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RESEARCH ARTICLE

The potential of cover crops to increase soil organic carbon storage in German croplands

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Abstract

Aims Soil organic carbon (SOC) stocks of croplands can be enhanced by targeted management, which boosts soil fertility and contributes to climate change mitigation. One SOC sequestration option is adopting cover crops. The aim of this study was to quantify the SOC sequestration potential of cover crops in Germany.

Methods We simulated SOC scenarios on 1,267 cropland sites with site-specific management data using an SOC model ensemble consisting of RothC and C-TOOL. A new method was developed to estimate carbon input from cover crops that included the effects of climate, sowing date and species on cover crop biomass production.

Results The recent cover crop area could be tripled to 30% of arable land in Germany. This would enhance total carbon input by 12% and increase SOC stocks by 35 Tg within 50 years, corresponding to an annual increase of 0.06 Mg C ha^{-1}, 2.5 Tg CO_2 or 0.8 per mill of current SOC stocks in 0–30 cm depth. On sites with cover crops, 0.28–0.33 Mg C ha^{-1} a^{-1} would be accumulated within 50 years. Our simulations predicted that even if the full potential for cover crop growth were realised, there would still be a decline in SOC stocks in German croplands within 50 years due to the underlining negative SOC trend.

Conclusions Cover crops alone cannot turn croplands from carbon sources to sinks. However, growing them reduces bare fallow periods and SOC losses and thus is an effective climate change mitigation strategy in agriculture.

Keywords Carbon sequestration · Modelling · Carbon input · Allometric function · Climate change mitigation

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Introduction

Growing cover crops is an agricultural management option that has multiple benefits. Cover crops replace bare fallow on croplands, mainly during winter, in order to reduce soil erosion and nutrient losses. They are planted to preserve nitrogen for the subsequent main crop, promote pest suppression, maintain soil fertility and water quality, reduce drought stress for the subsequent main crop when used as mulch cover, and enhance biodiversity (Smit et al. 2019; Snapp et al. 2005). Cover crops are usually used as green manure and ploughed into the soil before the subsequent crop is sown, but they can also be harvested and used to feed livestock.

Decreasing SOC stocks have been detected in many cropland soils in Europe in repeated inventories (Ciais et al. 2010), making these soils a source of CO_2 to the atmosphere. Increasing the organic carbon (C) input to cropland soils is seen as the main option for reducing their negative climate effect, or even reversing it by turning cropland soils into a net C sink via SOC sequestration (Amelung et al. 2020). SOC sequestration in cropland soils has been discussed as a climate change mitigation option (Lal 2004), and the 4 per 1000 initiative has even suggested that 20–35% of global anthropogenic greenhouse gas emissions could be offset by increasing global SOC stocks in the top 40 cm by 0.4% per year (Minasny et al. 2017). However, this target has been criticised for being unrealistic and there have since been many studies that have attempted to quantify a feasible SOC sequestration potential (Bruni et al. 2021; Lugato et al. 2014; Martin et al. 2021; Taghizadeh-Toosi and Olesen 2016; Wiesmeier et al. 2020). Cover crops have been identified as a cost-effective SOC sequestration solution and large SOC sequestration potentials have been suggested (McClelland et al. 2020; Pellerin et al. 2020; Poeplau and Don 2015). One advantage of growing cover crops compared to other SOC sequestration strategies such as ley cropping or converting arable land to grassland is that it does not negatively affect agricultural production, thus avoiding leakage effects (Lugato et al. 2014). However, the magnitude of the SOC sequestration potential of cover crops is a subject of debate (Rodrigues et al. 2021). Can cover crops reduce C losses from intensively used cropland soils, and how much SOC can be sequestered? Detailed data on the potential cover cropping area is needed if these questions are to be answered. These data are now available for more than 2000 sites in Germany from the first Agricultural Soil Inventory (Poeplau et al. 2020).

The development of cover crop biomass is affected by several factors such as the sowing date (Gselman and Kramberger 2008; Komainda et al. 2016), which in turn depends on the crop rotation and the main crop grown previously. The biomass production of cover crops also depends on the temperature and precipitation during the growing phase (Koch et al. 2017; Komainda et al. 2016), and on the species (Renius et al. 1992; Schulte 1980). Until now, there has been no model for reliably estimating the C input to the soil from cover crops, which takes these effects into account. Allometric functions are often used to estimate the C input by relating it to the yield (Bolinder et al. 2007; Kätterer et al. 2011; Taghizadeh-Toosi et al. 2014). For cover crops where no yield is available a mean yield is usually assumed (Riggers et al. 2019). However, when estimating a feasible SOC sequestration potential, it is important to consider a realistic cover crop biomass. The SOC sequestration potential could be overestimated if effects that reduce the biomass production are ignored. Therefore, a new model is needed for reliably estimating the C input to the soil from cover crops.

Changes in SOC stocks due to higher C inputs can be simulated using dynamic SOC models like RothC (Coleman and Jenkinson 1996) or C-TOOL (Taghizadeh-Toosi et al. 2014). They allow to estimate how effective the SOC stocks are increased by enhanced C inputs, depending on the climate and the soil e.g. by a clay dependant decomposition rate. To calculate a realistic national estimate of the cover crop SOC sequestration potential, they need to be applied on a large number of sites representing soils, management and climate of the country. The unique dataset from the German Agricultural Soil Inventory (Poeplau et al. 2020) comprising both soil and management data for over 2000 cropland sites offers the possibility to explore the national potential of cover crops to sequester SOC on regional scale.

The objective of this study was to simulate the SOC effect of growing cover crops on cropland soils. This was carried out in a case study for Germany, where a data-validated model ensemble has recently predicted a decline in SOC stocks (Riggers et al. 2021). The aim was to find answers to the following questions:

(1) How large is the potential area to incorporate winter annual cover crops into recent crop rotations in Germany? And to what extent is the winter annual cultivation window already being used?

(2) How much additional C input can be generated by maximising the cover cropping area on German cropland soils?
(3) To what extent do recent and additional cover crops affect SOC stocks, can they reduce SOC losses, and what is their SOC sequestration potential?

Materials and methods

Soil and management data

Soil and management data for this study were obtained from the first Agricultural Soil Inventory in Germany that was conducted between 2009 and 2018 (Jacobs et al. 2018). Soil profiles were sampled and soil samples were analysed in the laboratory. Management data for each sampling site were obtained from the farmers by means of a questionnaire. Details on the methodology and key results of the inventory are described in Poeplau et al. (2020). A total of 2,171 cropland sites were analysed. Some of these sites were excluded for the simulations due to limitations of the models (see Section 'Simulation of the effect of cover crops on soil organic carbon stocks'). In all, 24,917 years of management data were recorded for these sites, including information on crop rotation, main crop yield and fertilisation. The period for which information on the management is available ranged from one to 19 years, with an average of 12 years for each site (between 2001 and 2019).

The sites were classified in equally-sized regional groups according to the federal states. Based on the pedoclimatic conditions we defined three regions: the warm, wet and sandy *North* (Lower Saxony, North Rhine-Westphalia, Schleswig-Holstein, Hamburg, Bremen), the wet and clayey *South* (Baden-Wuerttemberg, Bavaria, Hesse, Saarland, Rhineland-Palatinate), and the dry and sandy *East* (Berlin, Brandenburg, Mecklenburg-Western Pomerania, Saxony, Saxony-Anhalt, Thuringia). Climate and soil characteristics of the sites in these regions are summarised in Table 1 and shown in the supporting information S1.

Scenarios for additional cover crops

We defined the time during winter fallow where cover crops could potentially be grown as “cultivation windows”. We identified cultivation windows for cover crops based on the previous and subsequent main crops and associated average harvest and sowing months. This was done in accordance with information from regional agricultural advisory services. *Long* cultivation windows were defined as occurring after the main crops that are typically harvested in July or August (e.g. winter wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.)). *Short* cultivation windows were defined as occurring after the main crops that are harvested in September or October (e.g. maize (*Zea mays* L.)). Growing cover crops after mid-October was not considered possible since on average the vegetation period is not long enough. Thus, there are no cultivation windows after root crops, which are typically harvested late in the year (e.g. sugar beet (*Beta vulgaris* L.)). The main crops following both the long and the short cultivation window are summer crops sown after March (e.g. maize or oats (*Avena sativa* L.)) to allow potential additional cover crops to cover the soil during winter. Details on the definition of the cultivation windows according to the main crops and a schematic crop rotation are given in the supporting information (S2 and S3). We determined the average annual cover crop area [% of total cropland] and the cultivation windows based on the management years of all sites (n = 24,917).

In order to estimate the SOC sequestration potential of cover crops, four scenarios were developed

Table 1 Mean climate and topsoil (0–30 cm) characteristics of the sites in each region with standard deviations. Only sites that were considered in the simulations are included (n = 1267)

Region	Mean annual temperature *°C*	Mean annual precipitation *mm*	Mean clay content %	Mean sand content %	Mean SOC stock *Mg ha^{-1}*
North	9.8 +- 0.6	760 +- 90	13 +- 9	53 +- 33	61 +- 21
East	9.3 +- 0.5	620 +- 80	15 +- 11	50 +- 30	52 +- 20
South	9.2 +- 0.8	780 +- 120	25 +- 11	27 +- 22	59 +- 19

with varying percentages of cover crops in the crop rotations. The aim was to estimate an easy to realise SOC sequestration potential that maintains agricultural productivity thus main crops were not changed in order to increase acceptance by farmers. In the first scenario, *no cover crops*, the cover crops in recent crop rotations are taken out of the rotation and only the main crops and organic fertiliser provide C input to the soil (0% cover crops on annual cropland area). In the *business-as-usual* scenario, the effects of the recent management are simulated. The C input in this scenario is provided by residues (roots and shoots) of recent crop rotations, including recent cover crops (10% cover crops on annual cropland area) and by organic fertiliser. In the *simple* scenario, it was assumed that cover crops would also be grown in *long* cultivation windows and therefore it includes recent cover crops and additional cover crops in *long* cultivation windows (10% + 13% = 23% cover crops on annual cropland area). In the *ambitious* scenario, both *long* and *short* cultivation windows are used for growing cover crops while the management, i.e. the main crops and fertiliser application, remains the same. Thus, it includes recent cover crops and cover crops in both *long* and *short* cultivation windows (10% + 13% + 7% = 30% cover crops on annual cropland area).

For the *simple* and *ambitious* scenarios, where additional cover crops are implemented in the crop rotations, it was assumed that the cultivation windows are filled with a set of the most common cover crops species in proportions according to their distribution in recent crop rotations. To do this, we first calculated the C input of each cover crop species for each site using the method described in subsection 'Estimating the carbon input from cover crops'. Based on this, we calculated a weighted mean C input for each site, with weights according to the prevalence of the ten most common cover crops (listed in the supporting information (S4)).

In the *business-as-usual* scenario, 84% of all cover crops are incorporated into the soil and 16% are harvested, e.g. for livestock feed, based on information given by the farmers. In the *simple* and *ambitious* scenarios, we assumed that all additional cover crops were incorporated into the soil. In those cases where the cover crops are harvested and removed from the field, the aboveground C input from cover crops was reduced at this site by 75% on the assumption that roughly three quarters of cover crops are harvested and the remaining aboveground biomass is left as stubble in the field.

Simulation of the effect of cover crops on soil organic carbon stocks

To simulate the four scenarios, a multi-model ensemble was used as multi-model ensembles were shown to decrease model uncertainty in SOC simulations for German croplands (Riggers et al. 2019). Our model ensemble consisted of two process-based SOC models combined with three different C-input estimation methods for the main crops, resulting in a total of three model combinations. This combination was selected based on the analysis by Riggers et al. (2019) and further checks of the ability of the models to simulate management related SOC changes on 15 long-term field experiments with 245 treatments in Europe and 139 permanent soil monitoring sites in Germany. The five-pool-model RothC (Coleman and Jenkinson 1996) was combined with the allometric functions described in Taghizadeh-Toosi et al. (2014) and initialised by an analytic solution from Dechow et al. (2019). The three-pool-model C-TOOL (Taghizadeh-Toosi et al. 2014) initialised with fixed fractions (Taghizadeh-Toosi and Olesen 2016) was combined once with allometric functions introduced by Jacobs et al. (2020) and once with allometric functions described in Rösemann et al. (2017). The allometric functions were used to calculate the C input provided by the main crops and were based on harvest information given by the farmers. To calculate the C input of the cover crops, we developed a new estimation method, which is described below. The C input from straw, manure and roots was partitioned to the SOC pools in RothC according to the partition coefficients introduced by Dechow et al. (2019).

Simulations were performed for the topsoil (0–30 cm) at 1,267 sites. Model runs were only performed for sites that had at least five years' recorded management, thus it could be assumed that the management was representative for the site. Out of the total 2,171 cropland sites, additional sites were excluded owing to the limitations of the SOC models. These were: (1) hydromorphic soils with a groundwater level of less than 80 cm from the surface (n = 79), (2) sites that had been under cropland use for less than 60 years (n = 185), and (3) organic soils with SOC contents above 8% (n = 8). In addition, there are sandy soils in Germany with a high SOC content (*black sands*) and a high proportion of recalcitrant organic matter, which is characterised by slower decomposition rates than would be expected (Springob and Kirchmann 2002; Vos et al. 2018). As the current parameterisation of SOC models is not suitable for describing these conditions, these *black sand* sites were also excluded (n = 41).

Current climate conditions for each recorded management year at each site were used for the simulations. Weather data were sampled from gridded datasets of monthly precipitation, temperature and sunshine duration and of daily precipitation and temperature (DWD Climate Data Center, 2020a, b, c, d). No climate change scenarios were considered since climate change not only alters temperature and precipitation, and thus the mineralisation and degradation of SOC stocks (Bruni et al. 2021; Riggers et al. 2021), but can also influence the produced biomass of main crops and cover crops, e.g. due to longer growing seasons and higher CO_2 concentrations (Olesen et al. 2007). An altered biomass production would lead to altered C input rates to the soil. However, based on current knowledge, there is great uncertainty about the effect size of climate change influencing C input and C decomposition, thus the impact of climate change was not included in this study. Therefore only data for a maximum of 50 years are shown.

Estimating the carbon input from cover crops

The development of cover crop aboveground biomass production mainly depends on: (1) the temperature and precipitation in the early growing phase (Koch et al. 2017; Komainda et al. 2016), (2) the species and (3) the sowing date, which limits the remaining vegetation days (McClelland et al. 2020). We developed a new method to estimate the C input from the aboveground and belowground biomass of cover crops taking these three factors into account. An illustration of this is given in the supporting information (S5).

A linear regression was used to account for the impact of temperature and precipitation on the aboveground biomass $a_{mustard}$ [Mg dry mass (DM) ha^{-1}) (Koch et al. 2017):

$$a_{mustard} = -2.937 + 1.16P_s + 0.021T_s \tag{1}$$

where P_s is the mean daily precipitation [mm d^{-1}] from the assumed early sowing date (18 August) up to 30 September, and T_s is the sum of the air temperature [°C d] from day 19 to day 31 after sowing. These variables were identified by Koch et al. (2017). For each of the soil inventory sites, this equation was used to estimate the site-specific aboveground biomass of white mustard (*Sinapis alba* L.) $a_{mustard}$ [Mg DM ha^{-1}]. The maximum production of $a_{mustard}$ was set at 7.5 Mg DM ha^{-1}, in accordance with regional data. This Eq. 1 was only developed for mustard biomass so it cannot be used for all cover crop species.

The influence of species on aboveground biomass a_{cc} [Mg DM ha^{-1}] was accounted for by rescaling the average aboveground biomass of the cover crop a_{cc*} [Mg DM ha^{-1}] according to the ratio between the calculated site-specific aboveground biomass of mustard $a_{mustard}$ [Mg DM ha^{-1}] and the average aboveground biomass of mustard $a_{mustard*}$ [Mg DM ha^{-1}] (Eq. 2).

The site-specific root biomass was calculated for each cover crop species $b_{r,cc}$ [Mg DM ha^{-1}] based on the same ratio $\frac{a_{cc*}}{a_{mustard*}}$ and the average root biomass $b_{r,cc*}$ [Mg DM ha^{-1}] (Eq. 3). Both the average aboveground and root biomass values were obtained from Renius et al. (1992) and Lütke Entrup (2001) who provided a large set of data on average aboveground and belowground biomasses of many cover crop species grown in Germany. The average root biomass data also contain stubble, which was considered here to be aboveground biomass. In order to estimate the aboveground and root biomasses appropriately, stubble was subtracted from the given root biomass values and added to the aboveground biomass, assuming that stubble is 10% of the aboveground bimass a_{cc} [Mg DM ha^{-1}]. The aboveground biomass a_{cc} and root biomass $b_{r,cc}$ were then calculated as described in Eqs. 2 and 3 below:

$$a_{cc} = \frac{a_{mustard}}{a_{mustard*}} a_{cc*} \frac{1}{1 - 0.1} \tag{2}$$

$$b_{r,cc} = \frac{a_{mustard}}{a_{mustard*}} b_{r,cc*} - \frac{0.1}{1 - 0.1} \frac{a_{mustard}}{a_{mustard*}} a_{cc*} \tag{3}$$

Only early sowing in *long* cultivation windows allows optimally developed cover crop biomass. The negative effect of late sowing on the biomass was accounted for by reducing the aboveground and root biomass by 35% in *short* cultivation windows based on Renius et al. (1992).

The calculated cover crop biomasses were considered plausible as the biomass ranges fitted well with reports by regional agricultural advisory services (Kanders and Berendonk 2013; LfL 2011; Schmidt and Gläser 2013).

The average root biomass from the literature has been evaluated for a depth of 0–60 cm (Renius et al. 1992), but since the aim here was to calculate the C input for a depth of just 0–30 cm, the root biomass was rescaled according to the root distribution introduced by Gale and Grigal (1987) (Eq. 4):

$$b_{r,30} = \frac{1 - \left(0.961^{30}\right)}{1 - \left(0.961^{60}\right)} b_{r,cc} \tag{4}$$

The total belowground biomass b [Mg DM ha^{-1}] providing C input to the soil was calculated by totalling the root biomass b_r and rhizodeposition. Rhizodeposition was assumed to be 31% f the root biomass $b_{r,30}$ [Mg DM ha^{-1}] (Pausch and Kuzyakov 2018). A C content of 47% was asumed for all biomasses to calculate the C input [Mg C ha^{-1}] (Jacobs et al. 2020).

Definition of soil organic carbon sequestration and accumulation potential

We define SOC sequestration potential or SOC accumulation potential as the simulated increase in SOC stocks [Mg C ha^{-1}] in relation to different scenarios (S6). *Recent* SOC sequestration by cover crops was accounted for by subtracting the SOC stocks of the *no cover crops* scenario from the SOC stocks of the *business-as-usual* scenario. The *additional* SOC sequestration by cover crops was defined in relation to the *business-as-usual* scenario and was calculated by subtracting the SOC stocks of the *business-as-usual* scenario from the SOC stocks simulated with the two scenarios of increased cover crop frequency (*simple* scenario and *ambitious* scenario). The *total* SOC sequestration was calculated by adding together the *recent* SOC sequestration and the maximum *additional* SOC sequestration. However, in cases where both the *business-as-usual* scenario and the *ambitious* scenario predicted decreasing SOC stocks compared with today, this was no SOC sequestration in a strict sense as C is released to the atmosphere rather than captured in the soil. We referred to these cases as *SOC accumulation* and *reduction of SOC losses* instead.

In order to provide annual SOC accumulation rates [Mg C ha^{-1} a^{-1}], the SOC stock increase [Mg C ha^{-1}] was divided by the corresponding simulated time span [a], assuming a linear increase in SOC stocks over the simulated period of two to 50 years. However, in reality, accumulation rates are nonlinear and decrease over time as SOC stocks reach a new equilibrium.

Software

The simulations were run in R version 4.0.4 (R Core Team 2021). The RothC implementation from the SoilR package (Sierra et al. 2012) and the C-TOOL implementation from Riggers et al. (2019) were used. Visualisation of the results was undertaken with the tidyverse package (Wickham et al. 2019). Errors are given as standard deviation or 95% confidence interval, unless stated otherwise.

Results

Potential area for cover crops in Germany

One third of the winter fallow area in German crop rotations is recently used for growing cover crops, thus the cover cropping area in Germany could almost be tripled. More than half of the additional planting area for cover crops offers a long cultivation window and is usable in the *simple* scenario (Fig. 1). The size of the cultivation window and whether it is already used differs by region. In relation to the total potential cover cropping area of each region, only 17% is recently used for cover crops in the *East*, which is less than in the *North* (39%) and *South* (41%). The total additional cover cropping area is distributed evenly across the different regions. Large parts of the unused cultivation windows in the *East* and *South* are long (60% and 40% of total cover cropping area respectively). Only in the *North* are more cultivation windows short so they are only usable in the *ambitious* scenario since a large proportion of maize cultivation with late harvest in this region only allows planting cover crops late in the growing season (34% of the total cover cropping area). As maize is predominantly

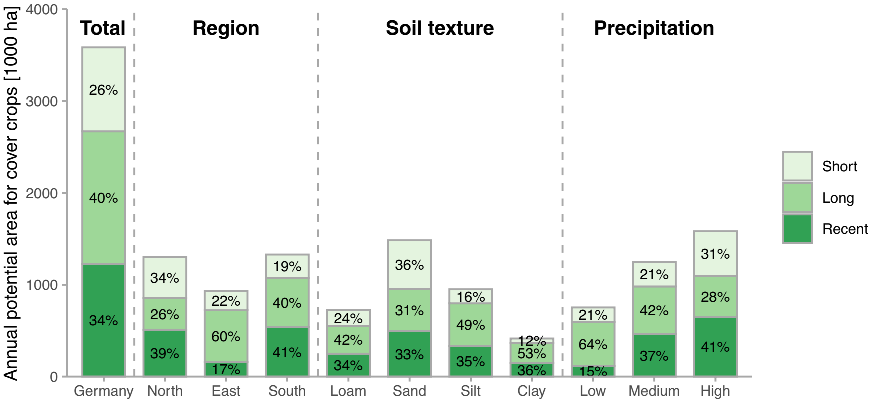

Fig. 1 Annual potential cover cropping area during winter fallow in Germany in 1000 ha in relation to the region, soil texture according to the German classification system (Ad-Hoc-AG Boden 2005), and mean annual precipitation classes (low < 650 mm, medium 650–800 mm, high > 800 mm). Colours reflect whether the cultivation window in that area is already used in recent crop rotations or whether it can be grown in long or short cultivation windows. Numbers reflect the proportion of the total cover cropping area of that class [%]

grown on sandy soils, cultivation windows on sandy soils are more often short (36% of sandy cover cropping area) compared with silt and clay soils (16% and 12%).

More *recent* cover crops are grown with increasing mean annual precipitation. At sites with low precipitation, most cultivation windows are long (64%) and usable in the *simple* scenario. Cultivation windows with high precipitation are often already used (41%). No differences in cover crop frequency were found between organic and conventional management (S7).

Biomass production and carbon input from cover crops

The mean annual biomass production of *recent* cover crops is estimated to be 5.6 (+- 1.2) Mg dry mass (DM) ha^{-1}, with a mean aboveground biomass of 4.4 (+- 1.1) Mg DM ha^{-1} and a mean belowground biomass of 1.2 (+- 0.4) Mg DM ha^{-1}. This corresponds to an average cover crop-induced C input of 2.6 (+- 0.6) Mg C ha^{-1} per crop (Fig. 2). The potential cover crop-derived annual C input is estimated to be on average 2.5 (+- 0.2) Mg C ha^{-1} per crop in *long* cultivation windows. In *short* cultivation windows, the average annual C input coming from cover crops falls to 1.7 (+- 0.2) Mg C ha^{-1} per crop due to its reduction by 35%.

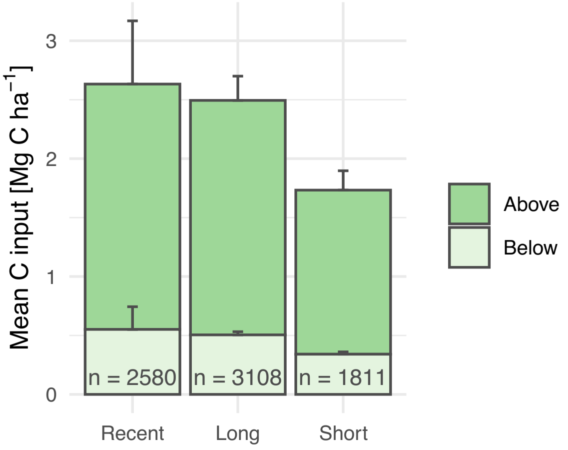

Fig. 2 Average annual C input [Mg C ha^{-1} a^{-1}] from cover crops in recent crop rotations (n = 2,580), long cultivation windows (n = 3,108) and short cultivation windows (n = 1,811) in all recorded years (n = 24,917) on all sites (n = 2,171) coming from aboveground and belowground biomass. Error bars represent the standard deviation

The potential C input increases in long cultivation windows are distributed almost evenly across Germany (Fig. 3b). Potential C input increases in short cultivation windows are mostly located in the *North* and *South* (Fig. 3c). The amount of the C input originating from *recent* cover crops is distributed unevenly across German croplands (Fig. 3a) according to the frequency of recent cover crops integrated in the crop rotation (S8) with less cover crops grown in the *East*.

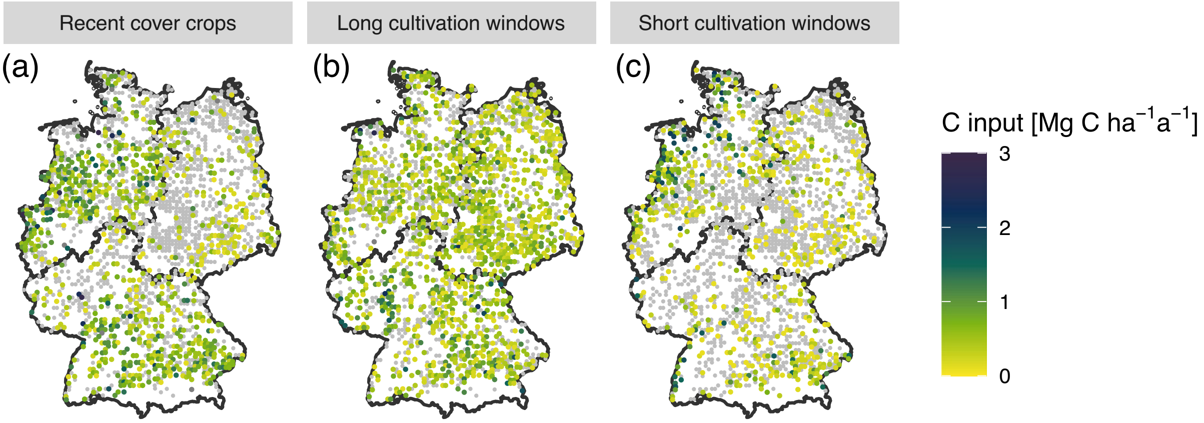

Fig. 3 Recent and additional site-specific mean annual C input [Mg C ha^{-1} a^{-1}] provided by cover crops in recent crop rotations (**a**), long cultivation windows (**b**) and short cultivation windows (**c**) given as average on each site (n = 2,171). Grey dots represent sites without cover crops or cultivation windows

Across all simulated sites, recent cover crops increase the C input to the topsoil by on average 0.18 Mg C ha^{-1} a^{-1} (5% of total C input), with 65% coming from aboveground biomass and 35% from belowground biomass (Fig. 4). Almost half of the aboveground biomass of recent cover crops is harvested and used for feeding livestock (*Business-as-usual* scenario).

The average C input provided by cover crops to the soil increases by 360%, from 0.18 to 0.62 Mg C ha^{-1} a^{-1}, if all cultivation windows in recent crop rotations are used (*ambitious* scenario). If only the *long* cultivation windows are used in addition to *recent* cover crops, the C input provided by cover crops could still triple to 0.52 Mg C ha^{-1} a^{-1} (*simple* scenario). The total C input including main crop residues and organic fertilisation averaged across all German croplands could be increased by 12%, from 3.68 to 4.13 Mg C ha^{-1} a^{-1} with ambitious cover crop adoption.

Soil organic carbon sequestration with cover crops: current status and scenarios

Increased C input to the soil via more cover crops leads to increased SOC stocks. However, compared with current SOC stocks, all scenarios show decreasing SOC stocks in the next 50 years (Fig. 5). Ambitious adoption of cover crops increasing the mean C input to 4.13 Mg C ha^{-1} a^{-1} prevents SOC losses only at 14% of all sites. Nonetheless, 53% of all sites would still lose SOC, with an average SOC loss of

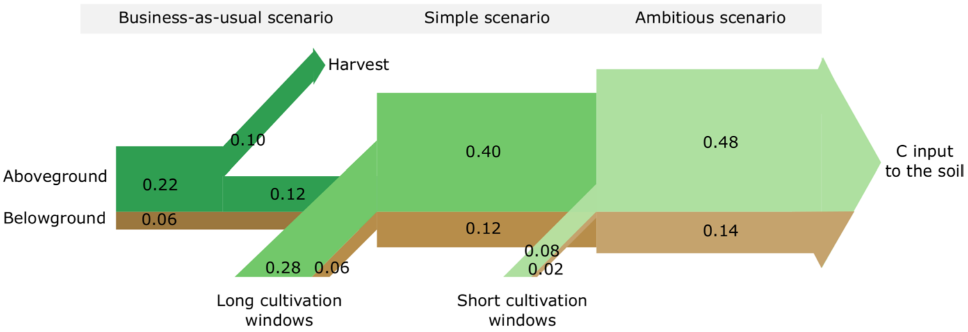

Fig. 4 Cover crop-induced C input [Mg C ha^{-1} a^{-1}] to German cropland soils in each scenario as average of the simulated sites (n = 1,267). Average annual cover crop frequency increases from 10% (business-as-usual) to 23% (simple) and 30% (ambitious) of total cropland area, thus increasing the C input from cover crops in each scenario

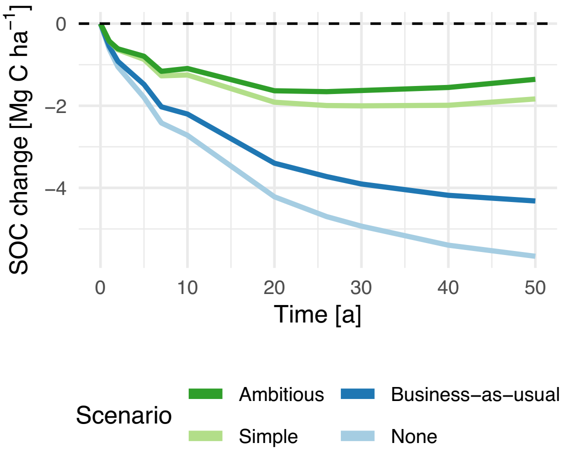

Fig. 5 Average SOC changes [Mg C ha^{-1}] on all simulated sites (n = 1264) in each scenario with increasing average annual cover crop frequency, none (0%), business-as-usual (10%), simple (23%) and ambitious (30%), over time compared with current SOC stocks (dashed line)

-1.2 Mg C ha^{-1} within 50 years. A linear regression indicates that a mean C input of more than 4.3 Mg C ha^{-1} a^{-1} would be needed to stop the recent trend of SOC losses on croplands within 50 years (S9). However, the ranges of both the C input and SOC stocks between sites are high.

Annual SOC accumulation rates due to cover crops in German croplands are highest in the *ambitious* scenario and for short simulation periods (Table 2). They decrease over time as SOC stocks approach a new equilibrium. Across all croplands, *recent* cover crops increase SOC stocks by on average 0.05 Mg C ha^{-1} a^{-1} within 10 years and by 0.03 Mg C ha^{-1} a^{-1} within 50 years in the topsoil. These rates could be tripled to a *total* of 0.16 Mg C ha^{-1} a^{-1} within 10 years and 0.09 Mg C ha^{-1} a^{-1} within 50 years (*ambitious scenario*). This corresponds to a *total* SOC accumulation potential of cover crops of 7.0 and 3.7 Tg CO$_2$ a^{-1} within 10 and 50 years respectively. Large parts of the *total* SOC accumulation potential are achievable in the *simple* (57%) or *business-as-usual* (32%) scenarios, while filling the short cultivation windows in the *ambitious* scenario only corresponds to 11% of the *total* SOC accumulation potential (Fig. 6).

The SOC accumulation potential is distributed unevenly across German croplands (Fig. 7), matching the uneven distribution of the cover crop-derived C input (Fig. 3). Recently, SOC accumulation by cover crops is mainly concentrated in the *North* and *South* of Germany (a). Increasing SOC stocks with cover crops is possible in all regions of Germany (c). Most of the *total* SOC accumulation potential can be achieved by filling long cultivation windows in the *East* and Central Germany (b).

Effect of cover crop frequency on soil organic carbon increase

The cover crop-induced SOC accumulation at each site is strongly affected by how often cover crops can be included in recent crop rotations. Higher frequencies of cover crops lead to higher SOC stock increases in the sequestration scenarios (Fig. 8), with a smaller increase in the *ambitious* scenario than in the *simple* scenario (0.28 Mg C ha^{-1} a^{-1} vs. 0.33 Mg C ha^{-1} a^{-1} with annual cover crops).

Table 2 Mean annual SOC accumulation rates [Mg C ha^{-1} a^{-1} and Tg CO$_2$ a^{-1}] of cover crops on all German croplands (11,672,000 ha, Federal statistical office (Destatis) (2020)) by scenario and simulated time span [years] compared with a scenario with no cover crops

SOC scenario	Reference scenario	Annual SOC change			Total annual SOC change		
		Mg C ha^{-1} a^{-1}			*Tg CO$_2$ a^{-1}*		
		10 years	20 years	50 years	10 years	20 years	50 years
Business-as-usual	No cover crops	0.05 +- 0.09	0.04 +- 0.07	0.03 +- 0.04	2.2 +- 3.7	1.7 +- 2.9	1.2 +- 1.9
Simple scenario	No cover crops	0.15 +- 0.12	0.12 +- 0.09	0.08 +- 0.06	6.3 +- 5.1	4.9 +- 3.9	3.3 +- 2.6
Ambitious scenario	No cover crops	0.16 +- 0.13	0.13 +- 0.10	0.09 +- 0.07	7.0 +- 5.5	5.5 +- 4.2	3.7 +- 2.8

The simple scenario includes recent cover crops and additional cover crops grown in long cultivation windows, and the ambitious scenario includes recent cover crops and additional cover crops in both long and short cultivation windows. Standard deviation represents site variability

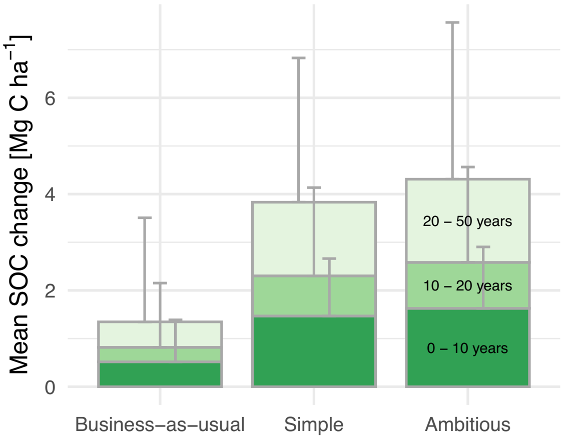

Fig. 6 Average SOC change [Mg C ha^{-1}] due to cover crops achieved within 0–10, 10–20, and 20–50 years in each scenario with the bars including 10 years, 10 years and 30 years, respectively. The simple scenario includes recent cover crops and additional cover crops grown in long cultivation windows, and the ambitious scenario includes recent cover crops and additional cover crops in both long and short cultivation windows

Discussion

Comparing the simulations with results from field experiments

Our simulated SOC accumulation rates are in line with results of meta-analyses summarising data from field experiments (Abdalla et al. 2019; Bolinder et al. 2020; Poeplau and Don 2015). This suggests that the approach taken here reflects field conditions and produced plausible results. SOC sequestration rates from the literature that are constant over time can provide a good estimate of the sequestration potential of cover crops on a large scale and can be applied in different contexts. However, one major advantage of dynamic SOC models compared with applying constant SOC sequestration rates from the literature is that they provide the opportunity to describe the temporal dynamic of SOC sequestration. Our simulated annual SOC accumulation rates are at the highest at the start and decrease over time as the SOC stocks approach a new equilibrium. This dynamic is well in line with other studies (Dendoncker et al. 2004; Lugato et al. 2014; Sommer and Bossio 2014). In order to compare our SOC sequestration rates with literature values, they were calculated for the same time periods considered in other studies.

We found similar annual SOC stock increases of 0.33 – 0.28 Mg C ha^{-1} a^{-1} (in the *simple* and *ambitious* scenario, respectively, within 50 years) to the meta-analysis of Poeplau and Don (2015), with an annual SOC sequestration rate of 0.32 Mg C ha^{-1} a^{-1} (study length up to 54 years). In the *ambitious* scenario, the SOC stock increase was slightly lower because it included cover crops in *short* cultivation windows, which are assumed to produce less biomass. Our annual SOC accumulation rates of cover crops ranged from 0.70 Mg C ha^{-1} a^{-1} within two years to

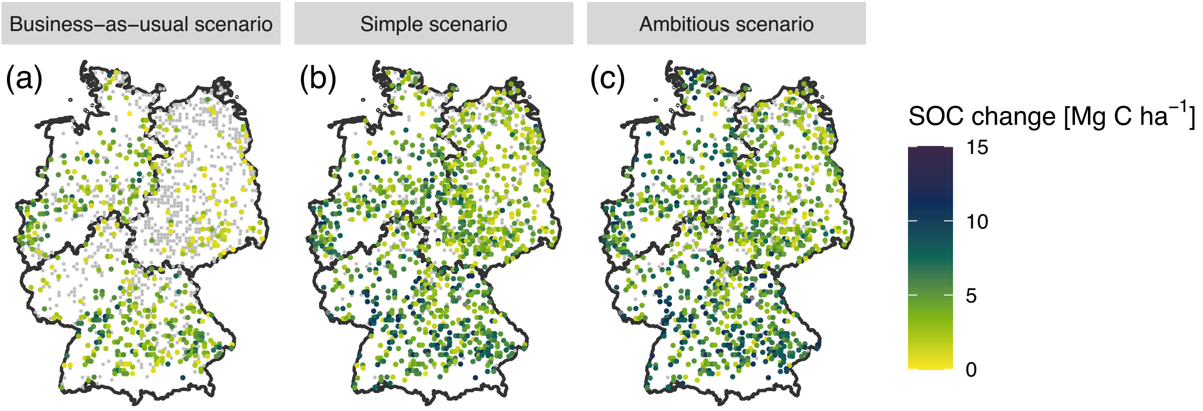

Fig. 7 Site-specific SOC change [Mg C ha^{-1}] within 50 years compared with the scenario with no cover crops. Plot (**a**) shows SOC accumulation achieved by recent cover crops in the business-as-usual scenario. The simple scenario (**b**) includes recent cover crops and additional cover crops grown in long cultivation windows, and the ambitious scenario (**c**) includes recent cover crops and additional cover crops in both long and short cultivation windows (n = 1,267 each)

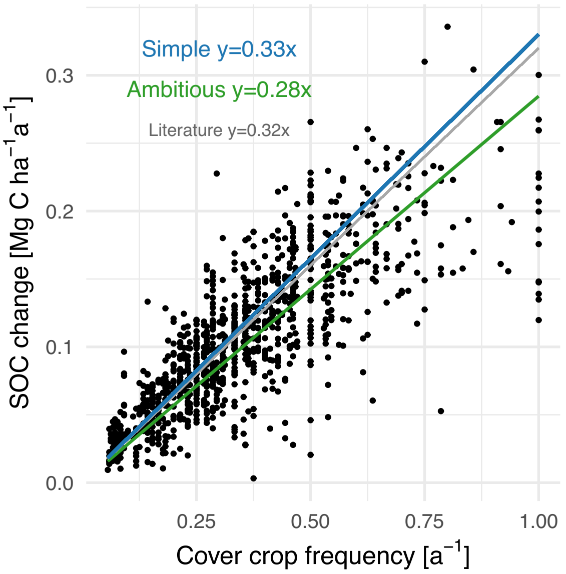

Fig. 8 Annual site-specific SOC increase [Mg C ha^{-1}a^{-1}] induced by cover crops within 50 years, depending on the frequency of cover crops [a^{-1}]. The dots represent the simulated SOC stock increases from the ambitious scenario on sites with cover crops (n = 1034). The lines illustrate the linear regressions from (**a**) the simple scenario with a mean cover crop frequency of 29% on 1013 cover crops sites (blue) and (**b**) the ambitious scenario with a mean cover crop frequency of 35% on 1034 cover crops sites (green) both with fixed intercepts at (0,0). The estimated slope is used as the SOC sequestration rate for annual cover crops to compare these results to other studies. The grey line shows the linear SOC increase for annual cover crops from a meta-analysis (Poeplau and Don 2015), shown here as a linear increase with cover crop frequency

0.54 Mg C ha^{-1} a^{-1} within 10 years for annual cover crops in the *ambitious* scenario. These results were similar to the mean SOC sequestration rate of 0.54 Mg C ha^{-1} a^{-1} of annual cover crops derived for topsoils in a global meta-analysis including studies with experiments lasting two to three years (Abdalla et al. 2019). Within a period of 20 years, *ambitious* annual cover crops would accumulate 0.43 Mg C ha^{-1} a^{-1}. This is the upper limit of SOC stock change rates that Bolinder et al. (2020) found ranged between 0.27 and 0.43 Mg C ha^{-1} a^{-1} in their meta-analysis (mean study length 7–22 years).

However, only the average SOC sequestration potential can be estimated with constant SOC sequestration rates, even though in reality the response varied between the sites. Key factors that impact the variation in this response have been identified as the seeding and termination date of the cover crops (i.e. growing window), annual cover crop biomass production, and soil clay content (McClelland et al. 2020). All these factors were considered in our modelling approach, either in the SOC models (clay content) or in the C input estimation method presented here (biomass production, seeding date). This indicates that our approach is a step towards describing better site-specific differences in SOC stock dynamics with cover crops.

The importance of the carbon input estimation method for simulating soil organic carbon stocks

Using dynamic SOC models to quantify the SOC sequestration potential of cover crops requires the estimation of C input. Besides other effects such as reduced evaporation due to soil cover, the increase in C input is seen as the main reason for SOC increases after implementation of cover crops (Bolinder et al. 2020). In the GSOCseq mapping approach coordinated by the FAO, simple SOC sequestration scenarios assume an increase in C input of + 5%, + 10%, and + 20%, which are supposed to be achieved via sustainable but unspecified management measures, including cover crops (FAO 2020). The results of this study show that in German croplands, the medium C input increase of 10% of the FAO GSOCseq approach could be achieved by including cover crops in recent crop rotations: the average total C input to German croplands increases by 12% in the *ambitious* scenario and by 9% in the *simple* scenario.

The method of how C input is estimated and distributed among SOC pools in the SOC models strongly affects simulated SOC stocks and thus the SOC sequestration potential (Taghizadeh-Toosi et al. 2020). For Denmark, Taghizadeh-Toosi and Olesen (2016) estimated the SOC sequestration potential of cover crops using both the model and allometric function of C-TOOL. They found a low cover crop-derived SOC sequestration rate of 0.05–0.13 Mg C ha^{-1} a^{-1} in two topsoils, which is smaller than our mean *ambitious* SOC accumulation rate of 0.19 Mg C ha^{-1} a^{-1} for the same frequency and simulation period. As their cover crop induced C input rate of 2.1 Mg C ha^{-1} a^{-1} is between our rates for the *simple* scenario (2.5 Mg C ha^{-1} a^{-1}) and the *ambitious* scenario (1.7 Mg C ha^{-1} a^{-1}), neither cover crop induced C input nor cover crop frequency alone can explain our SOC accumulation rates being twice as high. One explanation could be the different modelling approach as we used a model ensemble including RothC in addition to C-TOOL. Using only C-TOOL would lead to an underestimation of SOC stocks compared to using our model ensemble since C-TOOL reacts less sensitive to higher C inputs than RothC. This illustrates the value of model ensembles compared to single models when they proved to better describe management-induced SOC trends in that region (Riggers et al. 2019). In addition, Taghizadeh-Toosi and Olesen (2016) did not differentiate between aboveground and belowground C input, even though roots and their exudates contribute more effectively to the stable SOC pool (Kätterer et al. 2011; Poeplau et al. 2021; Taghizadeh-Toosi and Olesen 2016). In our approach, the different aboveground and belowground C inputs and their effectiveness were taken into account with different partition coefficients introduced by Dechow et al. (2019) for RothC. This is another possible explanation for our higher SOC accumulation rates, illustrating the strong effect of C-input quality (as root:shoot ratio) on SOC sequestration potential.

Improved estimates of the C input to the soil by cover crops requires cover crop biomass data, in particular for roots. However, these data are often not available or are based on old datasets, such as the one used here, which might not reflect current breeding, management or climatic conditions. Due to lacking data, some other factors were not considered here such as the variation in how sensitive different species react to a later sowing date, and the variation of the root:shoot ratio as the plants grow. Our approach of estimating the cover crop biomass thus remains a potential. Including crop mapping and crop yield prediction via remote sensing combined with more root measurements could be a step towards estimating a more realistic C input and SOC sequestration potential from cover crops.

The most important factor in increasing the total C input and SOC sequestration potential is the frequency of cover crops. To estimate the European SOC sequestration potential, Lugato et al. (2014) used the CENTURY model (Metherell 1993) in which the climate effect on biomass production and thus on C input is already implemented. Consequently, their regional distribution of the technical SOC sequestration potential of cover crops reflects the growing conditions for cover crops with greater potential in areas such as Ireland, northern France and central Germany, which are more suitable for growing cover crops than Spain, for example, due to higher precipitation and long growing seasons. Although we also included the climate's impact on biomass production, the regional distribution of C input and thus SOC sequestration did not reflect this climatic impact in Germany as explicitly as the work of Lugato et al. (2014) did for the same area. Instead, both the C input and the SOC stock changes due to cover crops were affected more by cover crop frequency. The highest SOC accumulation potential was found at sites where few recent cover crops have been grown (low *recent* frequency) but many could be grown (high *potential* frequency). The potential frequency of cover crops is mainly determined by crop rotation and the recent frequency is based on individual management decisions. This shows that including actual management data, i.e. crop rotations at field scale, can make a major difference when estimating the SOC sequestration potential. However, the management including crop rotations, cover-crop cultivation windows and recent cover-crop frequency is subject to constant change, which in turn alters the SOC sequestration potential.

Growing potential determines how much soil organic carbon can be sequestered by cover crops

How much additional SOC can be accumulated by cover crops is determined by the baseline scenario including the recent cover crop frequency, and the SOC sequestration scenarios based on the remaining potential area for cover crops.

We found more recent cover crops (15% vs. 12%) and a lower potential for additional cover crops (22% vs. 29%) in Bavaria's agricultural area than Wiesmeier et al. (2020) who used field-scale data. This lower growing potential leads to a lower SOC sequestration potential in our study (0.14 Tg SOC a^{-1} vs. 0.18 Tg SOC a^{-1}). However, these differences are only small and show that the management data of the Agricultural Soil Inventory offer a good estimate of actual management.

In contrast, Lugato et al. (2014) did not take recent cover crops into account in their pan-European estimation of SOC sequestration potential. Due to a different study design, they assumed the same cover crop coverage on all European croplands despite some regions being more suitable for growing cover crops than others. However, the average *recent* cover crop frequency in our study was higher (10%) than the highest cover crop frequency assumed by Lugato et al. (2014) in their sequestration scenarios (7%) as Germany belongs to the regions more suitable for growing cover crops. Due to the cover crop growing potential being four times greater (30% vs. 7%), we simulated SOC stock increases for German croplands that are about four times higher (3.8 +- 2.9 Mg C ha^{-1} over < 1 Mg C ha^{-1}). This confirmed that actual management data including the recent state of implementation are needed to calculate the SOC sequestration potential of cover crops.

In general, the available cover cropping area and its utilisation varies across Europe. While an annual potential area for growing cover crops of 30% was identified for the German cropland area, or 22% of the agricultural area (including grasslands), other studies from countries with a similar climate have estimated potential areas of 12% of the cropland area in Belgium (Dendoncker et al. 2004), 46% of the cropland area in Ireland (Lanigan et al. 2018), and 20–25% of the agricultural area of Denmark (Taghizadeh-Toosi and Olesen 2016). In France, less than 25% of the potential area is used for cover crops (Pellerin et al. 2020). However, Launay et al. (2021) assumed a large potential for growing cover crops on 93% of the French cropland area. Their SOC sequestration scenario included short cultivation windows of two months. In our scenarios, we only assumed additional cover crops during winter fallow since different climate conditions compared to France and the disproportionate effort involved prevent short-term cover crops in Germany. As the French cultivation window is more ambitious, a higher SOC sequestration potential has been estimated (0.131 Mg C ha^{-1} a^{-1} vs. 0.076 Mg C ha^{-1} a^{-1} within 30 years).

Constraints in realising the SOC sequestration potential of additional cover crops

The most important factor whether cover crops are grownis the farmer's management decisions. Only one third of the cultivation window for cover crops is recently used, with large differences between the three regions. While cover crops are recently grown on 10% of German cropland, their average annual frequency could be tripled to 30%.

There are several potential reasons why farmers do not grow cover crops in the available cultivation windows. One reason is dry weather conditions, especially in the summer when cover crops are established. This was supported by our results showing higher cover crop frequencies at sites with higher precipitation. Undersowing could help establish cover crops before this becomes more difficult in the late summer due to drought conditions.

Another reason for farmers not to grow cover crops is the fear that cover crops could reduce the soil water for the following main crop thus reducing the yields. However, the occasional occurrence of negative effects on water availability can be eliminated if the cover crop freezes during winter or is terminated in late autumn and left on the field as mulch (Kaye and Quemada 2017; Meyer et al. 2020).

Apart from water availability, important reasons given by European farmers for not growing cover crops are the associated costs, lack of know-how, and absence of perceived benefits for their farm (Smit et al. 2019). In order to take full advantage of the SOC sequestration potential of cover crops, it is therefore important to communicate more effectively the general advantages of growing cover crops, their positive effects on SOC stocks, and the related benefits with regard to soil quality. Additional subsidies would help compensate for the short-term costs incurred.

Climate change mitigation potential of additional cover crops

Our simulations indicate that recent management leads to SOC losses in cropland soils. Decreasing SOC stocks in cropland soils have also been found in other simulation studies (Riggers et al. 2021) and across Europe in repeated inventories (Ciais et al. 2010). The additional C input from cover crops increased simulated SOC stocks compared with the *business-as-usual* scenario and a scenario with *no cover crops*, but the results indicated that no net SOC sequestration could be achieved with cover crops alone within 50 years.

Recent SOC accumulation by cover crops could be tripled. *Recent* cover crops accumulate 2.2 Tg CO_2 a^{-1} and adding more cover crops could accumulate an additional 4.7 Tg CO_2 a^{-1} in the topsoils of German croplands (within 10 years on 11,672,000 ha). This suggests a *total* SOC accumulation potential of 7.0 Tg CO_2 a^{-1} or 11% of Germany's annual agricultural greenhouse gas emissions (62 Tg CO_2-eq a^{-1}). The additional SOC accumulation potential of 4.7 Tg CO_2 a^{-1} or 1.3 Tg C a^{-1} (within 10 years) corresponds to 1.5 per 1000 of the topsoil SOC stocks of German croplands. When expanding the simulation time to 50 years, the *total* annual accumulation rate falls to 3.7 Tg CO_2 a^{-1}, of which 2.5 Tg CO_2 a^{-1} originates from additional cover crops. This could still compensate for 6% of agricultural greenhouse gas emissions, with additional cover crops increasing the topsoil SOC stocks of German croplands by 0.8 per 1000. Thus, the SOC accumulation potential of additional cover crops makes up 20–40% of the 4 per 1000 goal for German croplands. The climate change mitigation effect is greater when cover crops are initially introduced into crop rotations and SOC accumulation rates are higher, and it decreases over time as SOC stocks approach a new equilibrium.

Cover crops are a promising option for enhancing SOC stocks in croplands and thus contributing to climate change mitigation. However, growing cover crops can potentially lead to more N_2O emissions that could counterbalance the positive SOC effects by about 5–10% (Guenet et al. 2021), with an increasing negative effect as SOC stocks approach a new equilibrium (Lugato et al. 2018). However, cover crops can reduce greenhouse gas emissions from fertiliser production and indirect N_2O emissions due to reduced nitrate leaching under cover crops (Abdalla et al. 2019). Additional climate change mitigation resulting from the increased albedo make up 13–19% of the total climate mitigation effects of cover crops in Europe (Lugato et al. 2020). In addition, cover crops enhance adaptation to climate change by reducing vulnerability to erosion and droughts (Kaye and Quemada 2017). Cover crops can therefore be viewed as a management option that has multiple benefits not only at farm level, but also on a continental and global scale for climate change mitigation.

Conclusions

Our detailed management data showed a large potential to increase cover crop adoption to 30% of the German cropland area what would increase SOC stocks by 7.0 Tg CO_2 a^{-1} compared to simulations without cover crops. However, our results revealed that cover crops alone cannot prevent German cropland soils from losing SOC without further transforming agricultural production.

A better regional scale estimation of cover crop biomass from both aboveground and belowground was important to estimate the C input for modelling SOC dynamics. The sowing date and climate strongly influenced how much cover crop biomass was produced resulting in the C input ranging from 1.3 Mg C ha^{-1} (late sowing, unfavourable climate conditions) to 3.6 Mg C ha^{-1} (early sowing, favourable climate conditions) per average cover crop across Germany.

Realising the ambitious scenario with cover crops after late harvested main crops will be challenging and requires subsidies to compensate short-term costs and additional farmer's know-how with cover crop establishment via undersowing. However, more cover crops are an important step towards permanent vegetation and soil cover in arable systems and thus a step towards sustainable and climate-smart agriculture.

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Author contributions All authors contributed to the study conception and design as well as verification of the results. Material preparation, data collection, analysis and visualization were performed by DS, LMF and RD. Programming was done by RD and DS. The first draft of the manuscript was written by DS and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The soil dataset used in this study is available in the OpenAgrar repository, https://doi.org/10.3220/DATA20200203151139. Management and C input data cannot be shared.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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