not benefit the main crops. The calculated average erosion is 14.7 t ha^{-1} for corn and 4.2 t ha^{-1} for wheat and rape. For each ton of soil eroded, 0.3 t CO_2e are imputed.

The results of the calculation of total emissions are shown in Table 1. It is clearly visible that the emissions from erosion, mineralization and fertilization determine the level of the CO_2 footprint, while the other parameters are less important. For example, corn causes about 6.8 t CO_2e ha^{-1}, while wheat and rapeseed cause only 3.4 and 4 t CO_2e ha^{-1}, respectively.

Figure 5 shows that the high carbon footprint of silage corn is mainly due to high soil erosion, while the remaining values are similar to those of wheat

Table 1. CO_2-footprint status quo farm Frese.

Carbon footprint of the status quo at farm Frese	Corn	Wheat	Rapeseed
	kg CO_2e ha^{-1}		
Residues	0	0	161.83
Fertilizer production	429.45	486.54	553.78
Soil / fertilization	993.03	890.07	1100
Mineralization after tillage	600	450	450
Soil erosion	4410	1260	1260
SOC accumulation	0	0	0
Plant protection	29.21	51.47	147.26
Fuel consumption field	367.7	281.4	335.8
Transport	3.69	4.4	3.9
Total	6833	3424	4013

and rapeseed. About two-thirds of the emissions for corn are caused by erosion. The figure for wheat and rapeseed is about one-third.

3.2.2. Scenario 1: conversion to Conservation Agriculture

In this scenario, the farm is assumed to convert to CA. This would initially involve only the elimination of all tillage, which is expected to reduce emissions from fuel consumption by 20–40%. Emissions from mineralization caused by tillage would be completely eliminated. In addition, permanently covered and uncultivated soil would reduce erosion by 98% and store an average of 0.625 t ha^{-1} y^{-1} of carbon. Calculated using the formula (ZPG Chemie, n.d.):

$$m(CO_2) = [m(C)/\ M\ (C)] \times M(CO_2)$$
$$= (0.625\ t\ /\ 12\ g/mol) \times 44\ g/mol$$
$$= 2291\ t\ CO_2$$

2.3 tons of CO_2 would be removed from the air by sequestering this carbon, which could be added to the CO_2 footprint of no-till. The weight of the CO_2 removed is therefore 3.67 times the weight of the carbon. Table 2 shows that by reducing emissions and sequestering carbon, the values are reduced to –500 kg CO_2e ha^{-1} (corn), –650 kg CO_2e ha^{-1} (wheat) and about 0 kg CO_2e ha^{-1} (rapeseed). The negative values for silage corn and winter wheat show that the emissions caused would be more than compensated by carbon storage in humus. Net carbon storage would therefore be possible with CA.

In Figure 6, the carbon storage due to the expected SOC accumulation is shown as bars extending into the negative range.

3.2.3. Scenario 2: Conservation Agriculture after 20 years

Kassam and Kassam (2020) note that the transformational change from the often-degraded conventional

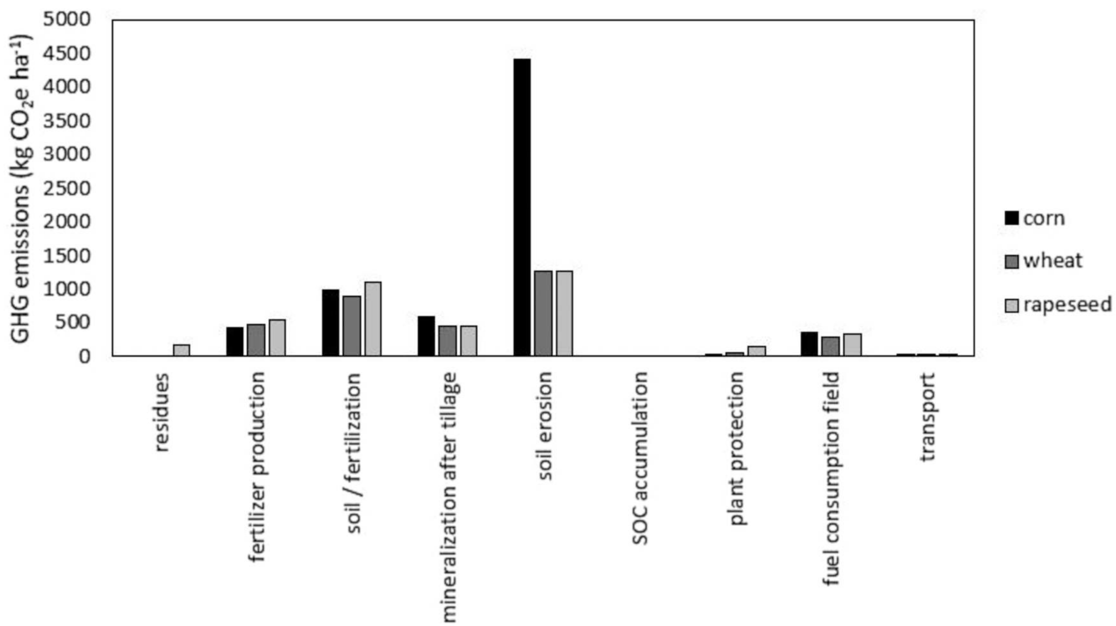

Figure 5. Emissions status quo farm Frese.

Table 2. CO_2-footprint CA Scenario 1.

Carbon footprint of the CA Scenario 1 at farm Frese	Corn	Wheat	Rapeseed
	kg CO_2e ha^{-1}		
Residues	0	0	161.83
Fertilizer production	429.45	486.54	553.78
Soil / fertilization	993.03	890.07	1100
Mineralization after tillage	0	0	0
Soil erosion	88.2	25.2	25.2
SOC accumulation	−2291	−2291	−2291
Plant protection	29.21	51.47	147.26
Fuel consumption field	239.9	186.83	269.27
Transport	3.69	4.4	3.9
Total	−508	−646	−30

tillage agriculture conditions to good-quality responsive CA conditions is a time- and biology-related multi-year evolutionary process of ecological regeneration. A range of benefits from CA management begin to accrue from the first season onwards and increase over time. Transition to new equilibrium can take 10 years or more depending on local situation and require the formulation of locally adapted practices based on the local biophysical, economic, social and management situation. Thus, the CA adoption process involves a system approach to managing change at the cropping system level.

One major co-benefit of CA in intensive production systems is the significant reduction in fertilizer and pesticide application which can be in the order of 50% or more after 10 or more years of continuous CA, while yields remain constant or increase. Global practical experience by CA farmers supports this productivity and efficiency gains, as do the reports of experienced CA farmers in Germany, who emphasize that the savings potential for mineral fertilizers and pesticides can vary from region to region, as climatic and site-related influences have a major impact on pest infestation and nutrient dynamics in the soil (Callsen, 2022; Kassam, 2020; Klümper, 2022; Zeitke, 2022; Zink, 2021). Scientific studies on CA systems in different parts of the world support the significant reduction in fertilizer applications as well as in overall application of production inputs (Carvalho et al., 2012; Freixial & Carvalho, 2010; Fuentes-Llanillo et al., 2021; Goddard et al., 2022; Kassam, 2020; Kassam et al., 2022). In smallholder CA systems and in organic CA systems, little agrochemicals are used (Goddard et al., 2022; Khan et al., 2020; Lalani et al., 2017; Owenya et al., 2011).

In a second scenario, the emissions that would remain after 20 years were calculated if fertilizers and pesticides could be reduced by 50%. The results are presented in Table 3. In particular, the reduction in fertilizer use would have a great impact on emissions from fertilizer production and use.

Overall, annual net carbon sequestration could be doubled for corn and winter wheat to −1100 and −1300 kg CO_2e ha^{-1}, respectively. Canola production could be transformed from a CO_2 neutral crop to a

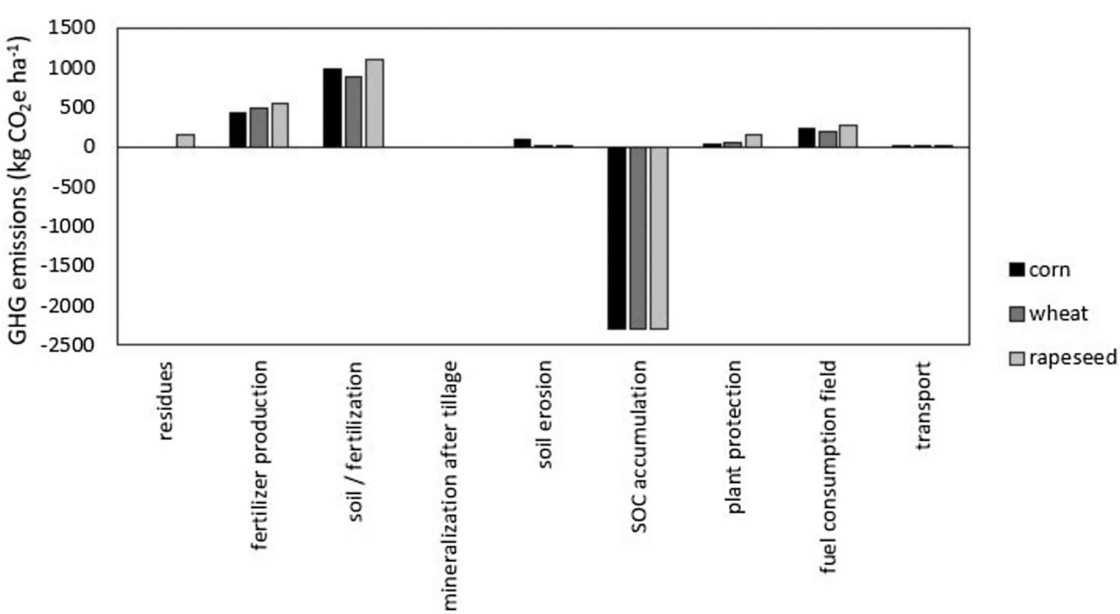

Figure 6. Emissions CA Scenario 1.

Table 3. CO_2-footprint CA Scenario 2.

Carbon footprint of the CA Scenario 2 at farm Frese	Corn	Wheat	Rapeseed
	kg CO_2e ha^{-1}		
Residues	0	0	161.83
Fertilizer production	188.52	234.29	321.74
Soil / fertilization	639.05	504.47	605.66
Mineralization after tillage	0	0	0
Soil erosion	88.2	25.2	25.2
SOC accumulation	−2291	−2291	−2291
Plant protection	14.61	25.01	73.37
Fuel consumption field	211.29	153.54	170.15
Transport	1.89	2.23	1.94
Total	−1147	−1346	−931

carbon sink of about −900 kg CO_2e ha^{-1}. Figure 7 shows a similar pattern to the previous figure. Emissions from fertilization would still account for the majority of total emissions under CA, although emissions from fertilizer production and fertilization itself would be half as high as in the previous scenario. Because of the different fertilizer rates, the soil/fertilizer values are also different. Clearly in the negative range are the humus accumulation columns, which would overcompensate for the tillage emissions.

3.2.4. Comparison of CO_2 footprints

Comparing the emissions presented in the three previous sections, it is clear that only status quo cropping on the Frese farm provides a clearly positive GHG balance (Figure 8). Switching to CA would (over-) compensate for the emissions from all crops and increase carbon storage over the years as fertilizer applications decrease.

Weighting the results for the three crops in the first scenario according to their share of Germany's arable land (54% cereals, 25% silage corn, 8% rapeseed (Statistisches Bundesamt, 2019)), the average carbon sequestration amounts to 500 kg CO_2e ha^{-1} per year. With the same weighting, the results of the second scenario are about twice as high with 1086 kg CO_2e ha^{-1} per year.

4. Discussion

4.1. Classification of the results

In Germany, there are 11.8 million hectares of cropland under cultivation (BMEL, 2017). In total, federal greenhouse gas emissions are projected to be 762 million tons of CO_2e in 2021 (UBA, 2022). Of this, 37.5 million tons of CO_2e are attributable to the management of cropland and grassland (Osterburg, 2013). If all of Germany's arable land were managed under CA, emissions from land management would be offset by carbon sequestration and subtracted from

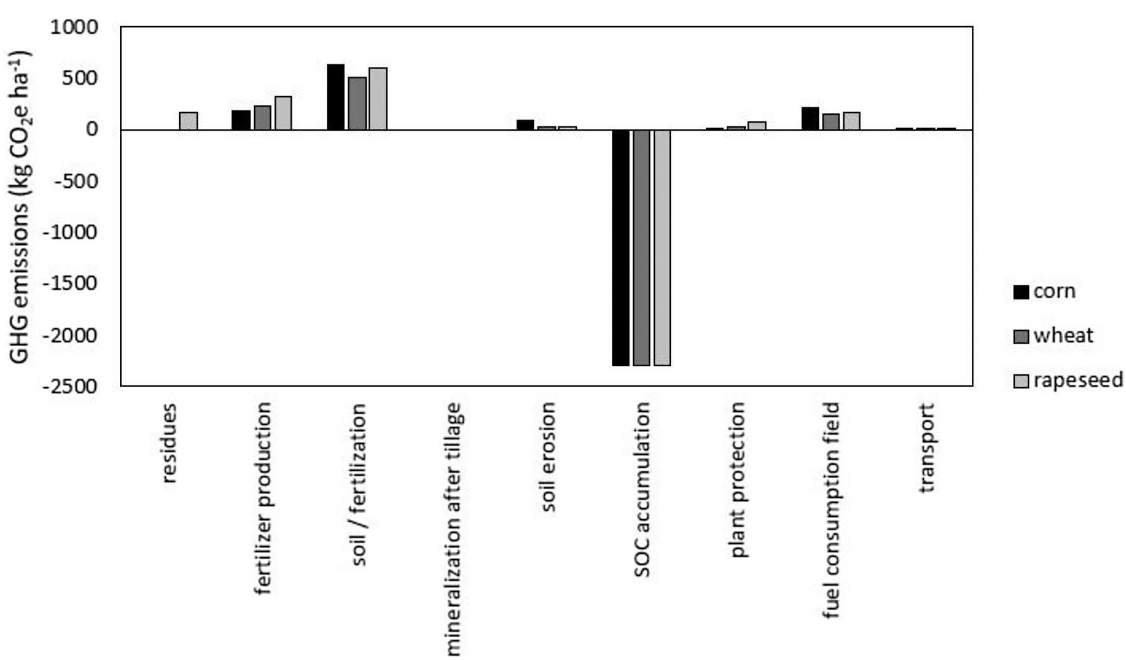

Figure 7. Emissions CA Scenario 2.

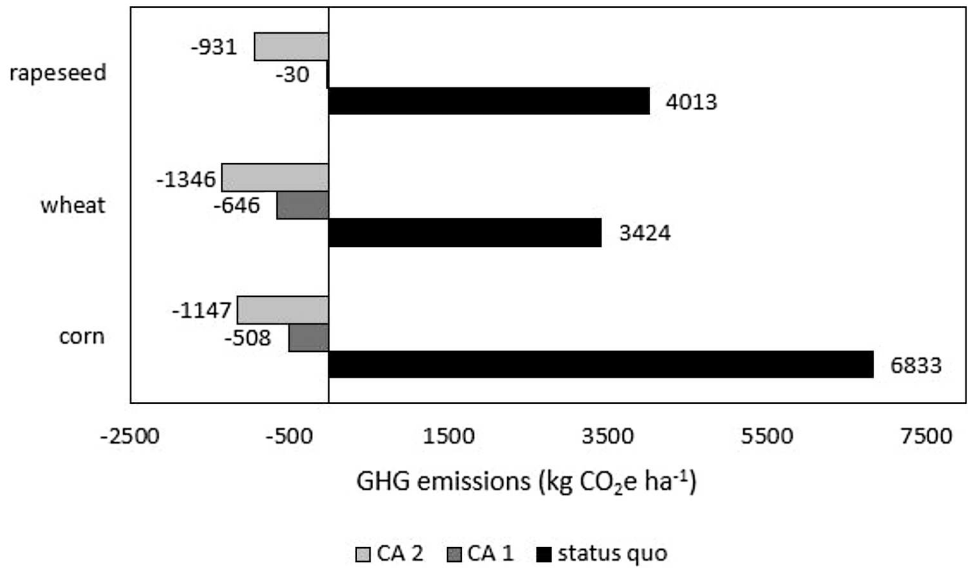

Figure 8. Emissions compared.

Germany's total emissions. Assuming an additional annual carbon sequestration of 500 kg CO_2e ha^{-1} (weighted average of Scenario 1), only about 0.8% of Germany's remaining GHG emissions could be offset. 69.6 million tons of CO_2e are emitted annually by German agriculture without land management. About 8.5% of these emissions could be offset by converting all cropland to CA. Assuming the weighted average from Scenario 2, which would occur automatically 20 years after conversion to CA, only twice as much could be offset. Worldwide, 34.1 billion tons of CO_2 were emitted in 2020. (Statista, 2021a). To offset these emissions, 68 billion hectares (Scenario 1) and 34 billion hectares (Scenario 2) would need to be converted to CA, but only 1.6 billion hectares of arable land are currently available worldwide (Statista, 2021b).

Therefore, CA alone can only offset emissions from crop production, not from other areas of agriculture such as storage, processing, and livestock production. This requires other options for carbon storage in agriculture.

With CA, agriculture has the opportunity to sequester carbon in current production without any additional effort (such as planting trees). This opportunity will become more important in the future. It is beyond the scope of this paper to consider and evaluate the many other positive effects of CA, such as lower capital input with increasing yields and lower labour requirements (= higher profitability), or positive effects on the environment and biodiversity. The fact that more and more farmers are switching to CA, or at least considering it, indicates that many farmers are convinced of the benefits of the system (Kassam et al., 2009, 2022).

4.2. Suitability of the Cool Farm Tool and limitations of the calculation

The CFT is designed to be easy for farmers to use. Therefore, only a few input data are required for the calculation. In the background, the programme works with flat values, e.g. for emissions from fertilizer production depending on the type and origin of the fertilizer, or for N_2O emissions from fertilization. Deviations from real emissions, both in the form of overestimation and underestimation, are therefore to be expected. The deviation of the final calculated CO_2 footprint from the real total emissions is unknown. However, the experiments to verify the CFT have shown that the results are in the same order of magnitude as more elaborate calculations. In addition, the CFT is regularly revised and updated, most recently in March 2022 (CFA, 2022).

The change in tillage (e.g. from ploughing to no-till) and the change in winter cropping (e.g. from no winter cropping to cover cropping) can be taken into account in the CFT. Positive effects due to these changes are credited as a lump sum, without taking account of the duration of the measures or the crop, with –400 kg CO_2e ha^{-1} for the conversion to no-till and –800 kg CO_2e ha^{-1} for the application of cover cropping. The weighting of individual sub-areas of these effects (e.g. SOC accumulation, erosion prevention, reduced CO_2/N_2O emissions from the soil) is not visible. In comparison with the results of the literature research on the emissions of these measures, which are both implemented in the context of conversion to CA, these values turned out to be inaccurate. Therefore, in order to allow for a more detailed calculation and consideration of the affected emission values, the effects of these measures were manually added to the result of the CFT based on the values researched in Section 3.1, without blanket inclusion of the measures in the calculation in the CFT as explained above.

As the CFT does not include emissions from, for example, erosion or tillage, these were also identified through the literature review and manually added to the CFT results. Care was taken to ensure that the data were from studies in Germany or Europe, as much as possible, to ensure similar soil and climate conditions. Where this was not possible, results from sites with comparable soil, climate and management were used.

A difficulty in any climate assessment is the definition of system boundaries and the availability of data. For example, the exact transport distances in the whole life cycle of input resources such as diesel and fertilizer are usually not known and therefore cannot be considered or can only be considered in a lump sum. Depending on how narrowly the system boundaries are drawn, emissions from upstream and downstream areas of agriculture may not be included or may have to be included without a valid data base. The narrower the system boundaries, the less accurate the carbon footprint. The broader the system boundaries, the more complicated the calculation due to incomplete data. In this work, the system boundaries were kept as narrow as possible, but all relevant emissions were included. In order to calculate an accurate carbon footprint for a company, all data would have to be collected on site. The effort required is beyond the scope of this work.

The product carbon footprint (PCF) is not designed to show the evolution of greenhouse gas emissions of a product or production process over time. However, as this was the question of this work, several PCFs were calculated from the same products. Starting from the status quo, through Scenario 1 to Scenario 2, a period of more than 20 years is considered, during which the production system changes with the application of different measures. PCF values were compared to evaluate the success of the measures. Since the data for the scenarios are initially based only on assumed values from the literature, the actual implementation of the measures must be accompanied by further data collection so that the predictions of this work can be checked and verified at a later date.

4.3. Testing of SOC accumulation and mineralization assumptions

Some scientists doubt that CA can accumulate SOC. But even among those who believe that SOC can be accumulated, it is unclear to what level can it be accumulated. This section examines this question in more detail. Since the range of values found in the studies examined is from 250 to 1000 kg C ha^{-1} of annual carbon storage through humus accumulation, 625 kg C ha^{-1} per year was assumed as the mean value for the calculations in this paper. In the meta-study of Don and Jantz (2013) an annual humus accumulation of 150 kg C ha^{-1} was found with reduced tillage. As noted above, many of the field trials evaluated there are not under no-tillage conditions, but the carbon storage found is still equivalent to removing 550 kg CO_2 ha^{-1} from the atmosphere every year. This shows that actual carbon sequestration may vary by site, crop and weather, but can offset a significant portion of emissions particularly under no-till conditions. In fact, about one-seventh of the emissions from Freses wheat production could be offset.

In contrast, Flessa et al. (2019) found an annual increase in carbon stocks of 400 kg C ha^{-1} over 20 years in Germany just trough long-term application of cover cropping. Assuming that the results in a field trial combining both subjects (no-till + long-term intercropping) add up, 550 kg C ha^{-1} would already be stored without considering all the principles of CA. As this value hardly differs from the assumed 625 kg C ha^{-1} under CA, the assumption seems to be realistic. The question is whether the assumed value is too low. However, even assuming the maximum value of 1 t ha^{-1} y^{-1} of bound C found in the literature on CA, the magnitude of the results does not change fundamentally (Corsi et al., 2012).

One criticism of carbon storage in humus is that humus formation is limited. West and Post (2002) found no further humus accumulation after 40–60 years under CA practices. For European conditions, Smith (2004) determined the duration to reach a new humus equilibrium of 100 years. This period should be used to implement one to two generations of CO_2-neutral CA. Meanwhile, new methods can be developed to reduce or offset greenhouse gas emissions from agriculture as well as from population and industry, so that carbon storage in humus is no longer needed when it is no longer available after 50–100 years. It is important that the use of CA principles that have allowed the built up of SOC is not changed to SOC depleting practices such as tillage, biomass removal and poor crop diversification. Otherwise, the carbon already bound in the SOC will be released into the atmosphere in the form of CO_2 within a short period of time.

A literature review was conducted to determine what emissions are caused by the mineralization of nutrients triggered by tillage. In various experiments, the authors found 100 to over 500 kg CO_2 ha^{-1} in the period up to 25 days after tillage, depending on the type and depth of tillage (La Scala et al., 2008; Mahdi & Xinhua, 2005). Emissions are highly dependent on soil moisture, climate, and soil type. Therefore, emissions can vary from site to site (La Scala et al., 2008). For the calculations in this paper, therefore, a very low value of 150 kg CO_2 ha^{-1} was assumed, regardless of the type and depth of tillage. In addition, it was assumed that no CO_2 would be emitted after 25 days due to a lack of sufficient basis for assumptions. However, La Scala et al. (2008) found that emissions from ploughed and unploughed soils equalize only after 90 days. Thus, emissions are likely to be almost four times higher due to the longer duration alone. If higher emissions are assumed (e.g. 300 kg CO_2e ha^{-1} as an average between 100 and 500 kg CO_2e ha^{-1}), the value increases again. Instead of the 450 kg CO_2e ha^{-1} for rapeseed and wheat or the 600 kg CO_2e ha^{-1} for corn, 3,600 and 4,800 kg CO_2e ha^{-1} respectively would have to be assumed for mineralization from tillage on the Frese farm. This would exceed the CO_2 footprint of the status quo for corn and rape/wheat by about 50% and 100% and increase the benefits of CA accordingly.

More research is needed on this topic to make better assumptions. There is a lack of data, especially under the climate and soil conditions in Germany. The most accurate values would be obtained by measuring in the areas studied. However, this is beyond the scope of the carbon footprint calculation of CA in this paper.

4.4. Uncertainties in the determination of the content of humus

The SOC content is not determined by analysis in the usual soil sample analyses, but is calculated from the SOM content with a factor of 1.72, since SOM consists of 60% carbon. (Stevenson, 1994) This is based on the assumption that all organic carbon found is bound in humus. However, this assumption is incorrect because much of the C in soil samples comes from incompletely decomposed plant biomass, soil animal body parts, and other materials. In addition, this analysis cannot be used to distinguish between short-term and permanent SOC. If carbon storage through SOC accumulation is to be rewarded with certificates, more precise methods than this should be used to determine both the initial condition and subsequent development with as much certainty as possible. Methods based on thermogravimetry could provide more sophisticated results in the future, and could quantify carbon storage in (permanent) humus (Kucerik et al., 2015; Siewert, personal communication, April 19, 2022).

4.5. Other environmental benefits of Conservation Agriculture

To assess the climate impact of CA, this work considered only the direct impact of the system on inputs and soil. However, CA has many other benefits that could also have an indirect impact on the carbon footprint. Some of these are discussed below (Kassam, 2020).

Biodiversity: Cropland managed according to CA principles has higher above and below ground biodiversity than conventionally managed land (Palm et al., 2014). This includes plants, fungi, and animals of all sizes, from microbes to birds. In the UK, studies have counted ten times more birds on CA plots than on conventional plots (FarmingUK, 2022). A Danish study found up to five times more arthropods and up to twenty times more birds on CA land than on organic land (Søby, 2020). As biodiversity loss is considered one of the greatest challenges facing humanity in the twenty-first century, and agriculture is blamed for much of the loss, CA is one way to counteract this trend (Europäische Kommission, 2021; WWF, 2021).

Infiltration: Because of the better soil structure in CA fields, rainwater infiltrates better than in tilled fields. At the same time, the mulch layer effectively minimizes soil water evaporation. Research shows that crop stands have more water available under no-till than under conventional practices. In irrigated regions, the use of CA practices has reduced irrigation rates by up to 50%. This is often accompanied by an increase in yield (Palm et al., 2014). Since irrigation causes greenhouse gas emissions of 30–100 g C m^{-3} due to the drawdown of groundwater and the energy required for pumping, every cubic metre of irrigation water saved is a contribution to climate protection (Kaur et al., 2016).

Water body pollution: Because of good water infiltration, fields managed according to CA principles have almost no surface runoff. In a trial in Italy, 60% less runoff and up to 95% less sediment in the water were measured during the no-till conversion phase (Carretta et al., 2021). As a result, 60–70% fewer pesticides and nutrients are detected in surface runoff from no-till fields compared to tilled fields (Palm et al., 2014). This is accompanied by a reduced load of agricultural xenobiotics in ground and surface waters. In Brazil, CA has been the basis for integrated watershed management in Parana to control sediment and agrochemicals in the water draining from the agricultural lands into the lake Itaipu which is used for generating electricity (Mello et al., 2021).

Kassam (2020) suggests lower nutrient leaching (e.g. of nitrate) from CA managed soils compared to tilled soils. As Germany and other countries increasingly complain about problems with nutrient leaching into groundwater, but the measures taken are not having any effect, it should be investigated whether CA could be a solution (van Grinsven et al., 2015). Water pollution and groundwater and surface water remediation activities result in greenhouse gas emissions that would have to be attributed to agriculture (possibly on a pro rata basis) (Dokulil & Teubner, 2011; Racoviceanu et al., 2007). If water pollution is reduced or eliminated through CA, the superiority of the carbon footprint of CA over conventional tillage-based agriculture is further enhanced.

Food nutrient density: Various studies show that the nutrient density of food has decreased by up to 50% for various minerals worldwide in recent decades (Davis, 2009; Ekholm et al., 2007; Fan et al., 2008). Reasons range from breeding for yield to intensive mineral fertilization to loss of soil fertility and soil life. A study published in the spring of 2022 compared the nutrient density of food from farms using CA principles with food from conventionally farmed farms. Up to 70% more minerals were found in vegetables and grains, and up to ten times more omega-3 fatty acids in beef and pork from CA farms (Montgomery et al., 2022). At the same time, the risk of chronic diseases has been significantly reduced by increasing the nutrient density of foods (Montgomery & Biklé, 2021). The amino acid ergothioneine may act as an anti-inflammatory and antioxidant in the human body. Because ergothioneine is produced by fungi and enters the food supply through them, products produced under CA have higher ergothioneine levels than products from other farming systems. The reason for this is that any soil tillage greatly depletes the soil fungi (Beelman et al., 2021). CA could therefore have very positive effects on human health. Further research is needed to consolidate and verify the findings.

Water cycles: Water circulates in large and small cycles between oceans, soil and vegetation, and clouds in the sky. In the small water cycle, precipitation infiltrates the soil and is transpired by plants using energy. Only a small fraction evaporates directly from surfaces back into the air. By extracting energy in the form of heat from the surrounding air, plants actively cool their environment through transpiration. When large areas are unvegetated, the lack of energy extraction results in a noticeable temperature increase of several degrees. In addition, the infiltration capacity of unvegetated soils decreases, so precipitation runs off superficially into water bodies, and water is lost from the small water cycle and transferred to the large water cycle. The result is less rainfall and a more uneven distribution of rainfall. Only growing plants can restore the function of the small water cycles and thus provide sufficient precipitation and a cooling effect (Kravcík et al., 2007). Because CA keeps the soil covered and minimizes surface runoff, it can contribute as a cropping system to the functioning of water cycles and regional temperature regulation (Schwarzer, 2021).

Considering the positive environmental effects of CA, transforming to CA seems to be justified for this reason alone, without knowing the exact climate impact. A more precise statement could be made in the context of a life cycle assessment (LCA) of CA. Further research is needed to fully evaluate and compare the systems.

4.6. Need for research and education

The literature review showed that there are sometimes conflicting research results for similar studies.

For example, it is unclear which factors are responsible for N_2O formation in the soil and in what order of importance. The contribution of different measures to SOC accumulation is also not clearly understood. Since there are always many factors involved in a natural production system, not all of which are known and many of which are uncontrollable, a precise determination of SOC accumulation or N_2O formation based on a few parameters of a production system will not be possible in the future. However, in order to assess the climate impact of different systems, it is necessary to investigate the multifactorial influences in more detail in the future. The results of this work show that soil or its management is a major contributor to climate-relevant emissions from agriculture. It was also shown that appropriate measures in agriculture have the potential to significantly reduce these emissions to the point of carbon sequestration. The results of future research on soil processes will not only enrich the knowledge of soil as an actor in the global climate but will also expand the limited existing knowledge of soil, its inhabitants and interactions with plants, and their implications for us humans.

CA cropping systems should also receive more attention in research, science and education in Europe. In other regions of the world, research and development of this pioneering cropping system is much more advanced, while in Germany and Europe, outdated views of its function and effects are still widespread and the benefits of the system are therefore overlooked. In order to avoid methodological errors in research and thus further conflicting research results, Derpsch et al. (2014) call for the standardization of research in CA. This work should be based on a uniform definition of the terms CA, no-till, direct seeding, etc., as well as a uniform methodology for field trials. This is the only way to ensure that misleading results based on a lack of understanding of the system can be avoided in the future.

5. Conclusion

Based on the review and the case study, it is concluded that conversion to CA significantly reduces GHGE from agricultural soils This work shows that transforming agricultural production systems to CA can significantly reduce GHGE from agriculture. As SOM builds up under these conditions, carbon can even be stored. This not only offsets the remaining emissions but makes the soil a net carbon sink. SOC accumulation starts in the first year of conversion to CA and stores at least 500 kg CO_2e ha^{-1}. If this cropping system is maintained in perpetuity, emissions will continue to decrease due to reduced fertilizer and pesticide application rates, increasing the annual net sequestration up to 1350 kg CO_2e ha^{-1}. The hypothesis that CA has a smaller carbon footprint than tillage-based systems can thus be considered confirmed. However, it also became clear that no-till alone is not effective. Only the full application of the CA concept, i.e. integration of a permanent soil cover with living plants or a mulch layer, together with the greatest possible plant diversity, leads to SOC accumulation with increasing yields and co-benefits. This can also be taken as indicator for the existing ambiguity and confusion in the international literature regarding the climatic impact of different tillage systems. In addition to reducing greenhouse gases, CA reduces erosion by 98%. This can stop the increasing soil degradation that causes enormous GHGE. Because these emissions have not been considered, it is likely that all carbon footprints and carbon neutral agriculture policies to date have fallen short of their goals. However, CA has numerous benefits not only for the climate, but also for the environment and human nutrition and health. In view of these results, it is suggested that the adoption of CA as the only known sustainable agricultural land management system so far be promoted further and accelerated along with relevant public and private sector development support in research, education, extension and policy.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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