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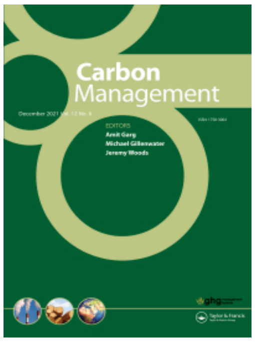

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Carbon removal potentials in agricultural systems – participatory scenario modelling with farmers in Sweden

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ABSTRACT

Estimates of theoretical climate change mitigation potentials in agriculture need to be complemented with investigations of factors that influence deployment. This study introduces a framework for landscape-level assessment of climate change mitigation in agriculture that accounts for existing land uses, soil carbon stocks, and farmers' preferences concerning specific mitigation options. The framework is used in an assessment of the deployment potentials for selected mitigation options in an agricultural landscape in Sweden, in which arable land covers approximately one-third of the land area. Three options were found to be preferable by farmers: biochar as soil amendment, cover crops, and (an increased) cultivation of ley crops in crop rotations. Cultivation of cover crops and leys was found to increase SOC stocks by 1.9 and 1.6 MgC ha^{-1} over three decades, respectively. About 10.2 MgC ha^{-1} is sequestered in soils over three decades when biochar is added as a soil amendment, if 50% of available residues are collected and utilized. This can be compared with GHG emissions from agriculture from the studied area, estimated at 1.6 Mg CO_2-eq ha^{-1} yr^{-1} (GWP100). The framework was found useful for assessing mitigation options in the agriculture sector, underlining farmer involvement to identify actionable strategies.

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KEYWORDS
Climate change mitigation; soil carbon; carbon dioxide removal potentials; agricultural systems; crop rotation; biochar

Introduction

Measures to increase, or reduce losses in, soil carbon in agriculture can contribute to climate change mitigation in the near term while also providing co-benefits such as higher yield levels [1–8]. Increases in the soil carbon content imply carbon dioxide removal (CDR) from the atmosphere, which counteracts warming caused by greenhouse gas (GHG) emissions. Considering the high complexity of soils and soil carbon dynamics and the influence of climatic conditions and current as well as historic land-use practices [9,10], any effect of soil carbon management measures should be considered context-dependent.

Changes in the soil organic carbon (SOC) content are determined by the balance between carbon inputs *via* biomass left on fields, roots, and organic amendments (e.g. manure) and carbon dioxide (CO_2) losses *via* biological decomposition processes [11]. In Sweden, a considerable amount of above-ground (AG) residues from agriculture practices, particularly from cereal cultivation, is left on fields [12]. Most of the carbon in these AG residues is emitted to the atmosphere *via* decomposition and therefore has a relatively small effect on SOC levels and hence soil carbon storage in agricultural soils. Other measures for enhancing SOC content in arable soils include the use of cover crops or catchment crops [8,13–15], and the inclusion of perennial grass-clover (ley crops) in the crop rotations [16]. These measures have demonstrated significant contributions to SOC in Swedish agricultural trials [17,18].

There is increasing interest in using AG residues as a feedstock to produce biochar for subsequent use as a soil amendment, which is expected to have a greater positive effect on soil carbon levels than current AG residue management as the carbon in biochar is less susceptible to decomposition [19]. Moreover, the porous structure of biochar can positively affect soil texture [20], phosphorus availability [21], and moisture retention capacity [22].

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Previous studies have investigated SOC dynamics and main drivers of SOC storage [23], as well as how context influences the feasibility of SOC management practices as climate change mitigation options [11]. For instance, Swedish dairy farms have higher rates of increase in SOC contents as well as greater SOC stocks than arable farms or pig farms [15]. This suggests that including knowledge about SOC dynamics associated with different agricultural production systems could improve regional and national estimates of SOC stocks and potentials for improving soil carbon levels through SOC management measures.

Farmers' land use reflects considerations of many factors, such as private economy, food markets, and crop insurance [4]. A study in Norway found that economy, time availability, subsidies, and the prospect of a farm persisting were the main motivations behind the implementation of specific management practices for climate change mitigation, while climate change was not an important motivation [24]. A study including 105 farmers in Finland found that farmers are more likely to implement SOC-enhancing measures that have co-benefits, especially enhancement of soil structure [25].

Here, we present a framework for landscape-level assessment of climate change mitigation in the agriculture sector that accounts for existing land uses, soil carbon stocks, and farmers' preferences concerning specific mitigation options. The framework is demonstrated in an assessment of measures to improve soil carbon levels in an agricultural landscape in western Sweden. Interviews and surveys with farmers were carried out and three measures were selected as reflecting farmers' views and preferences: pyrolysis of straw residues to produce biochar that is used as soil amendment, cover crops, and increased cultivation of ley crops in rotations. A GIS-based model was used to assess the mitigation effect of the measures, combining agriculture-related data for this landscape with scenarios developed based on agronomic principles and information from the farmers. We believe that the framework can help bridge theoretical estimates and practical realities, support policy development and implementation, and help farmers identify attractive climate change mitigation measures.

Materials and methods

Case study area

Swedish agricultural statistics are compiled for eight production regions (PRs, see Figure 1), defined according to latitude (climate) and other factors affecting crop choice and yields (e.g. lowland plains in agriculture districts and mixed agriculture/forest land in mid-altitude forest areas). The case study area (from here on, "the Landscape") belongs to PR3, which, together with PR1 and PR4, contains most of Sweden's cereal and oilseed cultivation. It consists of around 39,000 ha arable land (average clay content 30%), representing one-third of the land area in the two municipalities Mellerud and Vänersborg situated southwest of the lake Vänern in western Sweden. Cereal production occurs on around half of the arable land in the Landscape [26].

Land use and carbon flow model

Figure 2 shows the approach used in the assessment framework. First, crops and crop groups are selected and organized into standardized crop rotations (SRs). The SRs are subsequently combined to represent agricultural land use in the Landscape. Scenarios are then created by implementing specific changes in land management and/or biomass use.

The changes (measures) are made within one or several SRs. Finally, the Introductory Carbon Balance Model (ICBM) [27] was used to quantify the change in soil carbon stock over a 30-year time period, using the most recent updated parameters [28].

Construction of crop groups and standardized crop rotations

Crops were sorted into 8 crop groups (winter cereals, spring cereals, oil seeds, temporary grass/clover leys, seed leys, legumes, others, and fallow) that are used in the representation of land use in the model (Figure 2, details in Supplementary Table 1). Data on cultivated areas and yields were sourced from official agricultural statistics [26]. Yield levels (Yp) were set equal to the averages for 2019–2021 (Table 1). Seed leys, which is the cultivation of timothy, meadow fescue grass, red clover, etc., where the seed is harvested, are a specialized crop on arable farms in the Landscape. Seed leys typically yield around 1000 kg ha^{-1} for timothy and meadow fescue grass and 350 kg ha^{-1} for red clover, and the rest of the grass/clover crop is mostly returned to the soil after harvesting [29]. When running the model, we excluded the two groups "Other crops" and "Fallow." "Other crops" contains over 20 crops, making it hard to

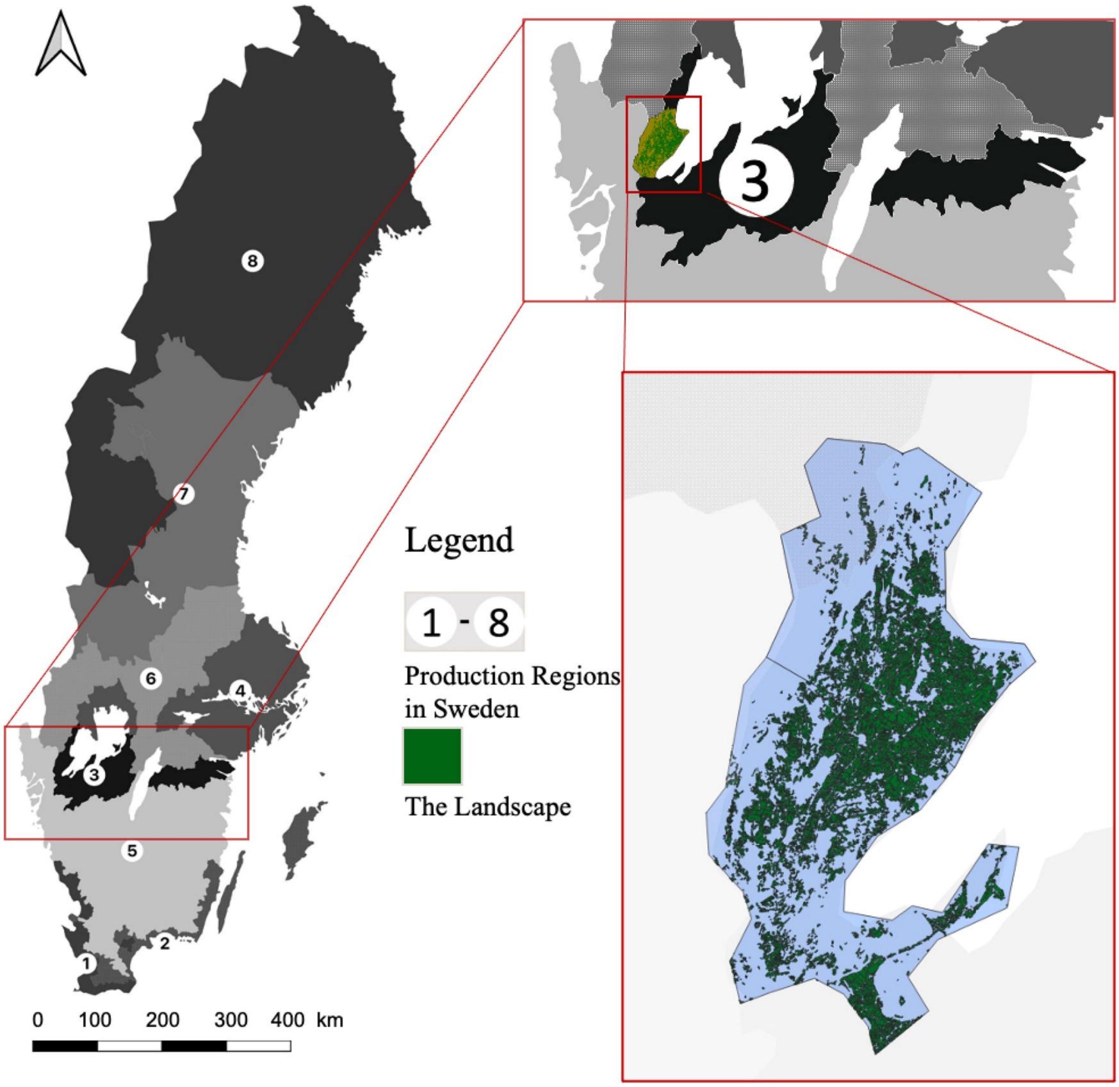

Figure 1. Sweden, Divided into eight agriculture production regions (PR), where the landscape is situated in PR 3 in Western Sweden. The lower right map shows the distribution of the arable land in the landscape.

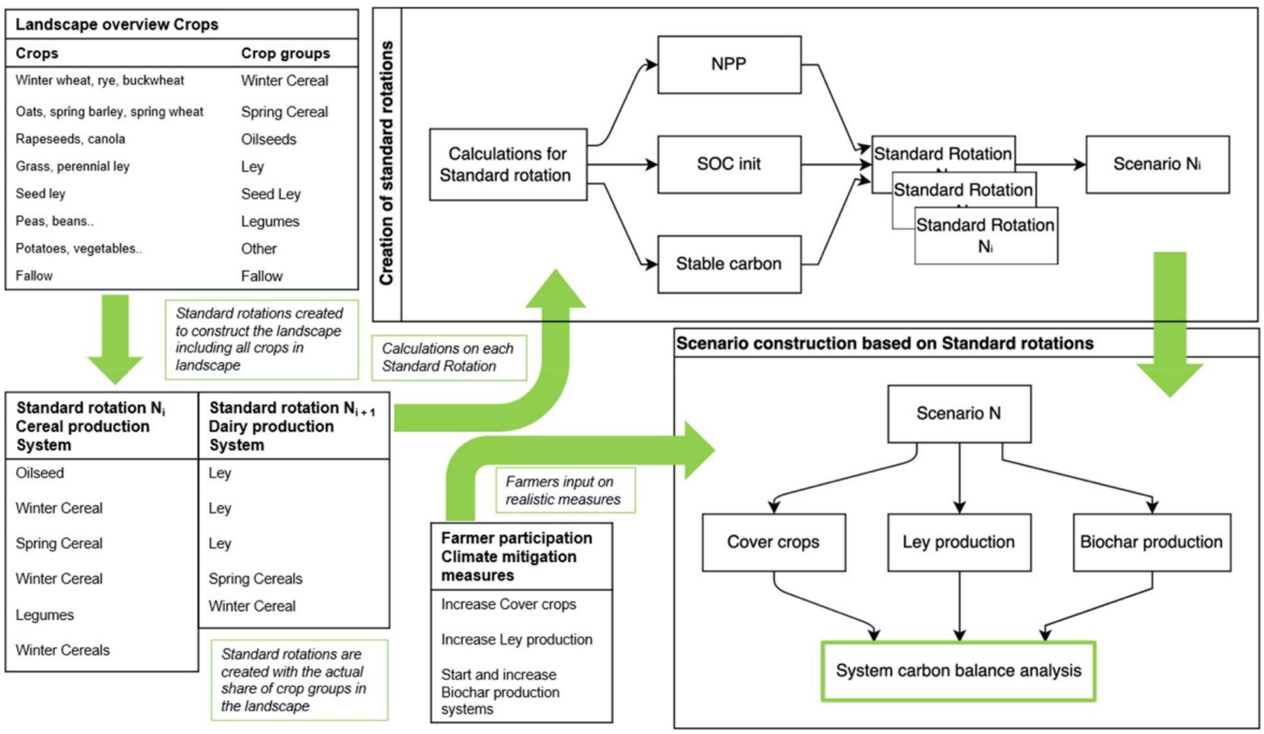

Figure 2. Graphical representation of the methodology to construct and combine SRs that are subsequently used in the scenario-based modeling and analysis.

Table 1. Average yields, Yp, (kg DM ha^{-1} yr^{-1}) for the 3 years 2019–2021, arable land per crop group, cultivated share of total arable land for each crop group in the landscape.

Crop group	Average yield (Yp), 3 year (2019–2021) [kg DM ha^{-1} yr^{-1}]	Arable land per crop group [ha]	Share of total arable land [share]
Winter cereal	5890	8713	0.22
Spring cereal	4740	11400	0.29
Ley	5700	9363	0.24
Seed leys	350–1000*	1945	0.05
Legumes	2850	1983	0.05
Rapeseed	3620	1449	0.04
Other crops	**	2437	0.06
Fallow	***	2271	0.06
Total		39 561	

*Depending on grass/clover species, yields of seed vary with lower in clover and higher in grass species https://sfo.se/kunskapsbanken/.
**No average yield is obtainable due to the vast differences among included crops.
***Fallow is assumed not to have any harvest.

Table 2. Crop sequences in standard rotations (SRs) representing five standard agricultural cultivation systems. Light grey in cursive "round 2", at end of the crop rotation, indicates a new round, as the rounds are continuous.

Year	SR1 83% Cereals	SR2 75% Cereals	SR3 63% Cereals	SR4 60 % Ley	SR5 57 % Ley
1	W Cereal	Rapeseed	Legumes	Ley	Ley
2	S Cereal	W Cereal	W Cereal	Ley	Ley
3	W Cereal	S Cereal	S Cereal	Ley	Ley
4	S Cereal	Legumes	Seed Ley	S Cereal	Ley
5	S Cereal	W Cereal	Seed Ley	S Cereal	W Cereal
6	Rapeseed	S Cereal	W Cereal	*Ley round 2*	S Cereal
7	*W Cereal round 2*	W Cereal	S Cereal	*Ley round 2*	S Cereal
8	*S Cereal round 2*	S Cereal	S Cereal	*Ley round 2*	*Ley round 2*

simplify. "Fallow" indicates unused agricultural land and was assumed not to be harvested.

Five SRs were defined and combined to represent arable land use in the Landscape, based on data on crop distribution in the Landscape [26] and statistics on management methods [30,31] (Table 2). Regional crop rotations for arable farming systems including cereals and oilseeds [31] were further developed into two SRs, one including legumes and the other including leys harvested for seed production, a specialized crop on arable farms in the region. The dairy farming systems (including leys) [32] were further developed into an SR with grass-clover ley reflecting general cattle farming systems and horse fodder production (Table 2). Information and statistics on cultivation practices reported at the level of production regions were also taken into account, e.g. pre-seeding crops for winter cereals and spring cereals respectively; composition of grass and clover in leys; distribution of temporary ley area by age; management of fallow land [33].

SR1 is a six-year cereal rotation with rapeseed as a break crop, reported as typical for arable farming systems in western Sweden [31]. SR2 is a modification of SR1, including legumes with eight-year intervals to reduce the risk of root rot pathogens (e.g. *Aphanomyces euteiches*) [34]. Seed cultivation of ley crops (clover, timothy, etc.) is a specialty in the Landscape, and SR3 is adapted for this based on discussions with farmers. SR4 reflects a typical land-use pattern in dairy systems and is based on data recorded from 1,849 dairy farms in a study where nutrient budgets were calculated [32]. SR5 is a modification of SR4, considering that around one-third of the ley area in PR3 is four years or older [35] (Table 2).

Initial SOC stock values were set based on SOC data for the region PR3 from the Swedish Agricultural Soil Survey and crop cultivation data from Integrated Administration and Control System (IACS)considering the frequency of ley crops versus annual crops in rotations [36].

Net primary production and distribution of carbon among crop components

The allometric equations in Bolinder et al. [37] were used to calculate the distribution of photosynthetically fixed carbon (net primary production basis) into four categories (Equations (1)–(4)), assuming that the C content in all plant components is 45% (DM basis), including *Harvest index* (HI) and *Shoot:Root* ratio (S:R). For crop groups containing several crops (winter cereal, spring cereal, and leys) a weighted average *HI* and *S:R* ratio value was calculated, see Supplementary Table 2.

$$Cp = Yp * 0.45 \quad (1)$$

$$Cs = Yp * (1 - HI)/HI * 0.45 \quad (2)$$

$$Cr = \frac{Yp}{(S : R * HI)} * 0.45 \quad (3)$$

$$Ce = Cr * Ye \quad (4)$$

$$NPP_{Carbon} = Cp + Cs + Cr + Ce \quad (5)$$

The *Ye* factor (in Equation (4)), representing extra carbon in rhizodeposition, is set at 65% of the root biomass carbon (*Cr*) for both cereal and ley crops. NPP_{Carbon} (Equation (5)) represents the total amount of photosynthetically fixed carbon calculated for each crop group [C ha^{-1} yr^{-1}], where *Cp* is harvest, *Cs* is straw (AG residues), and the sum of *Cr* and *Ce* is below-ground (BG) residues. Together with relative plant carbon allocation coefficients (Supplementary Table 2), these equations quantify the plant C allocation for all included crop types, i.e. the amount of C in harvest and in above- and below-ground residues.

Livestock population and associated manure production

The Landscape's livestock population is dominated by pigs managed for pork production and cattle managed for dairy and beef production. Additionally, there are some laying hens for egg production and a limited number of sheep. Horses are registered in the agriculture statistics only when they belong to the agriculture company. The real number of horses is thus underestimated in the statistics.

The total livestock population in the landscape was calculated per animal category and estimates were made of their respective consumption of roughage fodder, pasture, and cereals (Supplementary Table 3).

The quantifications were based on newly updated Swedish diets for cattle, pigs, and poultry [32] and horses and sheep [38]. Close to 30% of the Landscape's cereals are used as feed in livestock production, foremost in pig production, and roughly 60% of grass-clover roughage from the leys. An agricultural calculation tool (VERA) from the National Board of Agriculture (https://adm.greppa.nu/vera.html) was used to estimate the amount of produced manure based on the animal population, production level, feed intake, and manure management system (Supplementary Table 3).

The area required for spreading the manure, as specified in the Nitrate Directive (max 170 kg N ha^{-1} yr^{-1}), is 9,500 hectares, corresponding to around one-fourth of the Landscape's total area. The amount of manure used as an amendment on fields in the Landscape is assumed to be constant over the 30 years modeled.

Carbon model parameters and coefficients

To determine the stable carbon associated with each crop group in the five SRs, Equations (1)–(5) were combined with specifications of biomass uses to define carbon flow pathways for each crop group, as illustrated for winter wheat in Figure 3. Data on the current use of AG residues, today mostly used as bedding in livestock production, were obtained from national agricultural statistics [12]. Currently, about 60% of the AG residues from the total cereal grain area are not collected but ploughed down. For rapeseed, 100% of the AG residues are not collected. A list of factors and estimates concerning carbon flows in the Landscape, including usage of harvest for fodder, is available in Supplementary Table 5.

Scenario construction and analysis

Farmers' views and preferences concerning soil carbon management measures

The farmers' input concerning soil carbon management measures to implement within the SRs was collected through interviews, stakeholder meetings, and a survey. In the survey (response rate 60%), farmers were asked to rate their interest in measures to implement from a list based on a literature review [14,16,23,39]. Based on the answers, the measures were categorized as "high", "medium" and "low" interest, and three measures of "high" interest were included in the development of scenarios (Table 3). The complete list of measures suggested in the survey, including comments, is presented in Supplementary Table 4.

Cover crops

Cover crops in farming enhance nitrogen retention, carbon sequestration, and nutrient availability, and reduce erosion risk [40]. In Swedish long-term field (LTEs) trials (16–24 years), Poeplau et al. [16] reported that ryegrass cover crops increased SOC stocks by 0.32 ± 0.28 Mg C ha^{-1} yr^{-1}. A meta-review by Bolinder et al. [14], analyzing 20 long-term field trial publications, found an average SOC increase of 0.33 Mg C ha^{-1} yr^{-1}. The current study utilizes a fixed annual carbon input of 0.3 Mg C ha^{-1} yr^{-1}, the average of Poeplau et al. [16].

Increased ley cultivation

The increase in soil carbon stock resulting from inclusion of more ley cultivation in annual crop rotations is calculated with Equations (1)–(5). Carbon in the residues of ley crops is predominantly allocated to the root system [37], and the BG carbon contributes significantly to increases in the soil carbon stock since root-derived carbon contributes more to the stable SOC pool than AG carbon [39]. Previous studies have shown that

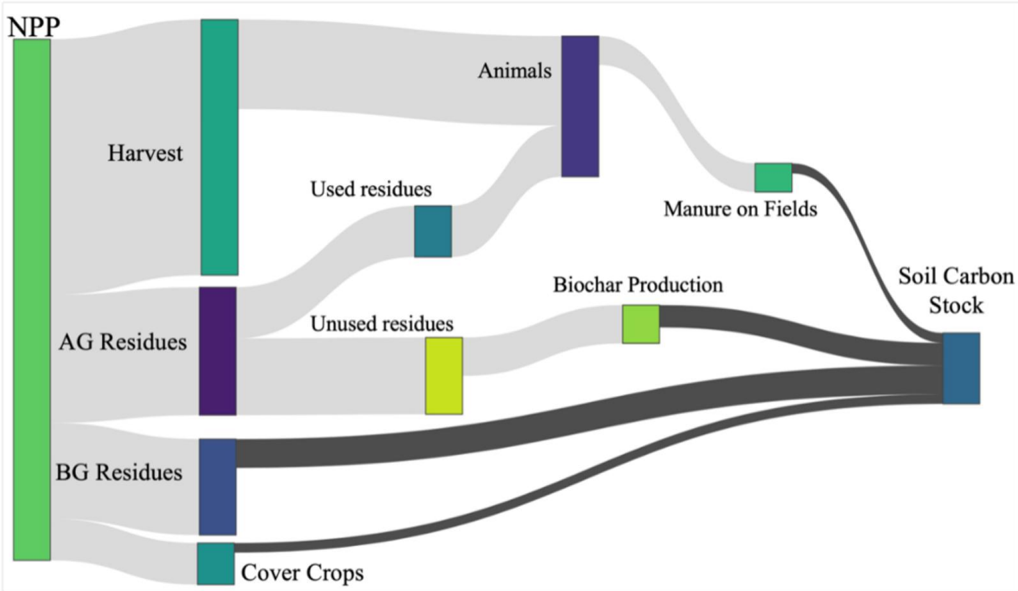

Figure 3. **Biogenic carbon flows associated with 1 ha of winter wheat with an under-sown cover crop that grows on the field in the autumn after the wheat is harvested. NPP-derived carbon is channeled to harvest, AG residues, BG residues, and cover crop, and further to different uses before contributing to the soil carbon stock. Only the flows relevant for the calculations are shown, e.g. cereal harvest used for other purposes than animal feeding and CO2 emissions from decomposition of BG residues left on fields are not depicted. The dark grey flows illustrate the contribution to the more stable soil carbon stock.**

Table 3. **Mitigation measures included in the scenarios. AG residues used to produce biochar are subject to availability based on either statistical use in the landscape or a theoretical maximum availability. In both scenarios, 100, 75, and 50% of available AG residues are modeled to acknowledge realistic levels of biochar production based on time management by farmers.**

		Collection of AG residues		
			Practical availability[c]	
Scenarios	Measures Implemented	Maximum[b]	% of Max	
Scenario 1 (Sc1) Includes more ley cultivation	Biochar from AG residues[a] Cover crops Ley in two annual rotations	100%	75%	50%
Scenario 2 (Sc2) No extra ley included	Biochar from AG residues[a] Cover crops	100%	75%	50%

[a]Straw residues available for biochar production include 60% of the straw from the Landscape's cereal cultivation (as 40% is collected and used for bedding and feed in animal production [12]) and 100% of the straw from rapeseed cultivation [31].
[b]Maximum (100%) AG collection represents 85% of total AG since a minor proportion of AG residues is not possible to harvest (short stubble and other surface debris) (Bolinder et al. [37]; Wiesmeier et al. [44]).
[c]"Practical" AG collection (representing 75% and 50% of Maximum) based on discussions with farmers (see further in the text).

ley-arable systems retain more carbon in soils than annual cropping systems [41].

Biochar production from straw residues

The persistence of biochar depends on its properties, which are influenced by the pyrolysis process and the characteristics of the feedstock. Additionally, the environment in which the biochar is applied plays a role in determining its recalcitrance [21,42]. The AG residue availability for biochar production is quantified based on harvesting statistics, Equations (2), and straw recoverability estimates [43], to obtain total straw production, from which straw use for (mainly) animal bedding [12] is deducted. Out of this, 85% is assumed to be theoretically possible to collect from the fields [44]; this is the maximum available AG residues not already used for something. The stable carbon content of biochar after 100 years was calculated following Azzi et al. [45] using data from Zhang et al. [46] assuming biochar produced from wheat straw at 400 °C, a biochar yield of 35.8%, carbon content of biochar at 64.2% and hydrogen content of biochar at 1.8%. These assumptions are in line with other studies [47,48]. Soil temperature was set to 7 °C, representative for average Swedish soil conditions [49]. The amount of biochar produced and the carbon content in that biochar is based on the results from Zhang et al. [46], while the persistency of this biochar is calculated with the presented model in the report by Azzi et al. [49].

Scenario construction

Two scenarios were developed (Table 3). In Scenario 1 (Sc1), leys and cover crops are included in the five standard rotations according to farmers' interest and adopting the maximum agronomic potential. Biochar is produced using the currently non-utilized AG residues from cereal and rapeseeds as feedstock. In Scenario 2 (Sc2) (No-ley) cover crops and biochar production are the same as in Sc1, but there is no inclusion of more ley crops in annual rotations. The availability of agricultural residues is modeled at three levels: 100, 75, and 50%. 100% represents a theoretical maximum, while the 75 and 50% levels are more conservative estimates reflecting practical limitations in collecting residues for pyrolysis.

Calculation and analysis of changes in soil carbon stock

Within each crop group and standard rotation, those SOC changes over time that can be attributed to AG residues, BG residues, or organic amendments (manure) are calculated using the ICBM model. Updated calibrations, such as humification factors and decay rates, from Bolinder et al. [50] are applied (Supplementary Table 6). Carbon input attributed to cover crops and carbon in biochar are added to the SOC changes to obtain the total soil carbon stock change in each scenario. The ICBM model was also used to calculate the SOC changes in a baseline (BAU) scenario in which crop rotations are not changed, the residues are incorporated in soils as in the current state, cover crops are not increased, and crop yields are assumed to remain constant. In this case, the soil carbon stock changes equal the SOC changes as there is no biochar production. The effect of implemented measures is then obtained as the difference in total soil carbon stock change over 30 years in a scenario compared to BAU.

The calculated soil carbon stock change in the two scenarios is compared with the greenhouse gas emissions (GHG) from the Landscape, with emission factors for N_2O emissions from N amendments and calculations following the 2019 refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [51] as applicable.

Results

Standard rotations – implemented measures and initial SOC stocks

The five constructed SRs account for 88% of the total hectares cultivated in 2022, slightly overestimating cereal cultivation. The discrepancy between this model and the real arable landscape is due to excluding the crop groups "Other crops" and "Fallow."

Specifications for Sc1 are shown in Table 4. Cover crops were included to the extent possible given that cover crops cannot be established before winter cereals and winter rape seed (sown in August and September), as the time window between harvesting the preceding crop and establishing the winter cereals and rapeseed is too short. Also, cover crops are not included the year before leys, as ley crops are established in the cereal crop during spring-summer as an under-sown crop in the cereal pre-crop of the ley. Ley crops were included in SR1 and SR2 only, as these rotations only consist of annual crops today, resulting in a 10% increase of perennial ley in the Landscape. Based on analysis of frequency of ley crops in rotations in relation to SOC contents and changes [36], initial (present) SOC stocks were established for the five SRs forming the basis for calculating SOC stock changes over time with the ICBM model (Table 4). As has been reported [15,36], farming systems with ley cultivation and cattle generally had higher SOC stocks than arable (annual crop) farming systems.

Potentials for increasing soil carbon storage at landscape level

The average initial SOC stock in the topsoil (0–20 cm) in the Landscape was estimated at 72 MgC ha^{-1} based on the distribution of the five SRs (see Table 4). The average SOC content increased to 77.6 MgC ha^{-1} in BAU (Figure 4), corresponding to an average increase rate of 0.19 MgC $ha^{-1}yr^{-1}$ over the 30-year period. This is in line with present average rates according to the Swedish soil survey [52].

The maximum C removal in the two scenarios (recovering 100% of available AG residues for biochar) was calculated over the 30-year period (Figure 4(a)). Biochar contributes to 75% and 86% of the C removal potential in Sc1 and Sc2, respectively, when assuming that all available AG residues from cereal and rapeseed crops can be utilized for biochar production. This SOC increase corresponds to a sequestration rate of 0.55–0.59 MgC $ha^{-1}yr^{-1}$ which is about three times higher than the SOC development in BAU.

When considering farmers' views on the practical availability of collecting straw residues and

Table 4. **The maximum change allowed in the five rotations when agronomic limitations are considered. Based on ley crop frequency, each SR is assigned an initial SOC stock [Mg C ha[-1]].**

Year	SR1 50% Cereals	SR2 50% Cereals	SR3 63% Cereals	SR4 60 % Ley	SR5 57 % Ley
1	W Cereal + CC	Rapeseed	Legumes	Ley	Ley
2	S Cereal	W Cereal + CC	W Cereal + CC	Ley	Ley
3	Ley	S Cereal + CC	S Cereal	Ley	Ley
4	Ley	Legumes	Seed Ley	S Cereal	Ley
5	W Cereal	W Cereal	Seed Ley	S Cereal	W Cereal + CC
6	Rapeseed	S Cereal	W Cereal + CC	*Ley round 2*	S Cereal + CC
7	*W Cereal round 2*	Ley	S Cereal + CC	*Ley round 2*	S Cereal
8	*S Cereal round 2*	Ley	S Cereal	*Ley round 2*	*Ley round 2*
Agricultural focus	Cereal production	Cereal production	Cereal production	Dairy production	Cattle and horse fodder production
Initial SOC stock [Mg C/ ha]	67.7[a]	67.7[a]	69.0[b]	75.4[c]	75.4[c]
Share of crop land in the Landscape [ha]	**15 % (6101)**	**16% (6451)**	**19% (7325)**	**17 % (6687)**	**21% (8289)**

CC = cover crop cultivated (with and) after the main crop. Ley = perennial grass clover leys substituting for cereal crops. Light grey in cursive "round 2", at end of the crop rotation, indicates a new round, as all SRs are assumed to be continuously repeated over time.
a = SOC stock based on fields with no ley; b = SOC stock based on fields with 20–40% ley; C = SOC stock based on fields > 60% leys (37).

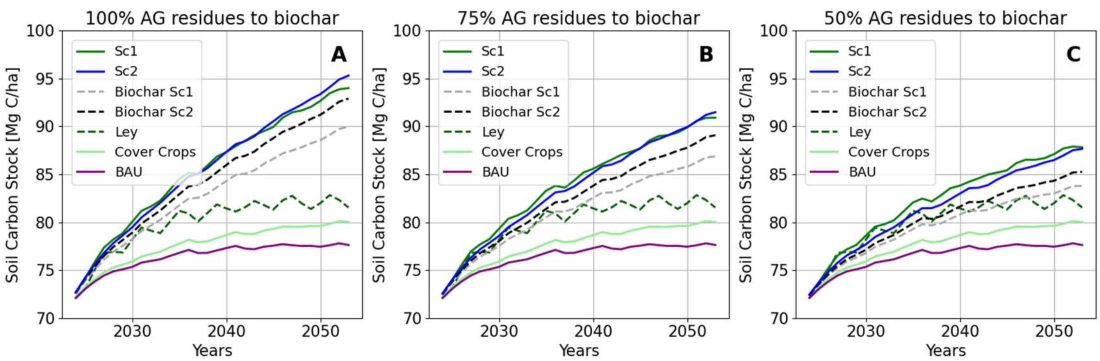

Figure 4. **Modeled soil carbon stock for the landscape, with 100, 75 and 50% (A, B, C) of available AG residues used to produce biochar. Ley, cover crops, and business as usual (BAU) are consistent across all three models. These results indicate that with decreasing biochar production due to lower availability of AG residues, the contribution of ley and cover crops becomes more significant for the total CDR in the landscape. This is found in the 50% AG residues to biochar (C), where Sc1 sequesters more carbon than Sc2.**

thus the utilization potentials of the residues (i.e. assuming that 75% or 50% of the maximum can be used for biochar, see Table 3), the total CDR effect decreases (Figure 4(b,c)).

When 50% of available AG residues are used to produce biochar, the total CDR effect was calculated at 10.2 and 10.0 MgC ha^{-1} in Sc1 and Sc2, respectively over the period (Figure 4(c)), corresponding to a yearly C sequestration rate of 0.34–0.33 MgC $ha^{-1}yr^{-1}$ which is still a considerable increase, close to double the rate in BAU.

The integration of cover crops increases C removal with an average of 1.9 MgC ha^{-1} after 30 years (SR1 = 1.5 MgC ha^{-1}, SR2 = 2.4 MgC ha^{-1}, SR3 = 3.3 MgC ha^{-1}, SR4 = 0.0 MgC ha^{-1}, SR5 = 2.4 MgC ha^{-1}). The use of leys in Scenario 1 increases C removal by on average 1.6 MgC ha^{-1} (SR1 = 5.1 MgC ha^{-1}, SR2 = 2.8 Mg C ha^{-1}, SR3-SR5 = 0.0 Mg C ha^{-1}) over the same period (Figure 4).

Over 30 years, the implemented measures correspond to an average CDR of 2 and 2.2 Mg CO_2-eq $ha^{-1}yr^{-1}$ in Sc1 and Sc2, respectively, for 100% use of available AG residues and 1.2 Mg CO_2-eq $ha^{-1}yr^{-1}$ in both Sc1 and Sc2, for 50% use of available AG residues for biochar. GHG emissions from the Landscape's agriculture due to enteric fermentation (CH_4) in livestock and nitrogen turnover in soils (from residues and direct N_2O emissions from input of mineral and organic fertilizers) correspond to around 1.6 Mg CO_2-eq $ha^{-1}yr^{-1}$ (Supplementary Table 7).

Potential of measures for increasing SOC storage in crop rotations

The opportunities to implement the measures and the resulting CDR potentials vary across the five rotations. In Sc1, rotations SR1 and SR2 have the highest annual average SOC increase over the 30-year period, calculated at 0.78 and 0.65 MgC $ha^{-1}yr^{-1}$, respectively, when 100% of the available AG residues are used for biochar (Figure 5(a)). Using 50% of the available AG residues for biochar results in an annual average SOC increase 0.50 and 0.41 MgC $ha^{-1}yr^{-1}$ respectively for SR1 and SR2. The inclusion of ley crops in SR1 and SR2 results in an annual average SOC increase of 0.17 and 0.092 MgC $ha^{-1}yr^{-1}$, respectively (Figure 5); the

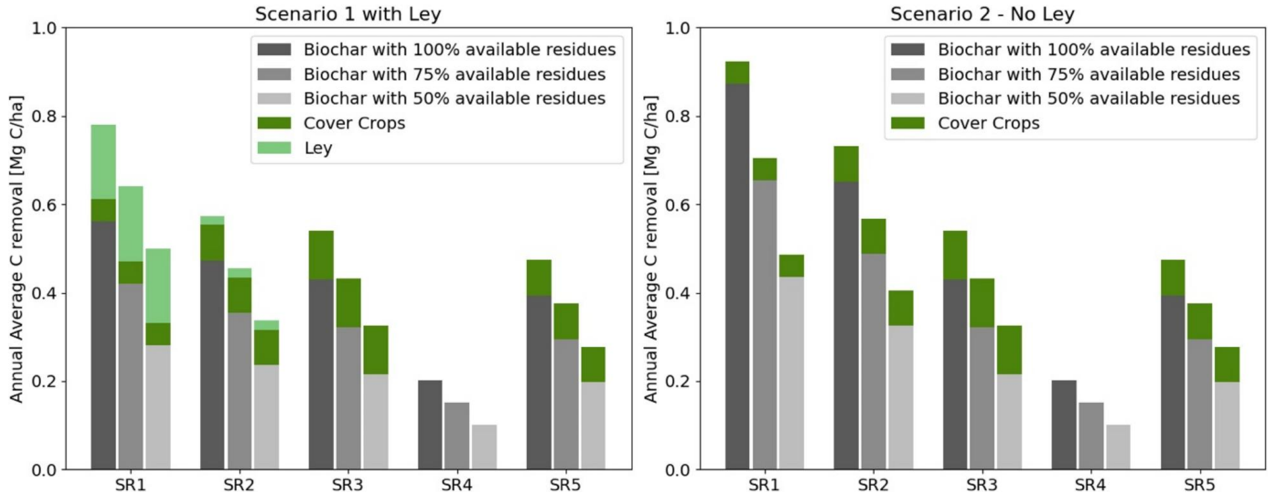

Figure 5. Soil carbon increase resulting from each measure included in Sc1 and Sc2—allocated among the five standard rotations in the landscape, expressed in annual average carbon removal contribution in each standard rotation for the years when the measure is implemented. The increase shown represents the soil carbon increase on top of the increase occurring in BAU.

difference is due to a higher incidence of leys in SR1, two years in the six-year rotation (33%) versus two years in the eight-year rotation (25%) of SR2, see Table 4.

In contrast, cover crops contribute more to SOC increase in SR2, as this rotation provides more opportunities for including cover crops due to a higher share of spring-sown crops. SR4, a typical dairy farm rotation, has the lowest potential for increasing SOC due to limited options for implementing the investigated measures. In this farming system, ley crops are already the dominating crop, grown in three years of the five-year rotation (60%); spring cereals are more frequently cultivated, and thus there is not much straw available for biochar production. However, it is important to note that this rotation, with leys dominating land use and high initial SOC content, represents an important part of the total soil carbon stock of the landscape.

The inclusion of cover crops is more important for the average annual SOC increase in SR3 and SR5, especially when considering the case of 50% availability of AG residue for biochar (Figure 5), which farmers considered more realistic for handling residues. In SR3, with cover crops in three years out of eight (Table 4), the average yearly SOC increase over the 30-year period was calculated as 0.11 MgC $ha^{-1} yr^{-1}$.

In Sc2, the cropping pattern in the landscape is unchanged, and thus the magnitude and distribution of responses to measures only differ in SR1 and SR2 (Figure 5(b)). Despite having no ley crops in the rotation in these two rotations, the average annual SOC increase is higher in Sc2 compared to Sc1 when 100% of available AG residues are used for biochar. This is due to the relatively high frequency of autumn-sown crops (especially in SR1, see Table 2) which have substantially higher AG residue production than spring-sown crops (foremost oats and barley). However, when looking at using 50% of available AG residues for biochar, the estimated outcome in SOC increase and thus CDR is relatively similar in Sc1 and Sc2, in the range of 0.10–0.50 MgC $ha^{-1}y^{-1}$ in annual average over the 30-year period, with the higher outcome in SR1.

Discussion

Both historical land use and current farming systems need to be considered when contemplating agricultural measures to increase soil carbon, as these are major determinants of initial SOC stocks [15] and affect how much flexibility there is in adjusting crop rotations. The options analyzed in this study were selected based on literature [8] and discussions with farmers to identify measures considered to be the most feasible. The consideration of crop rotations based on farming system and the adaptation of measures based on agronomic knowledge of these rotations were vital parts of the modeling framework. The modeling framework is developed to enable analyses of the effects of many different types of land-use interventions as well as changes in parameters, such as adjusting carbon allocation within crop groups (straws and roots), including manure (biofertilizers from biogas production are to be included), and using biochar as soil amendment. Also, combinations of crop groups, and thereby different crop rotations, can be constructed to reflect an agricultural landscape's structure, e.g. for assessing shifts from cattle production to other farming systems. Information on initial SOC stock was based on results from the Swedish soil survey combined with crop data over several years [36] and this input data can be modified based on specific knowledge of the agricultural system investigated.

The crop rotations constructed represent 88% of the agricultural arable land in the landscape and reflect present cultivation patterns including cereals, rapeseed, legumes, leys, and seed leys. Around 5% of the land is fallow; as there is no information on whether this land is bare, it is not included in the analysis. However, in the future, this acreage could be used for growing biomass as feedstock for biochar, biofuel, or other bio-based products, as it is a non-utilized land area. We could not find the information needed to assess the extent to which the “Other crops” land category can accommodate measures to increase soil carbon or other climate change mitigation measures. Given that around 7% of the Landscape falls into this category, research is warranted to clarify its potential.

Cover cropping showed a positive sequestration effect on the average annual SOC increase in the Landscape, but its contribution varies between the rotations depending on the frequency of cover crops (Table 4). The results also show that the potential to build soil carbon differs among the investigated rotations. Three rotations (SR3-5) already had, to a varying degree, ley crops included and thus higher initial SOC stocks. Consequently, there was less opportunity to incorporate the measures in these rotations compared to the two annual rotations (SR1-2) and thus not as large an increase in SOC in response to the measures. However, climate change mitigation is achieved not only when soil carbon stocks are increased but also when existing soil carbon is protected [8], and this is achieved in the rotations with leys from the beginning, too. The effects of including ley crops in crop rotations have been investigated in several studies, and it is well-documented how SOC decay varies between annual and perennial crops [53,54]. The calculated annual average SOC increase due to leys is in accordance with Kätterer et al. [41], but depending on the varying frequency of the ley crops in the individual rotations (e.g. SR2 25% and SR4 60%, see Table 4), their contribution to the total SOC increase over the 30-year period varies.

Establishing the initial SOC values is essential when modeling changes in SOC. One limitation of this study lies in the spatial modeling approach, where SOC stock estimates are affected by data granularity; higher spatial accuracy could generate more precise SOC estimates. Furthermore, this study focuses on the climate change mitigation resulting from soil carbon management and does not include other important co-benefits that arise from included measures. For example, including leys in rotation with annual crops leads to less pesticide use and lower nutrient leaching in the overall rotation.

The quantification of biochar production is directly correlated to the availability of crop residues, and attention should be paid to the substantially higher straw production from winter-sown cereals and rapeseed. Apart from feedstock origin, temperature of pyrolysis in biochar production is an important factor for yields and long-term C stability [42,46,49,55]. Zhang et al. 2020 [47] showed that the biochar yield decreases with increasing temperatures but stabilized above 400 °C, which was the temperature level adopted in the modeling. Higher temperatures result in slightly lower yields but higher carbon content, providing a stable estimate of carbon content in biochar.

Using crop residues for producing biochar has been identified as a promising land-based climate change mitigation option at a global scale [8], and in the agricultural landscape studied here, there were considerable amounts of straw available. However, while the farmers expressed a clear interest in biochar production, they also expressed concerns about the practical feasibility of this option. Collecting large amounts of crop residues from cereal and rapeseed fields was described as challenging, since this must be done at the busiest time of the year, coinciding with the harvest of all annual crops and the sowing of winter cereals, mainly wheat, and rapeseed, for the coming year. Farmers also expressed concern pertaining to possible negative effects on soil fertility from removing major amounts of straw residues and returning biochar to the fields. In the most extreme case, rotations SR1 and SR2 in Scenario 2, the maximum AG residue outtake for biochar production means that straw residues are collected every year in the rotation. This would mean much less energy from straw for the soil organisms in the fields, and, further, it is not fully known how soil microbial communities respond to biochar application under European conditions [56].

Farmers’ uncertainty about the amount of straw residues to use for biochar production was the basis for quantifying alternatives in which lower shares of the available straw residues were collected. As seen in Figure 5, with a lesser amount of residues going to biochar, contributions of leys and cover cropping become relatively more important for the overall SOC increase; therefore Scenario 1, in which both measures are implemented, seems to be a more attractive future scenario for farmers who want to enhance soil carbon stocks in their cropland. This scenario involves changes in crop cultivation since ley crops substitute for cereals in rotations that currently have annual crops only (SR1-2), which requires a new market for the harvest of the ley crops, as the pre-condition for the study was to keep present animal production at a constant level. However, this can be realized through developing new uses of grass-clover biomass as feedstock for green biorefineries producing protein concentrates (replacing soy imports), biofuels, and other bio-based products, making this a promising option for improving land management [57,58] and gaining interest among farmers.

Calculations on GHG emissions included the most important emissions sources, namely methane emissions from enteric fermentation by livestock and direct nitrous oxide emissions from synthetic and organic nitrogen fertilizers, and nitrogen in crop residues (both above-ground and below-ground) [59]. The GHG emissions from the Landscape were calculated at 1.6 Mg CO_2-eq $ha^{-1} yr^{-1}$ (GWP100), slightly lower than the national average in Swedish agriculture [60] and lower than the emission reduction achieved in the most optimistic cases.

Conclusion

By combining analytical modelling and statistical data with information about farmers' views and preferences, this framework proved to be useful for assessing climate change mitigation options across varied agricultural systems and location-specific conditions. The findings highlight the mitigation potential of cover crops, leys, and biochar from crop residues in agriculture. The implementation of cover crops and leys in crop rotations showed that agronomically feasible implementation has a positive impact in reducing the net GHG emission from the modeled landscape. The production and use of biochar as a soil amendment increases the soil carbon stock substantially, contributing the most to carbon sequestration. When utilizing 50% of the available AG residues to produce biochar, the net CDR is more than the annual average for cover and ley crops combined. This information about the CDR effects of various farming practices can be useful for stakeholders considering options for climate change mitigation in the agriculture sector, allowing for comparison with alternative uses of biomass to support mitigation in other sectors.

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Authors' contributions

Andreas Rehn (AR), Göran Berndes (GB), Christel Cederberg (CC) and Oskar Englund (OE) contributed jointly to conceptualize the research and writing the article. AR performed the method development with support from OE, visualization, and formal analysis with support from GB and CC.

Code availability statement

The code used for data analysis and model development in this research is available online at a public repository on GitHub and can be accessed at the following URL: https://github.com/climatecarbonlanduse/CDR_landscape_Sweden

Disclosure statement

The authors declare that they have no competing financial interests or personal relationship that could have appeared to influence the work reported in this paper.

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Data availability statement

The input data of this study are available by following the respective references. No physical field studies nor any collection of any type of biomass have been conducted in this study.

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