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Managing Soil Carbon Sequestration: Assessing the Effects of Intermediate Crops, Crop Residue Removal, and Digestate Application on Swedish Arable Land

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ABSTRACT

Promoting the bioeconomy to aid in the achievement of sustainability goals has increased demand for biomass as feedstock. Residual biomass from agricultural production is an attractive option, as it is a by-product that does not compete with food production. However, crop residues are important for the preservation of soil quality, especially for the maintenance of soil organic carbon. Therefore, their use can conflict with environmental goals and initiatives that aim to preserve soil fertility and carbon stocks. Nevertheless, the adoption of intermediate crops could compensate for the negative effects of crop residue removal. Moreover, if crop residues are used for a bioeconomy pathway such as biogas production, the resulting digestate derived from the anaerobic digestion process could be returned to the soil, providing an input of highly recalcitrant carbon. In this study, we modeled the effects of removal of crop residues, the cultivation of intermediate crops, and the application of digestate on Swedish soil organic carbon stocks. Our results suggest that the inclusion of intermediate crops could raise the carbon stocks at equilibrium by an average of 1.93 t C ha^{-1} (~3% increase) with a notable spatial variation. Digestate application showed a higher average increase (3.3 t C ha^{-1}, ~5%) with an even higher variation. The removal of crop residues was detrimental in some areas, resulting in a loss of carbon, which could not be compensated for entirely by the introduction of intermediate crops or digestate recycling. Combining these two practices showed overall positive effects on soil organic carbon stocks; however, the results cannot be generalized at any spatial location, and we emphasize the importance of assessments tailored to local conditions.

1 | Introduction

Among the sustainability goals presented in the Agenda 2030 (UN General Assembly 2015), action to mitigate climate change and tackle its negative impacts has gained considerable global attention. The European Green Deal stated the target of reaching climate neutrality in the European Union by 2050 (European Commission 2019). The set of proposals devised in the “Fit for 55” package support this target by facilitating the implementation of initiatives aligned with climate goals (European Council 2023). However, recent reports from the United Nations stress the insufficiency of current national plans and the pressing necessity to increase efforts aimed at limiting the global temperature rise, as specified in the Paris Agreement (UNFCCC et al. 2023a, 2023b).

The implementation and further development of the bioeconomy strategy in Europe (European Commission 2018) can aid in reducing net greenhouse gas emissions by promoting the transition to socio-technical systems increasingly less reliant on fossil resources (Kludze et al. 2013; Sharma and Malaviya 2023). Other approaches, such as the 4 per mille program (Minasny et al. 2017), focus on carbon capture measures to combat climate change. This program proposes that increasing the world's soil organic carbon (SOC) stocks by 0.4% annually can offset CO_2 emissions, over a period of 20 years (Martin et al. 2021). Due to the interconnectedness and indivisible nature of sustainability goals (Weitz et al. 2018), strategies aiming to address indicators related to climate change often have an effect on other goals and targets (Pham-Truffert et al. 2020). Promoting the bioeconomy can boost the development of the biofuel industry and other biobased products (Björnsson and Prade 2021; Gustafsson and Anderberg 2023; Soltaninejad, Jazini, and Karimi 2022), while enhancing the circularity of production systems and nutrients with technologies like anaerobic digestion (AD) for biogas production (Gustafsson and Anderberg 2023; Launay et al. 2022; Levavasseur et al. 2022). Such applications not only allow for the production of materials and energy solutions but also generate valuable by-products that can be used in agricultural production as organic amendments (OA; Gustafsson and Anderberg 2023). Also, a widespread implementation of the 4 per mille program would not only harness the ability of soils to sequester atmospheric CO_2 but also contribute to the resilience of food systems by improving soil fertility (Soussana et al. 2019).

However, some trade-offs, limitations, and drawbacks related to these schemes have been highlighted (Björnsson et al. 2013; Lantz et al. 2018; Martin et al. 2021). The initial approach of first-generation biofuels generated a demand for non-food biomass, which brought up the "fuel vs. food" debate. This approach threatened food security and sovereignty, while generating emissions from indirect Land Use Change (iLUC) due to the displacement of agricultural land (Lantz et al. 2018; Prade et al. 2017). Developing second-generation biofuels reliant on waste or residual biomass has been a promising alternative to that problem (Lantz et al. 2018; Prade et al. 2017). However, there have been concerns regarding the role of crop residues in agroecosystems and the negative effects of their removal from the agricultural land (Liu et al. 2014; Poeplau, Bolinder, et al. 2015), which would contradict the intention of the 4 per mille program. Moreover, the feasibility of this program has also been questioned, thanks to the natural limitations of the carbon storage capacity of soils (Martin et al. 2021) and applicability limitations at different spatial scales (Soussana et al. 2019). In several instances, it is not possible to achieve the levels of carbon input required to maintain this level of carbon sequestration (Poulton et al. 2018).

Although the role of crop residues in long-term soil quality has been highlighted (Kludze et al. 2013; Kluts et al. 2017; Liu et al. 2014), it has also been suggested that their use in bioeconomy applications can have an overall positive impact on SOC accumulation and carbon emission reduction (Andrade Díaz et al. 2023; Björnsson and Prade 2021; Poeplau, Kätterer, et al. 2015). Moreover, other agricultural practices, like fertilization and the application of manures, reduced tillage, and intermediate crops (ICs), have proved to have a more significant effect on soil fertility than the incorporation of crop residues (Kätterer and Bolinder 2022). IC is an umbrella term that encompasses cover crops, catch crops, and green manures, regardless of their function in the agroecosystem (Barrios Latorre et al. 2024; Björnsson and Prade 2021). The distinction between "catch crops" and "cover crops" can be particularly problematic in the Swedish context, where farmers apply for different types of subsidies based on which type of ICs they are cultivating (Jordbruksverket 2023). Therefore, for our purposes, we use "IC" as a single concept. ICs offer several benefits for agricultural production and the mitigation of environmental impacts, within aspects like plant nutrient recovery and the prevention of soil erosion (Abdalla et al. 2019; Aronsson et al. 2016). They have also gained attention as a potential source of biomass for bioenergy production, which can simultaneously increase SOC stocks (Herbstritt et al. 2022; Launay et al. 2022; Levavasseur et al. 2022). In Northern Europe, IC's capacity to compensate for the carbon losses from crop residue removal has been analyzed (Barrios Latorre et al. 2024; Jensen et al. 2022).

While previous research has explored the effects of bioeconomy pathways on soil in the European context (Andrade Díaz et al. 2023), there is no study that quantifies the long-term effects on SOC stocks arising from the combination of crop residue removal and use and the inclusion of IC in crop rotations. By making use of the Introductory Carbon Balance Model (ICBM) (Andrén and Kätterer 1997; Menichetti, Kätterer, and Bolinder 2024), we aim to investigate these potential consequences. Here, our main goal is to model the effect of introducing IC in typical crop rotations, combined with the removal and use of crop residues for AD and the return of the resulting digestate to the soil. Furthermore, our objectives are to (1) describe SOC development over time and stocks at equilibrium or steady state for a base scenario assuming conventional management; (2) compare the evolution of SOC under alternative scenarios, defined by the presence of IC and the use of crop residues for AD; and (3) evaluate trends of SOC stocks in relation to achieving the "4 per mille target" for carbon sequestration.

2 | Methods

The analytical framework of this study comprehends the assessment of the long-term effects on SOC stock arising from the use of crop residues for a bioeconomy pathway and the cultivation of IC on Swedish arable land. This is done by designing and comparing different scenarios defined by the use of crop residues and the cultivation of IC, as presented in Table 1. A base or reference scenario (1) was defined assuming no removal of crop residues and no IC cultivation. However, in reality, some residues are currently used for purposes other than incorporation into the soil (e.g., bedding and heating) and IC are cultivated to some extent. The base scenario definition provides a baseline for a contrasting comparison of the effects of growing IC and using the biomass for AD with the return of digestate to the soil. For this study, oilseed radish (OR) was selected as a model IC, as in Barrios Latorre et al. (2024).

The geographical scope of this analysis includes the 84 Swedish yield survey districts (SKO, in Swedish *skördeområde*) considered by Barrios Latorre et al. (2024). These districts correspond to areas approved by the Swedish Board of Agriculture for environmental compensation, where farmers are incentivized to

TABLE 1 | Scenario definition for the comparison of the effect on SOC of the inclusion of IC and the use of biomass for anaerobic digestion (AD).

Scenario	Harvest and AD of residues	Cultivation of IC	Harvest and AD of IC biomass
S1 (base)	No	No	No
S2 (IC)	No	Yes	No
S3 (AD)	Yes	No	No
S4 (IC+AD)	Yes	Yes	No
S5 (IC+AD+)	Yes	Yes	Yes

grow IC (Jordbruksverket 2023). The SKOs are the most detailed geographical units used by Statistics Sweden (SCB) and the Swedish Board of Agriculture (*Jordbruksverket*) for reporting agricultural statistics. More detailed information about the utilization of these data is provided in the following sections.

All the analyses were carried out at a geospatial level using the GIS software ArcMap 10.8.1. Several inputs required for the carbon modeling were included as layers, either as vector or raster datasets. Initial vector data inputs were rasterized at a 100 m × 100 m (1 ha) spatial resolution, in order to perform model calculations using Map Algebra. The outputs of the application of the model were values of changes in carbon steady state relative to the base scenario and annual changes in SOC stocks that could be compared to the 4 per mille initiative proposal. Data inputs and results aggregated by SKO are compiled in an open data repository (Barrios Latorre 2024b).

2.1 | The Introductory Carbon Balance Model

Like other models describing organic carbon dynamics in the soil (Bruni et al. 2022), the ICBM takes into consideration that carbon decomposition follows first-order kinetics. The original model developed by Andrén and Kätterer (1997) considers a young (Y) and an old (O) carbon pool, each with distinct decomposition rates, k_Y and k_O. A third edaphoclimatic factor is summarized in the r_e parameter and describes the external influence of climate and soil physical properties on the decomposition rates of the young and the old pools. This parameter was further explored in the ICBM regional model (Andrén, Kätterer, and Karlsson 2004) as a version that adapts to different production regions in Sweden. Eight different values for each of the production areas covering Sweden were presented by Andrén et al. (2008) and are extrapolated in this study to the SKOs under examination.

A humification coefficient (h), determining the fraction of the input that is stabilized over the long term (Andrén and Kätterer 1997), is dependent on the type of organic input and affected by factors such as the biomass' lignin content (Andrén et al. 2008). A combined analysis of these parameters allows the model to predict annual changes in Y and O (dY/dt and dO/dt) as well as establish the point in time when the carbon pools reach steady state conditions (Y_{ss} and O_{ss}), given constant carbon inputs. Therefore, overall carbon at steady state (C_{ss}) is defined as the sum of Y_{ss} and O_{ss}.

Here, we used a recent calibration of the ICBM (Menichetti, Kätterer, and Bolinder 2024). It considers three young pools representing different carbon input sources: debris from aboveground residues (Y_l), belowground/root biomass (Y_r), and additions of OA like manure (Y_m). Additionally, Menichetti, Kätterer, and Bolinder (2024) presented updated values for the decomposition rates, k_Y and k_O, as well as h for aboveground and belowground crop residues, and several organic materials like manure and sewage sludge. Most of these values are used in this study and are presented in Table 2 (h for digestate was assumed to be the same as for manure). However, due to the low stabilization of organic carbon from aboveground residues observed in Swedish sandy soils (Poeplau, Kätterer, et al. 2015), a humification value for these carbon inputs was selected as a function of clay content:

$$h = 0.1571301 - \frac{0.1515885}{1 + \left(\frac{\text{Clay}}{35.3256091}\right)^{7.8835713}} \quad (1)$$

where h is the humification coefficient and the clay content is expressed in percentage (%). The selected function was developed based on the original data from Poeplau, Bolinder, et al. (2015) and Poeplau, Kätterer, et al. (2015) and is further described in the Supporting Information (Figure S1; Table S1). Clay content values for calculating humification coefficients come from a raster dataset for Sweden provided by Piikki and Söderström (2019).

2.2 | Estimation of Organic Carbon Inputs

Carbon inputs were determined by establishing total biomass inputs at the SKO level. This was achieved by using available crop production statistics, as is described in the following sections. For the spatial analysis, we assumed that all carbon inputs were a yearly constant and homogenously distributed within single SKOs. This analysis does not include the total agricultural land, as it focuses on arable land, excluding pastureland (*betesmark*). Furthermore, within arable land, the areas dedicated to grazing meadows (*betesvall*) are also not included.

2.2.1 | Aboveground Biomass

Aboveground biomass (AGB) inputs considered in this study include the residual biomass from crop production and IC biomass. Differences in total AGB inputs between different scenarios rely on whether there is cultivation of IC, and whether crop residues and IC biomass are harvested. The information source for these biomass estimations is a freely

TABLE 2 | Parameter values used for the ICBM.

Parameter		Value
Decomposition rate	Young pool(s), k_Y (year^{-1})	0.28[a]
	Old pool, k_O (year^{-1})	0.0095[a]
Humification coefficients (h)	Aboveground biomass	$h = 0.1571301 - \frac{0.1515885}{1+\left(\frac{\text{Clay}}{35.3256091}\right)^{7.8835713}}$
	Belowground biomass	0.33[a]
	Manure	0.26[a]
	Digestate	0.26[b]
Edaphoclimatic parameter (r_e)	Region 1	1.30[c]
	Region 2	1.05[c]
	Region 3	1.04[c]
	Region 4	1.04[c]
	Region 5	0.99[c]
	Region 6	0.88[c]
	Region 7	0.69[c]
	Region 8	0.67[c]

[a]Reference values taken from Menichetti, Kätterer, and Bolinder (2024).
[b]Assumed to be the same as manure.
[c]Values for Swedish regions or production areas according to Andrén et al. (2008).

accessible dataset published in the Swedish National Data Service (Barrios Latorre 2024a). This information includes residual biomass estimations for 17 major agricultural crops in Sweden and biomass calculations for OR as an IC, with a grass–clover mixture (G–C) as an alternative IC. Additionally, the carbon contribution from ley grass was calculated using the yields of ley grass at the county level and extrapolated to the SKO level (Jordbruksverket 2022). It was assumed that of the total yields of AGB for ley grass, 30% is left on the field, which is consistent with the assumptions of Prade et al. (2017) and the National Inventory of Sweden on greenhouse gas emissions (Naturvårdsverket 2023).

In all scenarios, the stubble and non-recoverable harvestable biomass from crop residues is included, assuming that it is technically feasible to recover only 80% of harvestable biomass (Barrios Latorre 2024a, 2024b; de Toro et al. 2021). In scenarios 1 and 2, the recoverable residual biomass is included in the AGB inputs, while in scenarios 3–5, it is excluded from AGB input calculations. In scenarios 1 and 3, there is no cultivation of IC; thus, there is no contribution to the AGB; in scenarios 2 and 4, all the shoot biomass of OR as IC is considered to be part of the AGB input, while for scenario 5, the recoverable biomass of OR, harvested for utilization in AD, is excluded. The effect of G–C cultivation as an alternative to OR was analyzed by using a more simple assumption of crop yield for the whole country (917 kg ha^{-1}) in the same way as presented in Barrios Latorre et al. (2024).

The estimation of total carbon input was made by assuming a carbon content of 43.6% as an average value from herbaceous stem and leaves, as provided by Ma et al. (2018).

2.2.2 | Belowground Biomass

Belowground biomass (BGB) contribution to carbon inputs only varied depending on whether IC was cultivated or not. Thus, the contributions of IC to BGB were included only in scenarios 2, 4, and 5. This information was also available in the dataset provided by Barrios Latorre et al. (2024). To estimate the BGB input contribution, we utilized BGB to AGB ratios sourced from the National Inventory of Sweden (Naturvårdsverket 2023) and Prade et al. (2017) as conversion factors (Table 3). The carbon content of root biomass was assumed to be 42.9% (Ma et al. 2018).

2.2.3 | Organic Amendments

Organic amendments contributing to SOC inputs originate from manure and digestate application, resulting from the AD of biomass. Scenarios 3 and 4 include the application of digestate from crop residues, while scenario 5 adds the digestate resulting from IC biomass digestion. To estimate the carbon input from manure applications, we analyzed the information on the use of fertilizers and animal manure in agriculture from SCB (2023). This dataset provides information on regional applications of nitrogen from different sources and for specific crops. Thus, nitrogen values from manure application were converted to carbon inputs using C/N ratios (Lindfors and Feiz 2023) and excluding the proportion corresponding to bedding straw. Further explanation on this calculation is provided in the Supporting Information.

For estimating the total carbon remaining in the digestate, the losses of carbon during crop storage (ensiling and aerobic deterioration) in the AD process and during storage of the digestate prior to soil application were calculated. The crop residues were grouped as shown in Table 4, and the carbon remaining in the applied digestate was 32%–55% of the carbon initially in the crop residue or IC, with the choice of biochemical methane potential (BMP) in AD resulting in the greatest impact on carbon loss (Molinuevo-Salces et al. 2013; Zhang et al. 2021). Further explanations and input data for this calculation are provided in the Supporting Information.

TABLE 3 | Ratios of BGB to ABG used for calculation of BGB inputs (Naturvårdsverket 2023).

Crop	BGB:AGB ratio
Spring barley	0.22
Winter barley	0.22
Oats	0.25
Rye	0.22
Triticale	0.22
Spring wheat	0.28
Winter wheat	0.23
Mixed grain	0.22
Peas	0.19
Canned peas	0.19
Faba beans	0.19
Flax	0.22
Spring rapeseed	0.22
Winter rapeseed	0.22
Sugar beet	0.2
Table potatoes	0.2
Starch potatoes	0.2
Grass (uprooting year)	0.88
Grass (regular growth year)	0.54

2.3 | Initial Total SOC Stocks

An important consideration when modeling the changes in SOC stocks over time is the initial carbon content of the soil. The total carbon content in tons per hectare (t ha^{-1}) was calculated for arable land in Sweden based on the raster dataset from Piikki and Söderström (2019), who provided soil organic matter (SOM) percentage values. These were converted to SOC (%), assuming that carbon constitutes 50% of organic matter in soils (Pribyl 2010). Furthermore, the calculation of SOC stocks (t ha^{-1}) required the estimation of bulk density (ρ). The use of a pedotransfer function was considered an appropriate way to estimate ρ as a derivative function of soil carbon percentage (Eriksson, Mattsson, and Söderström 2010; Kätterer, Andrén, and Jansson 2006; Piikki and Söderström 2019). For the Southernmost Swedish region (Skåne), we used an equation (Equation 2) that expresses ρ as a function of carbon content, as proposed by Eriksson, Mattsson, and Söderström (2010):

$$\rho = 1.741 - 0.112 \times \text{SOC}\,(\%) \quad (2)$$

For the rest of the country, we used an exponential model (Equation 3) that was developed based on the data collected by Eriksson, Mattsson, and Söderström (2010), instead of the original linear model they proposed.

$$\rho = 1.671 \times e^{-0.101 \times \text{SOC}\,(\%)} \quad (3)$$

The logic behind the use of this model choice is further explained in the Supporting Information. Here, soil bulk density allowed for the transformation of the percentage of carbon to kilograms per hectare by multiply the SOC percentage by the bulk density (g/cm^3), the soil layer depth (cm), and the area factor. We considered a depth of 25 cm for topsoil, consistent with the assumptions of the Swedish National Inventory report of GHG emissions (Naturvårdsverket 2023). The initial SOC was corrected for gravel content following the same approach described in Andrén et al. (2008) and using the soil texture map provided by Piikki and Söderström (2019).

Since at constant carbon inputs the young pools of the soil tend to reach steady state in a few years, it was assumed that for all scenarios, the initial young pool (Y_0) corresponded to the steady state value for the base scenario ($Y_{ss\text{-}S1}$). Therefore, the initial content of the old pool was the difference between

TABLE 4 | Carbon (C) remaining after each step in handling crop biomass and as total carbon remaining in the applied digestate (%).

Crop biomass	C after biomass storage (%)	C in digestate after AD (%)	C in digestate after storage (%)	C in digestate from harvested crop (%)
Cereal straw	94	60	99	55
Oilseed straw	94	36	98	34
Legume straw	94	43	98	40
Sugar beet and potato tops	89	43	99	38
Oilseed radish (IC)	94	34	99	32

the total calculated carbon and the value of the corresponding young pool.

2.4 | Sensitivity Analysis

Four parameters were considered in a sensitivity analysis to assess the impact of the assumptions on the outcome of SOC modeling: (1) BMP of crop residue and IC biomass, determining the amount of C remaining in the applied digestate; (2) the humification coefficient of digestate (*h*-digestate), impacting the long-term stability of C from the applied digestate; (3) the edaphoclimatic factor (r_e), which is susceptible to variation due the alterations in climatic conditions; and (4) total carbon inputs (*i*, maintaining the proportions of AGB, BGB, and OA), connected to primary production and dependent on both environmental factors and the development of new crop varieties through plant breeding. Each parameter was modified by plus and minus 10% of the original value. Since scenario 5 was the only one that included the AD of IC, it was selected as the reference scenario of the sensitivity analysis.

3 | Results

3.1 | Organic Carbon Inputs

The estimated total carbon inputs exhibit a spatial variation that reflects the total biomass production in Swedish arable land, as shown in Figure 1a. An average yearly contribution of 2.57 t ha^{-1} under the base scenario (S1) shows a major contribution from the production of BGB (1.22 t C ha^{-1}), followed by the production of AGB (1.05 t C ha^{-1}), and the application of OA (0.30 t C ha^{-1}). The introduction of IC into the system (S2) raises the total average C inputs by about 6% (to 2.73 t C ha^{-1}), due to the increased contribution of AGB and BGB. In contrast, when crop residues are removed for biogas production (S3), AGB inputs are noticeably reduced, while there is an increase in OA, resulting in an overall input reduction (2.39 t C ha^{-1}). The combination of IC production and AD of residues results in lower total inputs than the base scenario, whether the IC biomass is incorporated into the soil (S4) or used for biogas production (S5).

3.2 | Estimations for the Base Scenario

The analysis of projected carbon stocks for arable land in Sweden using the ICBM for the base scenario is presented in Figure 2. Under this scenario, where crop residues are incorporated into the soil and there is no cultivation of ICs, an average decrease of SOC stocks is projected over time (Figure 2a). From an initial value of 72.2 t C ha^{-1}, the average carbon stocks decrease to 69.9 t C ha^{-1} within the first 20 years (meaning an average rate of −0.11 t C ha^{-1} year^{-1}). At the steady state (C_{ss}), the carbon stocks could reach an average of 61.6 t C ha^{-1}. However, there is a notable spatial variability in SOC stocks across the landscape (Figure 2b) with a deviation of 10.4 t C ha^{-1}, meaning that a majority of values (~95%) would range between 40.8 and 82.4 t C ha^{-1}. The projection shows that values below 55 t C ha^{-1} can be found scattered across the country, but especially in the southernmost region and the northeast area of the study region. The highest values (> 85 t C ha^{-1}) could be reached mainly in the central zone of the area under study, a geographical area known as Småland characterized by a relatively high presence of ley crops. This also means that although there is a negative average trend for SOC stocks, there are locations where the carbon content in the soil is increasing (Figure 2c).

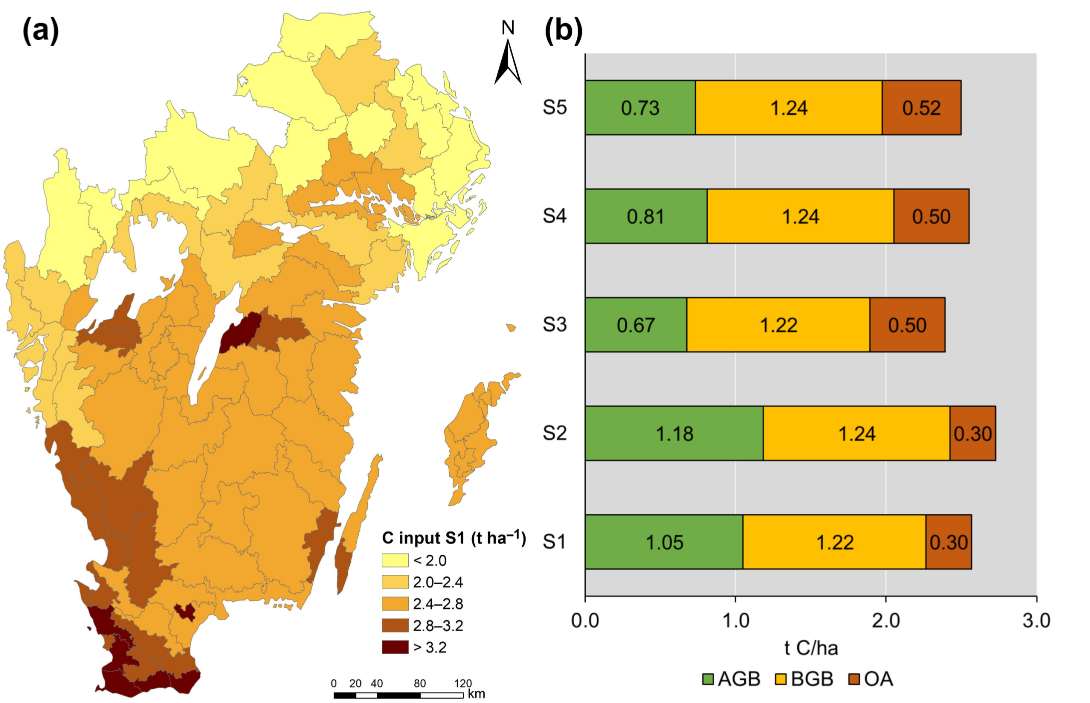

FIGURE 1 | Total yearly organic carbon inputs from different biomass sources: (a) total inputs per each SKO for the base scenario (S1), and (b) contribution from aboveground biomass (AGB), belowground biomass (BGB), and organic amendments (OA) to total organic carbon inputs under different scenarios. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

3.3 | Comparison With Alternative Scenarios

The comparison of SOC stocks reached at the steady state (C_{ss}) between the different scenarios is depicted in Figure 3. The maps show the difference in C_{ss} between the base scenario and each of the alternative scenarios (Δ t C ha^{-1}). When including the cultivation of IC into the crop rotations (S2), there is an average increase of 1.93 ± 1.2 t C ha^{-1} in the C_{ss} respect to the base scenario (Figure 3a). If crop residues are used for biogas production and the digestate is returned to the soil (S3), the average increase is higher, with a value of 3.30 ± 2.9 t C ha^{-1}. However, for some areas, this scenario results in net decreases in carbon at the steady state when compared with scenario 1 (Figure 3b). A combination of the cultivation of IC and use of crop residues for AD results in average increases of 5.23 ± 3.1 t C ha^{-1} when IC biomass is incorporated into the soil (S4, Figure 3c) and of 5.46 ± 3.3 t C ha^{-1} when IC biomass is harvested and used for biogas production, with digestate return (S5, Figure 3d).

There are also differential effects of different strategies on SOC stocks over time (Figure 3e). The inclusion of IC (S2) results in a rapid increase in SOC during the first 10 years due to the quick accumulation of carbon in the young pool (Y). However, as Y reaches a new steady state, the relative increase in soil is more dependent on the slower change in the old pool (O). This results in a total average contribution of 0.67 t C ha^{-1} over the first 20 years. Conversely, the use of crop residues for AD (S3) results in an initial overall reduction in SOC stocks relative to the base scenario due to lower carbon inputs and a subsequent contraction of Y. However, after about 4 years, this negative trend shifts and the accumulation of stable carbon in O drives the increase in SOC. After 15 years, the average SOC under the S3 projection returns to the levels of the base scenario. After 20 years, the overall accumulation, driven by the application of digestate, results in an average increase of 0.15 t C ha^{-1}. Although the initial effect of combining IC and AD is less significant than the inclusion of IC alone, both S4 and S5 show a higher contribution to SOC over 20 years with average values of 0.88 and 0.80 t C ha^{-1},

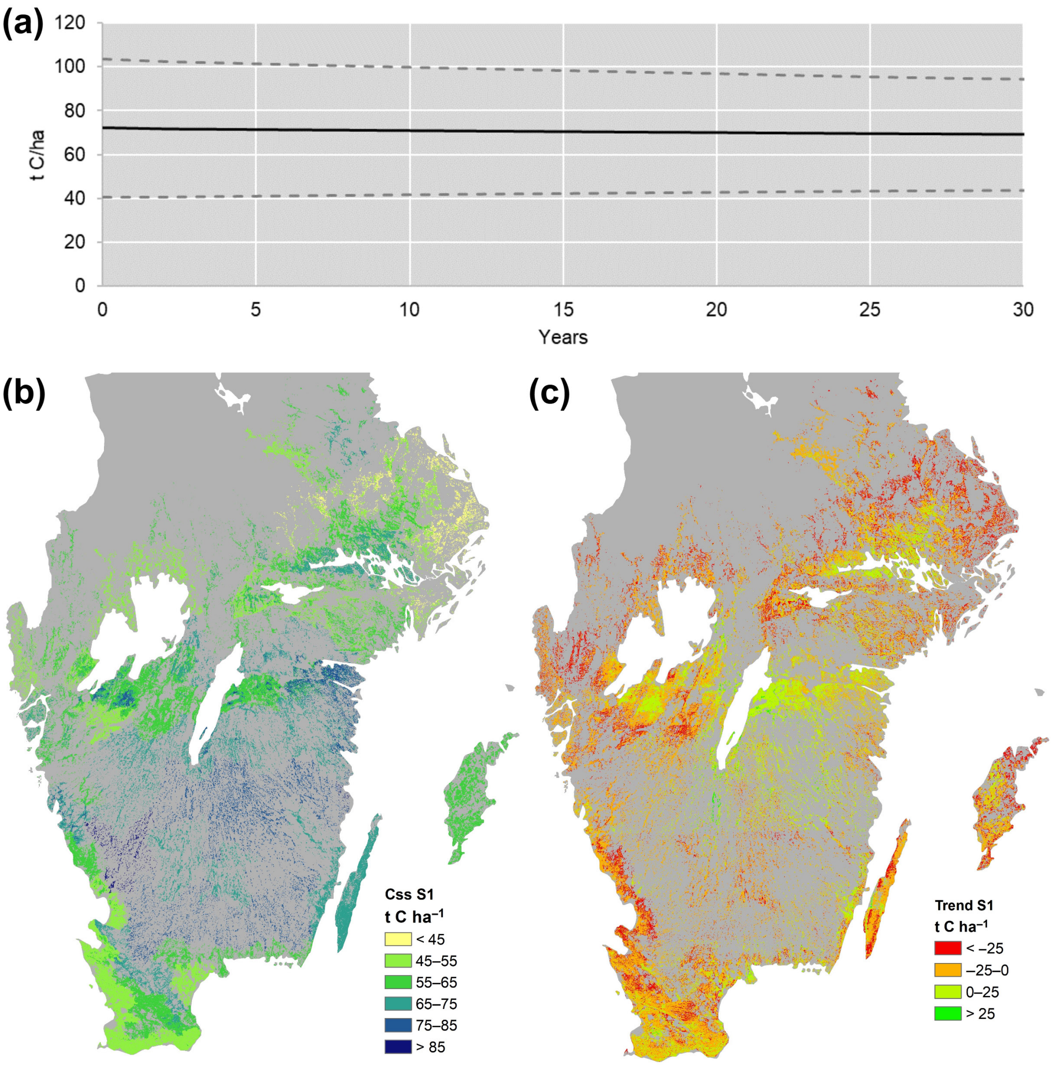

FIGURE 2 | Projection of SOC stocks for arable land in Sweden under the base scenario (S1) using the ICBM: (a) projected change in SOC stocks over time (dotted lines show ±2 standard deviations), (b) SOC stocks at steady state (C_{ss}), and (c) difference between initial SOC stocks and C_{ss} showing spatial differences in the development of SOC over time. Grey areas show non-arable land. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

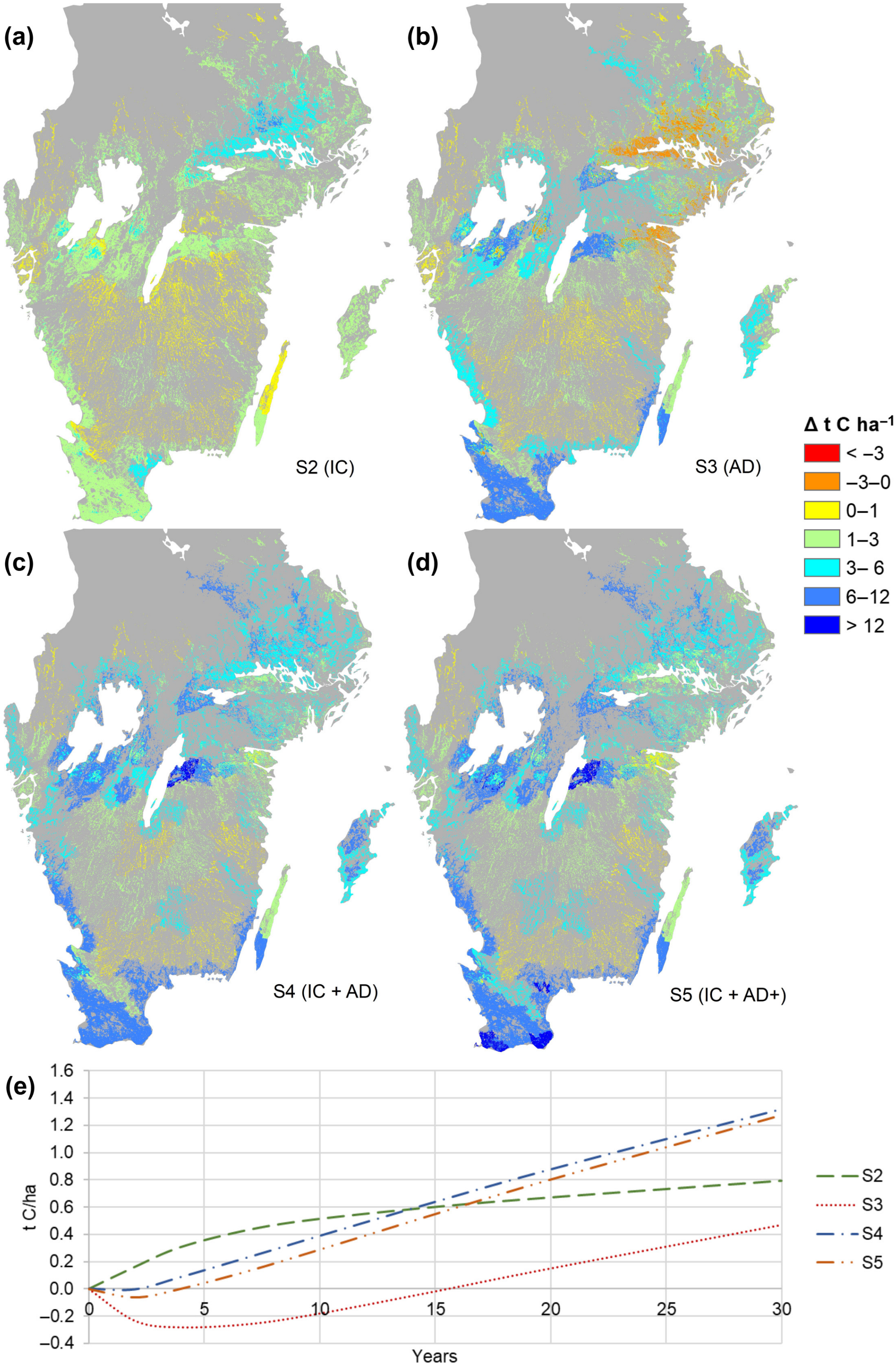

FIGURE 3 | Comparison of SOC stocks under different scenarios. The maps show the change in C_{ss} in respect to the base scenario when: (a) including IC (S2), (b) using crop residues for AD (S3), (c) combining the inclusion of IC and AD of crop residues (S4), and (d) combining the inclusion of IC and AD of both crop residues and IC biomass (S5). The development of carbon over time relative to the base scenario is also shown (e). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

respectively. The trend also shows that the initial negative effect of removing crop residues can be compensated by the inclusion of ICs, on average.

When comparing the different alternatives, no single scenario is optimal for achieving maximum carbon sequestration on the totality of the land, but there is a spatial differentiation on the

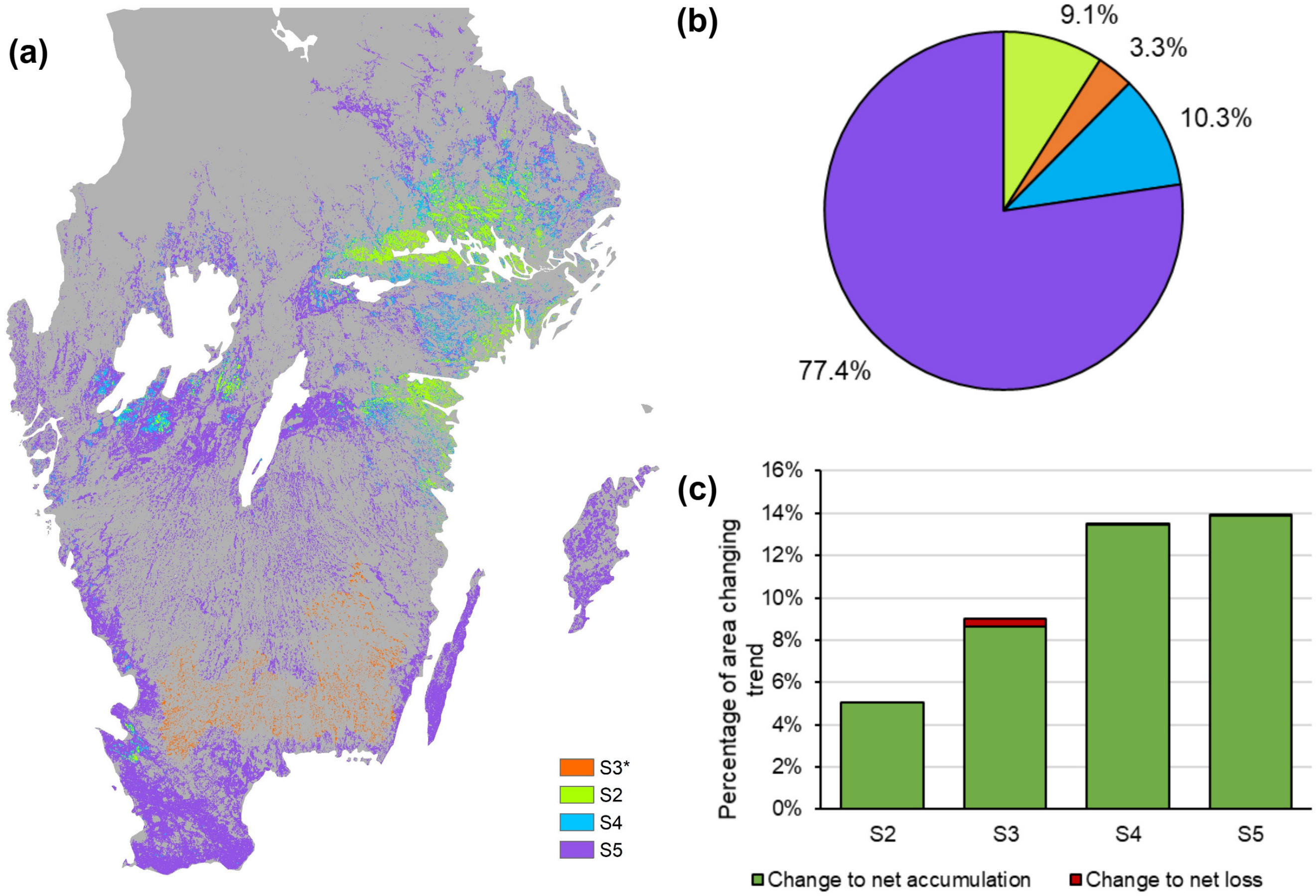

FIGURE 4 | Preferred scenarios for SOC accumulation according to the C_{ss}: (a) spatial distribution of optimal scenarios, (b) area percentage of optimal scenarios, and (c) effect of each scenario on changing trends of net carbon loss or accumulation. *S3 is preferred only in areas where IC cultivation is not possible. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

preferred strategy (Figure 4a). However, on most land represented by 1 ha pixels (77.4%), the C_{ss} value is maximized when combining the cultivation of IC with biogas production using both crop residues and IC biomass as feedstock (S5, Figure 4b). In a smaller portion of the land (10.3%), it is more beneficial from a SOC perspective to incorporate the IC biomass into the soil while removing the residues for AD (S4). In another similar share of land (9.1%), it is best to grow IC without removing crop residues. A small fraction (3.3%) consists of arable land scattered across a vast region, where the only feasible alternative management is removal of crops residue (S3), since there are virtually no openings for IC cultivation. Furthermore, Figure 4c shows the impacts of the four scenarios on altering the trends from the base scenario of net carbon loss or accumulation. Combining IC cultivation and application of digestate from AD of agricultural biomass could change the trends from loss to accumulation in nearly 14% of the arable land analyzed.

3.4 | SOC Change Rates and 4 per 1000 Initiative

The 4 per mille target implies a sustained rate increase of 0.4% in SOC stocks over time. With this threshold comparison, average SOC change rates for the different scenarios are shown in Figure 5a. The graph also illustrates the effect of selecting different time frames to analyze the rate change and how these rates tend to revert to zero over longer time periods when C inputs remain constant. These results reflect the trends seen previously, where an average carbon release from arable was expected under the base scenario (S1). When compared with the alternative scenarios, the inclusion of IC (S2) shows a notable effect on increasing the SOC change rate during the first years. Then again, the scenarios contributing the most to higher SOC change rates over longer periods of time are those where IC and AD are combined (S4 and S5). Since there is a considerable variability in the SOC change rate across the landscape, there are areas with positive trends, among which are scenarios where the 4 per mill target is already fulfilled in the base scenario S1 (Figure 5b), about 1.67% of total arable land for the 20-year average. As expected, Figure 5b shows that the alternative management practices considered in the analyzed scenarios raise the total share of land fulfilling the target differentially. Combining IC and AD (S4 and S5) doubles the amount of land fulfilling the target, over 20 years. Including IC drastically increases SOC change rates and the share of area with values higher than 0.4% within the first years, but this effect is not sustained over longer time periods.

3.5 | Alternative IC Species

The use of G–C in comparison to OR as IC is presented in Figure 6. From the perspective of long-term SOC accumulation

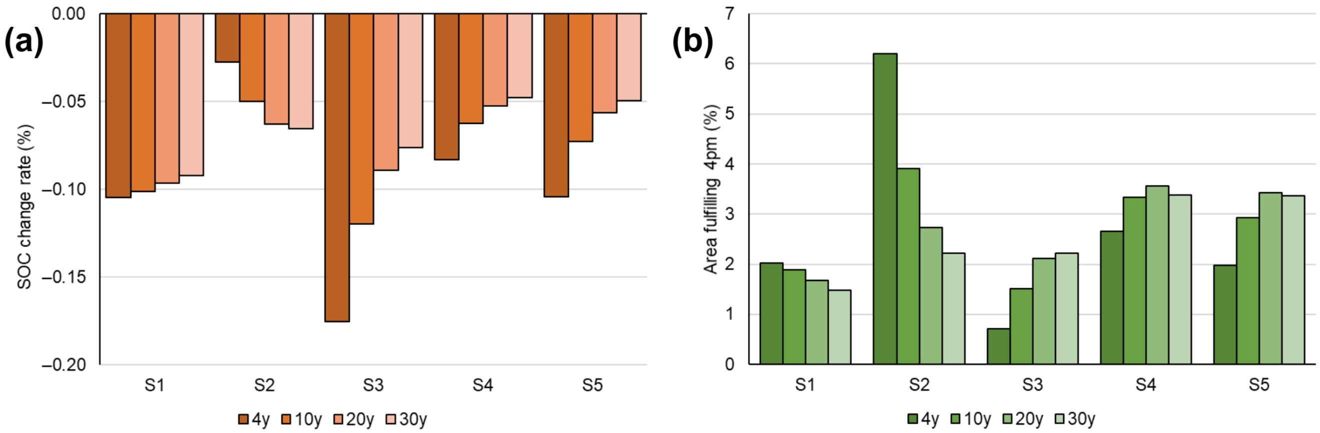

FIGURE 5 | Average SOC change rate (a) and fulfilment of the 4 per mille target (b).

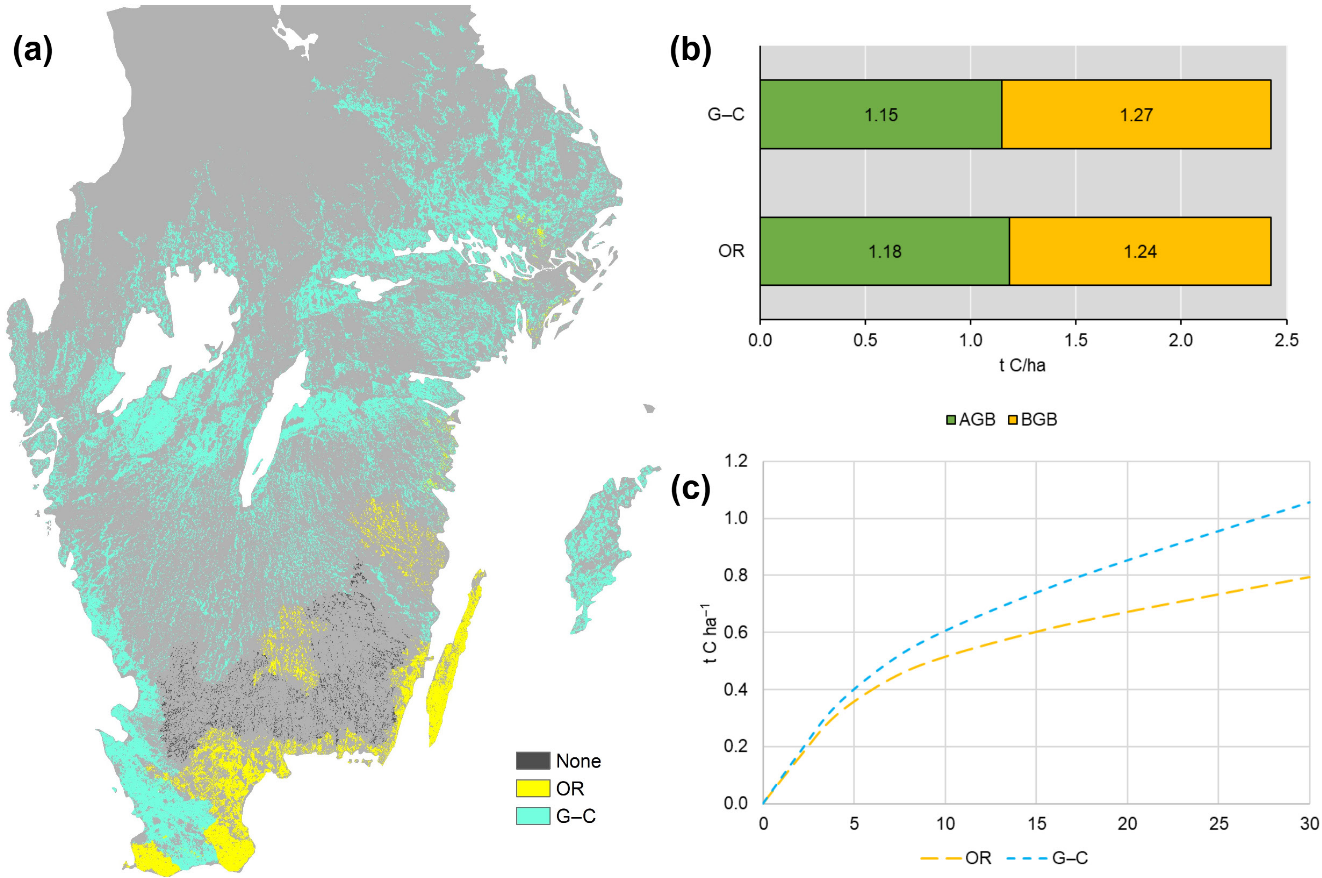

FIGURE 6 | Comparison of oilseed radish (OR) and grass–clover mixture (G–C) as alternative IC species: (a) map showing best alternative according to the carbon stock at steady state (C_{ss}) in the spatial scale, (b) total average inputs from each crop, and (c) development of carbon over time relative to the base scenario. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

(C_{ss}), OR is a preferred species in southern regions, while G–C is more beneficial for a larger area (Figure 6). This is partly due to the slightly higher proportion of carbon contribution from BGB in G–C, since OR has a higher shoot: root ratio (8.36) than G–C (4). On average, the development of SOC stock over time shows an advantage of using G–C over OR. However, it is worth noting that the yield assumptions for OR are based on a more complex spatial analysis, which could lead to more accurate estimates, and that the AGB fraction of OR is considerably higher, making it a more interesting IC species for biomass harvesting.

3.6 | Sensitivity Analysis

The results of evaluating the impact of four key parameters are presented in Table 5, with the values obtained for S5 serving as the reference scenario. Altering the values of both BMP and h-digestate by 10%, results in changes of only about 1.0% of the total average SOC stocks at steady state (C_{ss}). As expected, higher biogas production results in lower carbon content in the digestate and lower carbon inputs from OA. On the contrary, a higher humification coefficient of the digestate leads to a higher

TABLE 5 | Resulting values of the sensitivity analysis on selected parameters: Biochemical methane potential (BMP), humification coefficient of digestate (*h*-digestate), edaphoclimatic factor (r_e), and total inputs (*i*). Red shades indicate negative changes and green shades indicate positive changes.

Parameter	Change	Total average C_{ss} (t C ha^{-1})	Percentual change (%)
BMP	+10%	66.4 ± 9.0	−1.02 ± 0.58
	−10%	67.6 ± 8.9	0.89 ± 0.53
h-digestate	+10%	67.7 ± 8.9	0.94 ± 0.53
	−10%	66.5 ± 9.0	−0.94 ± 0.53
r_e	+10%	61.0 ± 8.1	−9.10 ± 0.00
	−10%	74.5 ± 9.9	11.10 ± 0.00
Total *i*	+10%	73.7 ± 9.8	9.94 ± 0.03
	−10%	60.3 ± 8.0	−10.05 ± 0.03
Reference value (S5)		67.1 ± 8.9	—

accumulation of stable carbon. The parameters that showed the highest impact on the resulting C_{ss} were the edaphoclimatic factor (r_e) and total inputs (*i*), with the edaphoclimatic factor having a negative effect and the total inputs having a positive effect. Due to their similar magnitudes, their effects could potentially cancel each other out.

4 | Discussion

This study has explored the effects of crop residue removal and use and cultivation of ICs on SOC stocks in Sweden. The scope included arable land in areas approved for environmental compensation, used for annual crops and ley grass, accounting for about 70% of the arable land in those regions. Recently, the balance of organic carbon inputs from the removal of crop residues, in combination with ICs, has been examined as a sustainable intensification strategy (Barrios Latorre et al. 2024). In this study, we have also considered AD as a suitable bioeconomy pathway for agricultural biomass in Sweden (Gustafsson and Anderberg 2023) and modeled the development of SOC stocks by making use of the most recent version of the ICBM/3 (Menichetti, Kätterer, and Bolinder 2024). By expanding the boundaries of the analyzed system, including the return of some of the carbon removed in form of digestate, our findings give a more holistic view on the fate of SOC stocks in arable land under different scenarios.

A recent study estimated net SOC losses during the last decade for Nordic countries, including Sweden (De Rosa et al. 2023). The analysis of the base scenario presented here confirms this negative trend for a large area across the country, suggesting that it is likely to continue if current practices are maintained (Figure 2). This is especially concerning, given that Nordic countries are among the countries that have the largest SOC stocks in Europe (De Rosa et al. 2023). Nonetheless, the Swedish National Inventory has suggested that there has been a net accumulation of carbon in Swedish agricultural soils over the years (Naturvårdsverket 2023). It has been confirmed that the decrease in cropland areas and their conversion to grassland in Sweden has increased the SOC in mineral soils at an average annual rate of 0.65% (Johansson et al. 2024). Also, positive trends in carbon storage of Swedish agricultural soils have been recorded, due to increased ley production connected to the introduction of subsidies during the 1990s (Poeplau, Bolinder, et al. 2015). This supports the wide recognition of the beneficial effects of converting cropland to grassland (De Rosa et al. 2023; Martin et al. 2021; Poulton et al. 2018), and the benefits of the inclusion of ley grass in crop rotations (Poulton et al. 2018; Prade, Kätterer, and Björnsson 2017). Similarly, our results also show higher carbon accumulation in areas associated with ley production (Figure 2b). However, in this study, we excluded pastureland in agricultural land and areas dedicated to grazing meadows in arable land, representing 15%–20% of total arable land in Sweden. Furthermore, we included a humification coefficient of AGB dependent on soil clay content, unlike the conventional use of a constant value, resulting in lower accumulation values reported for sandy soils (Poeplau, Kätterer, et al. 2015).

On the other hand, our analysis suggests that the introduction of ICs in rotation sequences is always beneficial in terms of SOC effects, showing variations in the magnitude of the effect across the landscape (Figure 3a). These results are consistent with the current state of the art that acknowledges the use of ICs as one of the most beneficial practices for increasing the SOC stock change rates and overall soil fertility (Abdalla et al. 2019; Aronsson et al. 2016; Kätterer and Bolinder 2022). Its net effects show, however, spatial differentiation connected to IC yields and agroecological conditions (Barrios Latorre et al. 2024). Moreover, this study does not account for priming effects, which have been observed to cancel out the effect of carbon contributions of IC for Nordic conditions (Liang et al. 2023). Yet, this outcome has only been reported at low yield values with a threshold between 0.7–1.1 t ha^{-1} for AGB (Liang et al. 2023), whereas in our case, yields reported for OR in the majority of locations exceed this threshold (Barrios Latorre 2024a). However, the yields reported for the grass–clover mixture (within the above mentioned range) add a source of uncertainty for the estimations done when using this alternative IC.

In contrast, while the return of digestate to the soil generally showed an average positive impact on soil, there were areas where the application of digestate alone did not fully compensate for the removal of crop residues, leading to a net decrease of stabilized carbon over the long term. Similarly, Andrade Díaz et al. (2023) reported that the application of digestate derived from crop residues can contribute to SOC build up in certain areas of France, while in others, there are predicted net losses due to the residue removal. Here, we showed that combining the residue removal with the inclusion of ICs could effectively compensate for the losses. Using IC biomass for biogas production is a suitable application which can benefit carbon storage in a large portion of the investigated area.

The comparison with the 4 per mille target (Minasny et al. 2017) has shown that under the base scenario without the inclusion of IC or application of digestate, less than 1% of the analyzed area fulfils the target (Figure 5b). However, these results should be interpreted in light of several considerations. To begin with, the relative increases for soils that are depleted or start with a low initial SOC value are frequently higher and might make it easier to reach the target, even if there is an actual low net increase (Minasny et al. 2017). In contrast, soils that currently have high levels of SOC (like Nordic soils) or are near saturation exhibit a low carbon sequestration potential (Martin et al. 2021), which is linked to reduced carbon accumulation rates when approaching equilibrium or steady state (Poulton et al. 2018). In the context of the present study, since the relative increase rate depends on the state of the soil at the beginning (Soussana et al. 2019), areas that could fulfill the target are likely to have an initial low SOC value. It is also important to consider the inherent uncertainty of the models that produced the initial values for SOC used here (Piikki and Söderström 2019), despite the corrections applied in this analysis.

Since soil does not constitute an infinite carbon storage option and carbon accumulation rates diminish over time, the feasibility of the target has been called into question (Martin et al. 2021; Poulton et al. 2018). Regarding climate change mitigation, the 4 per mille target is a finite strategy and other long-term solutions are required (Poulton et al. 2018). However, although it has been regarded as an ambitious aspirational target, setting a global goal promoting soil management can significantly contribute to climate change mitigation while improving soil quality and functioning, water management, and food security (Minasny et al. 2017; Poulton et al. 2018; Soussana et al. 2019). Achieving a 0.4% increase in SOC stocks requires a substantial increase in carbon inputs, which has been recognized as the primary limiting factor (Bruni et al. 2022; Martin et al. 2021). Depending on the geographical location, estimated requirements for total carbon input increase range from a 30% increase (Bruni et al. 2022) to more than double the current input (Martin et al. 2021). Therefore, the availability of biomass and biomass production are key factors to increase the SOC stocks (Martin et al. 2021).

Although the application of OA can contribute to increasing SOC stocks, primary productivity should gain special attention to promote actual carbon sequestration from the atmosphere (Bruni et al. 2022; Martin et al. 2021). Accordingly, several practices have been devised to increase net primary productivity, including cover cropping (Bruni et al. 2022; Minasny et al. 2017; Poulton et al. 2018; Soussana et al. 2019), the introduction of ley grass in rotations (Abdalla et al. 2019; Prade, Kätterer, and Björnsson 2017), and the establishment of perennial crops (De Rosa et al. 2023; Kätterer and Bolinder 2022). Here, we have simulated how the inclusion of ICs (cover cropping) can increase the soil area fulfilling the 4 per mille target in Sweden, which is enhanced when combined with the application of digestates derived from AD. We have simulated how increasing primary productivity can benefit the SOC as an important factor influencing the physical and chemical properties of soils (Soussana et al. 2019) and, thus, the overall state of the agroecosystem. Our findings support previous analyses claiming the relevance of cultivating cover crops in pursuing carbon capture (Bruni et al. 2022).

We also observed differences in the effects on SOC when harvesting the IC biomass in comparison to when incorporating it in the soil (Figure 3). For the larger part of Swedish arable land, harvesting IC biomass and using it for AD with a return of digestate to the soil would result in a higher benefit to SOC stock than only incorporating it. However, in the remaining area, the latter alternative had larger benefits. These varying results are likely influenced by the different productivity of OR, as IC in different parts of the land and the clay content affects the humification of the AGB (Barrios Latorre et al. 2024; Poeplau, Kätterer, et al. 2015). Nevertheless, it is important to note the intrinsic uncertainty of SOC simulations (Bruni et al. 2022). There is both structural uncertainty inherent to the model assumptions and uncertainty associated with the model inputs (Menichetti, Kätterer, and Bolinder 2024). Here, we do not intend to give a definitive answer as per the fate of soil carbon development, but rather provide an analysis that contrasts different agricultural management strategies, which can also benefit the bioeconomy through increased availability of agricultural biomass (Gustafsson and Anderberg 2023).

It is worth noting the difficulty in capturing complex dynamics of SOC. Minor errors in parameter estimation affecting SOC dynamics (e.g., carbon content in biomass, initial SOC, and stabilization coefficients) can significantly impact the accuracy of results, which also may be true for the transferability and scalability of modeling approaches (De Rosa et al. 2023). The variability of carbon input estimates due to differing methodologies can lead to divergent outcomes (Martin et al. 2021). Also, model selection and parameter assumptions are key determinants affecting the interpretability of the outcomes (Menichetti, Kätterer, and Bolinder 2024). However, to our benefit, multi-model analyses have shown that the ICBM outperforms other models, demonstrating a high reliability associated with a strong determination coefficient in European cases (Bruni et al. 2022).

In this study, we established a set of assumptions that may not directly mirror real-world conditions at a detailed spatial level but serve to facilitate the generalization of our findings. These assumptions include the homogeneous spreading of digestate in arable land within each SKO, from which the biomass originated, and that all crops are present at some point within the rotation sequence. In contrast, Metson et al. (2020) suggested the optimization of nutrient balances in arable land through the transportation of biomass to different locations, which offers multiple benefits. Therefore, it is advisable to be cautious about deriving conclusions at a detailed spatial level. Moreover, to the authors' knowledge, there are currently no specific humification values for digestate derived from long-term field trials. Thus, we also assumed a humification coefficient for digestate equal to that of manure (Menichetti, Kätterer, and Bolinder 2024), considering that the AD digestion process resembles that of ruminant digestive systems. However, the consequences of digestate application on soil are still under investigation, and the long-term effects on SOC and microbial interactions remain to be clarified (Barłóg, Hlisnikovský, and Kunzová 2020; Cattin et al. 2021).

Furthermore, we considered alternative scenarios that could be adapted to current production systems with the premises of maintaining same production levels and assuming that other aspects of agricultural productions would not change. However, transitioning to more sustainable food systems might require more disruptive systemic changes and other kinds of agricultural production diversification (Tittonell 2014). Further research could consider alternative bioeconomy pathways such as pyrolysis, gasification, and ethanoic fermentation (Andrade Díaz et al. 2023) and the use of other ICs like winter rye (*Secale cereale*), phacelia (*Phacelia tanacetifolia*), and clovers (*Trifolium* sp.) (Aronsson et al. 2023). Moreover, although our study considers the fate of carbon alone, it is also important to consider the flows of plant nutrients within agroecosystems and the broader circular bioeconomy system (Metson et al. 2020).

The consequences of alternative soil management practices and strategies for land use have not been evaluated on a national scale in Sweden. This study offers a general overview and captures a notable variance in the results across the arable land. From this, we can infer that when adopting strategic measures, it is advisable to evaluate the best option at individual farms or fields. These analyses should also consider a more holistic approach, where other factors, such as economic limitations or other environmental impacts, are balanced. In many cases, farmers may not have the means necessary to achieve SOC sequestration goals (Poulton et al. 2018), so it becomes imperative to formulate schemes that support carbon farming. Currently, there is an incentive for the cultivation of ICs in Sweden, which distinguishes between catch crops, aimed at nutrient retention, and cover crops, aimed at carbon sequestration (Jordbruksverket 2023). However, it also limits the use of the resulting biomass, because farmers are not allowed to terminate the IC before the 20 October. In practice, this has proven to be a deterrent for farmers to harvest the biomass of non-hardy cover crops, since it is not advisable to undergo field operations after this date due to the increased risk of soil compaction late in the growing season. Our findings contribute to broadening the perspectives on agricultural biomass use and sustainable agricultural practices. This could promote the reformulation of policies supporting crop diversification in arable land, while making diverse biomass sources available for the bioeconomy.

5 | Conclusion

By making use of a model describing SOC dynamics, we estimated the fate of SOC stocks in arable land under different scenarios considering the cultivation of ICs and the use of agricultural biomass for AD. ICs can play a significant role in carbon sequestration and in reversing negative trends in SOC stock development. Similarly, the use of digestates, instead of biomass incorporation in the soil, can contribute to a large stabilization of carbon over the long term, although there is notable spatial differentiation in its effects due mainly to variations in crop yields and soil texture. The cultivation of ICs coupled with the use of residual biomass can have important benefits for carbon sequestration, aiding in the fulfilment of environmental goals and promoting soil fertility and food security. However, strategies that facilitate the implementation of such practices need to be devised, and policy development plays a pivotal role in realizing this potential.

Author Contributions

Sergio Alejandro Barrios Latorre: conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, writing – original draft, writing – review and editing. **Lovisa Björnsson:** conceptualization, formal analysis, methodology, supervision, writing – original draft, writing – review and editing. **Thomas Prade:** conceptualization, methodology, project administration, resources, supervision, validation, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in the Swedish National Data Service at: https://doi.org/10.5878/rsvb-cb29.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.