Agricultural Systems 215 (2024) 103873

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Exploring the benefits of intermediate crops: Is it possible to offset soil organic carbon losses caused by crop residue removal?

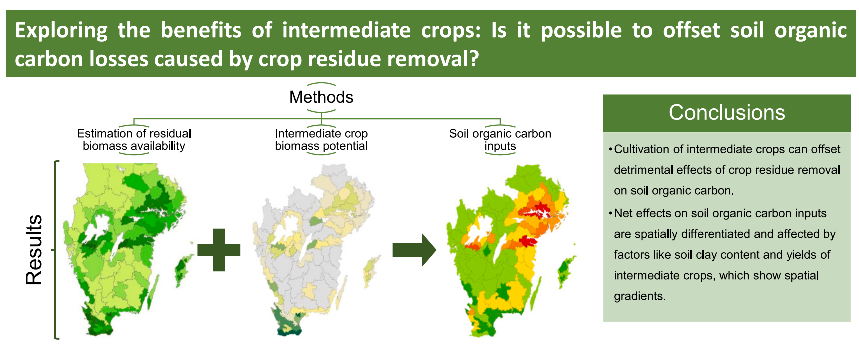
Sergio Alejandro Barrios Latorre [a,*], Helena Aronsson [b], Lovisa Björnsson [c], Maria Viketoft [d], Thomas Prade [a]

[a] Department of Biosystems and Technology, Swedish University of Agricultural Sciences, Box 190, 234 22 Lomma, Sweden
[b] Department of Soil and Environment, Swedish University of Agricultural Sciences, Box 7014, 750 07 Uppsala, Sweden
[c] Department of Technology and Society, Lund University, Box 118, 221 00 Lund, Sweden.
[d] Department of Ecology, Swedish University of Agricultural Sciences, Box 7044, 750 07 Uppsala, Sweden

HIGHLIGHTS

- In Sweden, 2139 kt of residual crop biomass are available for use in the bioeconomy, of which 84% consists of cereal straw.
- A model estimating Swedish land availability for intermediate crops yielded 383 kt of recoverable oilseed radish biomass.
- Crop residue removal and intermediate crop cultivation affect soil organic carbon inputs differently across the landscape.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor Name: Kairsty Topp

Original content: Biomass availability from the harvest of crop residues and oilseed radish as an intermediate crop at yield survey district level in Sweden (Original data)

Keywords:
Bioeconomy
Sustainable intensification
Cover crops
Residual biomass
Soil organic carbon

ABSTRACT

CONTEXT: Agriculture plays a central role as a feedstock provider for the bioeconomy. However, utilization competing with food production and associated land use change have previously been a matter of debate. Nonetheless, strengthening the productivity of agroecosystems through sustainable intensification can prevent the depletion of natural resources, enhance food security, and facilitate adaptation to and mitigation of climate change.

OBJECTIVE: This study explores the effects of combining crop residue removal for use as biomass feedstock with the establishment of intermediate crops to compensate for organic carbon depletion in arable land in Sweden.

METHODS: The analysis relied on Swedish national agricultural statistics at the highest available spatial resolution (yield survey district). Crop residue calculations factored in crop:residue ratios, and harvestable and recoverable potentials. A model was devised to estimate land availability for cultivating intermediate crops based on generalized crop rotation sequences, and a spatial interpolation was employed to determine oilseed radish yields as a model intermediate crop. Estimates of long-term soil carbon inputs hinged on biomass carbon content and humification coefficients dependent on soil clay content.

* Corresponding author.
E-mail addresses: alejandro.barrios.latorre@slu.se (S.A. Barrios Latorre), Helena.Aronsson@slu.se (H. Aronsson), lovisa.bjornsson@miljo.lth.se (L. Björnsson), Maria.Viketoft@slu.se (M. Viketoft), Thomas.Prade@slu.se (T. Prade).

https://doi.org/10.1016/j.agsy.2024.103873
Received 25 September 2023; Received in revised form 11 January 2024; Accepted 12 January 2024

RESULTS AND CONCLUSION: The total annual residual biomass availability in the country stands at approximately 2139 kt per year. The potential harvestable biomass production from intermediate crops was estimated at 383 kt per year. However, spatial differences were evident in total biomass production and effects on soil organic carbon inputs. For the majority of districts, the inclusion of intermediate crops could offset the negative effect of a complete removal of crop residues on soil organic carbon inputs. In other cases, establishing intermediate crops could not compensate for these negative effects, but some differences were observed when comparing the harvesting and the incorporation of the intermediate crops' biomass. Spatial disparities originated from variations in soil texture, intermediate crop yield, and rotation sequences.

SIGNIFICANCE: This research is an attempt to address the challenge of maintaining and increasing the soil carbon stocks under the context of a growing biomass demand in a developing biobased economy. It highlights the divergent effects of combining crop residue removal with the inclusion of intermediate crops under distinct agroecological conditions in the Northern European context. By giving estimates on biomass availability and effects on soil organic carbon inputs, we provide information that can support decision making for bioeconomy planning and sustainable resource utilization. This also has long-term implications for preservation of soil fertility, agricultural productivity and climate change mitigation.

1. Introduction

For most of the societal challenges outlined in the Agenda 2030 for Sustainable Development (UN General Assembly, 2015), the agricultural sector plays a major role as a driver of several goals and targets. Agriculture is the foremost source of several goods and services, including the provisioning of non-food biomass as a renewable resource for the growing bioeconomy. Transition to a biomass-based economy has been proposed as a sustainable alternative that can reduce our dependency on fossil-derived resources and reduce the environmental impact of human activity (Kludze et al., 2013; Bennich et al., 2018; Sharma and Malaviya, 2023). Moreover, fostering the bioeconomy in Europe can aid in realizing the ambitious package of goals, initiatives, and measures of the Green Deal, which aims to make Europe climate neutral by 2050 (European Commission, 2019). In sight of this, the implementation of sustainable agricultural practices that promote adequate soil management and the production of non-food biomass can aid in the fulfilment of global and regional targets and environmental policies (Montanarella and Panagos, 2021).

Despite the benefits of a biobased circular economy (Kludze et al., 2013; Sharma and Malaviya, 2023), the utilization of agricultural biomass has been a subject of continuous debate, especially regarding the initial approach to modern bioenergy production. Issues concerning the displacement of food crops ("food versus fuel") and indirect land use change (iLUC) arising from first-generation biofuels have been previously discussed (Tomei and Helliwell, 2016). However, second-generation biofuels produced from residual biomass offer an alternative that prevents greenhouse gas (GHG) emissions associated with iLUC (Prade et al., 2017; Lantz et al., 2018). In fact, crop residues constitute an abundant and renewable resource that can be used in several applications; not only for the production of energy and biofuels (Prade et al., 2017; Lantz et al., 2018; Brunner et al., 2021; Olofsson, 2021; Shams Esfandabadi et al., 2022), but also for biocompound extraction (Prade et al., 2021; Maravić et al., 2022; Soltaninejad et al., 2022), and materials production (Pinto et al., 2019; Chen et al., 2022). Residual crop biomass has been acknowledged as an attractive bioeconomy feedstock that has gained attention in the European context (Hamelin et al., 2019), where biomass estimations for 2050 in EU28 account for a bioenergy potential ranging from about 5000 to 10,000 PJ (Ruiz et al., 2019).

However, agricultural residue plays a relevant role in long-term soil quality, which is strongly linked to its organic carbon content (Kludze et al., 2013; Hamelin et al., 2019). Incorporating crop residues into the soil can reduce erosion, enhance nutrient cycling, improve soil structure, and promote plant growth through their contribution to the SOC pools (Liu et al., 2014; Poeplau et al., 2015). Besides, it has been estimated that the global amount of carbon stored in soils (about 1415 Gt) greatly surpasses the carbon found in the aboveground terrestrial ecosystem biomass (FAO and ITPS, 2015). Given the significant role of soil as a carbon sink, preserving and increasing SOC stocks are current priorities on the global agenda. The European Commission has suggested increasing focus on carbon farming initiatives to contribute to the land carbon sink that is required to meet the 2030 climate target of the net removal of 310Mt CO_2 from the atmosphere (European Commission, 2021). Moreover, the 4 per 1000 program has set the ambitious goal of increasing soil carbon stocks by 0.4% a year as a way to offset the global emissions of GHG and mitigate climate change (Minasny et al., 2017). Therefore, it has been suggested that estimations of crop residue availability should account for certain removal restrictions that prevent detrimental effects on soil organic carbon (SOC), aiming for "sustainable removal potentials" (Kludze et al., 2013; Liu et al., 2014; Poeplau et al., 2015; Björnsson and Prade, 2021).

While the incorporation of crop residues in soil has been encouraged as a way of sequestering carbon and preserving SOC, soil quality, and ecological function (Kludze et al., 2013; Liu et al., 2014; Kluts et al., 2017), other agricultural practices have shown larger contributions to carbon storage in topsoil. These include the establishment of perennial crops, the application of manure, nitrogen fertilization, and the inclusion of cover crops in rotation sequences (Kätterer and Bolinder, 2022). In addition, roots often contribute more to SOC due to a higher degree of carbon stabilization than that of aboveground biomass; in fact, aboveground plant tissues and straw have the lowest carbon stabilization among different organic inputs (Kätterer et al., 2011; Poeplau et al., 2015). Therefore, adopting residue removal restrictions for crop residues has been questioned as an approach that limits the availability of a renewable resource (Poeplau et al., 2015; Björnsson and Prade, 2021; Andrade Díaz et al., 2023). Instead, a suitable approach that can provide alternative solutions for soil preservation is that of sustainable intensification: enhancing natural capital and the flow of environmental services to increase productivity and limit negative environmental impact (Tittonell, 2014; Wezel et al., 2015).

A combination of the use of intermediate crops (ICs) and unrestricted removal of wheat straw has been proposed as a sustainable intensification strategy resulting in overall reductions in GHG emissions. Even though the establishment of ICs can lead to increased GHG emissions from field operations, a reduction in total emissions due to the contribution of increased SOC stocks has been observed (Björnsson and Prade, 2021). Intermediate crops, which here encompass the terms 'catch crops' and 'cover crops' (Björnsson and Prade, 2021), provide multiple benefits for the productivity of agroecosystems by preventing nutrient losses and soil erosion, and improving resource use efficiency (Basche et al., 2014; Aronsson et al., 2016; Abdalla et al., 2019). Their inclusion in rotation sequences also has positive environmental effects, including an initial reduction in nitrous oxide emissions from residual soil nutrients, lowered eutrophication effects, and increased agrobiodiversity (Dabney et al., 2010; Aronsson et al., 2016; Abdalla et al., 2019). In conservation and organic agriculture, ICs can also increase yields, provide weed control (Nichols et al., 2020), and have positive effects on soil physical, chemical, and biological properties (Hao et al., 2023), facilitating the ecological intensification of these systems (Wittwer et al., 2017). A commonly used IC in Northern Europe is oilseed radish, due to its ability to reduce nitrogen and phosphorus losses from arable land (Aronsson et al., 2016), render high yields (Munkholm and Hansen, 2012), and have a sanitizing effect against nematodes (Gruver et al., 2010). The role of cover crops for CO_2 removal and carbon storage in the soil has proven to be substantial, with mean values varying between 270 and 560 kg C ha^{-1} yr^{-1} (Poeplau and Don, 2015; Bolinder et al., 2020; Jian et al., 2020). They, thereby, play a significant role in climate mitigation strategies within the EU, where carbon farming business models for C removal trading are suggested (European Commission, 2022).

Although the benefits of establishing ICs are widely acknowledged and there is a continuous development of this research field, their capacity to offset negative impacts derived from crop residue removal is largely unknown. Long-term experiments in Denmark have shown the potential of ryegrass as an intermediate crop to compensate for carbon loss in the soil due to the removal of large amounts of straw (Jensen et al., 2022). In Sweden, the effects on SOC of wheat straw removal in combination with the establishment of oilseed radish as IC have been evaluated for large areas, assuming general values for IC yields and frequencies within rotations (Björnsson and Prade, 2021). However, there are no estimations on residue availability of wheat and other crops at a higher spatial resolution, nor estimations of potential land availability for intermediate crop production defined by rotation sequences.

This study investigates a strategy for sustainable intensification in the Northern European context, where the removal of crop residue is combined with the establishment of ICs. We aim to quantify the effect on potentially-stabilized soil carbon inputs if this practice is widely implemented in crop rotations in Sweden. This involves: (1) estimating the total amount of harvestable main crop residue per yield survey district, (2) identifying the potential production of ICs per yield survey district, and (3) determining the potential of ICs to compensate for SOC loss due to crop residue removal in different districts. Here we examine residue availability at the highest spatial resolution according to data availability for a variety of agricultural crops, designing individually generalized model crop rotations in order to determine spatially relevant intermediate crop frequencies. Ultimately, the goal is to provide guidance on the conditions under which residual biomass can be removed from arable land without causing negative impacts on soil organic carbon. The scope of this study is limited to the comparison of potentially stabilized carbon input and does not include a full carbon balance nor a full life cycle assessment, which requires considering factors such as the total residual biomass from all crops in a rotation, underlying carbon mineralization values, addition of organic materials such as manure or digestate, cultivation operations and related greenhouse gas emissions. These aspects are part of an undergoing broader project.

2. Methods

Quantifying the effects of residue biomass removal in combination with the inclusion of intermediate crops (ICs) in rotations required the estimation of biomass availability from crop residues and the potential biomass production from intermediate crops. As a rule, the estimation of biomass availability was based on standard yields and corresponding cropping areas for each of the 106 Swedish yield survey districts (SKO, in Swedish *skördeområde*). Standard yield calculations by Swedish official statistics show the yield that can be expected under normal growing and weather conditions providing a first forecast of the year's total harvests. The yield survey districts (SKO) constitute the highest spatial resolution area units for reporting statistics utilized by Statistics Sweden (SCB) and the Swedish Board of Agriculture (Jordbruksverket). However, the approaches for estimating available total dry biomass are different for crop residues and ICs, and are described below. Mean values for the 2017–2021 period were used for all estimations (Jordbruksverket, 2022). This study does not consider potential positive or negative effects on main crop yields from the inclusion of intermediate crops in the crop rotation.

2.1. Estimation of residue biomass availability

The 17 most important main crops in Sweden in terms of land use were analyzed for residue calculation (Table 1), covering 77% of the total cropping area (excluding grazing and mowing areas). The total theoretical, harvestable, and recoverable potentials of residue dry biomass in tonnes (t) normalized by total SKO area (t dry weight (DW) km^{-2}) were calculated. Estimation of the theoretical residue potential was based on annual standard crop yields and total dry residue:crop ratios. Nilsson and Bernesson (2009) provide information about straw: grain ratios for cereal crops and rapeseed, while the values for legumes, flax, sugar beets, and potatoes were calculated as average values that considered either residue:product ratios or harvest indices taken from literature (Li et al., 1999; Högy and Fangmeier, 2009; Yang et al., 2010; Kreuger et al., 2014; Yetimwork et al. 2014; Pellicanò et al. 2015; Ramirez-Cando et al., 2017; Wegi et al. 2018; Dudarev 2020; Locker 2021). When required, residue:product ratios where recalculated on a dry matter basis. The harvestable potential was defined considering the technical limitations of residue harvesting, which, for the majority of crops, was assumed would leave a stubble of 20 cm in the fields (40 cm for rapeseed and no stubble considered for sugar beet and potato) in accordance with Nilsson and Bernesson (2009). Moreover, de Toro et al. (2021) suggested the use of recovery coefficients that consider the limitations posed by weather conditions in calculating the proportion of residue that can be recovered. Therefore, a recoverable coefficient (RC) for all crops was defined at 80% of harvestable biomass as a conservative value, considering the findings of de Toro et al. (2021) for cereal crops in different regions of Sweden, and of Kreuger et al. (2014) for sugar beets.

The results of the residue yield calculation were then contrasted with the cropping area of each crop in each SKO to obtain total values of biomass availability.

2.2. Intermediate crop biomass potential

Estimating the potential biomass production for intermediate crops required both the estimation of yields and the area available for IC cultivation. This analysis was limited to 84 SKOs located within the areas approved by the Swedish Board of Agriculture for environmental compensation for intermediate crops for carbon storage and reduced nitrogen leakage, which also marks the area where ICs can be cultivated. At higher latitudes in Sweden, climate and crop rotations restrict the possibility to use ICs in a meaningful way.

2.2.1. Estimating IC yields

Oilseed radish (OR), sown after harvest of the main crop (aftersown), was selected as the model IC species for two reasons. Firstly, many farmers in southern Sweden prefer to use ICs sown after harvest of the main crop, rather than ICs sown together with the preceeding main crop (undersown). Secondly, species from the *Brassicaceae* family are suitable as ICs in this climate where the number of possible species to sow in autumn are few due to climate constraints. Oilseed radish, which provides fast growth, is quite frost tolerant and does not constitute a high risk to cause pathogen infection of the main crops, is one of the most commonly used ICs today (Aronsson et al., 2016). It is also the one with the best availability of information resulting from more extensive research compared to other IC species sown after harvest. An alternative strategy for farmers is to use an undersown IC, e.g. grass or grass in mixture with clover, which is more common for farms in the more northern districts included in this study. A Swedish study that compiled data from cover crop studies showed that the amount of aboveground biomass produced during autumn by undersown grasses was largely comparable with that produced by OR, but with less variability between

Table 1
Information used to calculate crops residue biomass.

Crop	Moisture content (%)		Residue:product ratio (Dry weight)	Harvestable residues (% of theoretical)	Source
	Product	*Residue*			
Spring barley	14	18	0.72	48.68	Nilsson and Bernesson (2009)
Winter barley	14	18	0.90	60.64	Nilsson and Bernesson (2009)
Oats	14	18	0.87	57.14	Nilsson and Bernesson (2009)
Rye	14	18	1.03	72.22	Nilsson and Bernesson (2009)
Triticale	14	18	0.92	67.71	Nilsson and Bernesson (2009)
Spring wheat	14	18	1.02	61.68	Nilsson and Bernesson (2009)
Winter wheat	14	18	0.90	63.83	Nilsson and Bernesson (2009)
Mixed grain	14	18	0.70	61.64	Nilsson and Bernesson (2009)
Peas*	15	–	1.30	60.00	Yang et al. (2010); Yetimwork et al. (2014); Pellicanò et al. (2015)
Canned peas*	75	–	2.10	60.00	Yang et al. (2010); Yetimwork et al. (2014); Pellicanò et al. (2015)
Fava beans*	15	–	1.10	79.80	Li et al. (1999); Wegi et al. (2018)
Flax	9	60	2.23	70.15	Ramirez-Cando et al. (2017); Dudarev (2020)
Spring rapeseed	9	18	0.85	47.24	Nilsson and Bernesson (2009)
Winter rapeseed	9	18	0.92	66.23	Nilsson and Bernesson (2009)
Sugar beet	87.6	87.3	0.53	100.00	Kreuger et al. (2014); Locker (2021)
Table potatoes	79	79	0.13	100.00	Högy & Fangmeier (2009); Locker (2021)
Starch potatoes	79	79	0.13	100.00	Högy & Fangmeier (2009); Locker (2021)

* Residue:product ratios for legumes calculated from harvest indices.

regions (Aronsson et al., 2023). Therefore, it was considered appropriate to include the analysis of a grass-clover mixture as one of the scenarios in the sensitivity analysis described in section 2.4.

The estimation of the yields of OR for each of the 84 harvest yield districts was performed by a spatial analysis that encompassed results from several field experiments conducted in Sweden. The general assumption was that yields are not homogeneous in the landscape but follow a spatial distribution affected by factors such as latitude, climate, growing period, and light. It was therefore deemed necessary to use a model that could reflect the spatial variability of yields based on individual data. Information about yields was collected from a report with data compiled from Swedish field studies of cover crops over the 1983–2021 period (Aronsson et al., 2023).

A total of 118 yield measurements of OR in 22 different locations in Sweden were entered as data (Appendix A). This dataset contained different fertilization levels, with the most frequently specified value (modal value) being 40 kg N ha^{-1}. Although selecting a single fertilization rate was preferable, the exclusion of data points based on this criterion would lead to a notable reduction of the already limited spatial dataset. Also, increasing fertilization values from 40 kg N ha^{-1} has not shown significant differences in yield results (Aronsson et al., 2023). In view of the number of data points and their spatial distribution, inverse distance weighting (IDW) was selected as a suitable interpolation method. Employing ArcMap 10.8.1, a raster surface reflecting a spatial continuum of OR yields was generated using the IDW spatial analyst interpolation tool. To capture spatial variation into individual SKOs, the dataset raster was further processed by running the Zonal Statistics as Table Tool, which allowed to summarize the information within the boundaries defined by the harvest yield districts and calculate the average as a reference yield value for each of them.

2.2.2. Estimating area available for IC cultivation

Openings for establishing intermediate crop cultivation in a rotation sequence depend on the types of crops that are grown in a particular agricultural system. Hence, we considered that an appropriate approach to estimate the available area for IC cultivation was to determine potential crop rotation sequences. Accordingly, we assumed that an aftersown IC must be sown no later than in August in order to produce a satisfactory amount of biomass by late autumn (October–November). Also, ICs cannot be placed after main crops harvested later than that; e.g., certain types of potatoes and sugar beets. Openings for IC cultivation in the crop rotation always occurred before spring-sown crops.

Moreover, to apply this approach to the SKOs, arable land potentially under rotation was defined as the total arable land excluding the areas occupied by ley crops dedicated to grazing, which are not typically part of crop rotations in Sweden. For this purpose, the information available on the proportion of ley grass was obtained at the county level (Jordbruksverket, 2022) and was further processed as a weighted average using the relative areas of each county in each SKO as weighing factor.

Given the high diversity of cropping systems reflected in the number of SKOs and the varying composition of crops within each of them, it was necessary to aggregate this diversity in order to obtain a general overview of the cropping systems. This was done by running a hierarchical cluster analysis using the Euclidian distance as similarity index and a paired group algorithm in the free software for Windows PAST 4.03. This analysis used the relative areas of all different crops within the SKOs, i.e., the cropping areas for each crop standardized by the total land under rotation. After an initial visual inspection of the resulting dendrogram, a cut level at a dendrogram distance of 0.2 was selected. This distance corresponds to the point where the first cluster with a single SKO appeared. Therefore, the SKOs were grouped into 10 clusters that exhibited similar cultivation patterns.

Subsequently, the average relative area of crops within each cluster were taken as reference values that reflected the relative frequency within rotation sequences to generate crop rotation models representative of each cluster. The criteria for designing the models were taken from Johnsson et al. (2022), who defined restrictions for crop combinations in crop sequences and combinations where intermediate crops are possible. However, to simplify the analysis and maximize the area covered by the rotations, crop groups showing similar characteristics and restrictions relative to the crop sequence were defined (Table 2).

Table 2
Groups of crops defined to create crop rotation models.

Crop group	Crops
Spring crop	Spring barley, oats, spring wheat, legumes.
Winter cereal	Winter wheat, winter barley, rye, triticale
Sugar beet and potato	Sugar beet, potato
Winter rapeseed	Winter rapeseed
Grass	Ley grass, grass for seed production
Fallow	Fallow
Excluded	Horticultural crops, maize, green fodder, spring rapeseed, flax, mixed grain

There were also a few crops excluded from the analysis, mainly due to their very low representation in the total area (<5%) and because they didn't fit in any of the other groups (Table 2).

For each of the 10 clusters, an iterative process was employed to create between 2 and 3 rotation models spanning 4 to 8 years, resulting in a total of 28 rotation models. This allowed for calculation of relative areas covered by each rotation and a general potential IC frequency for the entire cluster. Nonetheless, it was observed that within single clusters the variability in cropping areas was considerable, and the calculated IC frequency could be an under- or overestimation if applied directly to individual SKOs. Moreover, an initial observation indicated that the prevalence of certain crop groups potentially affected the frequency of IC. Therefore, this was tested using a multiple regression analysis that considered the calculated IC frequency as the dependent variable and the crop groups as independent variables, resulting in an initial mathematical model.

To enhance the accuracy and reliability of the model, eleven supplementary scenarios extracted from the main clusters were incorporated. The additional scenarios included four subgroups within the main clusters that showed variations in respect to the main clusters and seven individual SKOs, which were the most dissimilar members within each group according to the hierarchical analysis. For these cases, the same process for creating rotation models was applied, resulting in additional 28 rotation sequences. This augmentation increased the number of observations, strengthening the overall robustness of the regression analysis (see Appendix B for more details). The generated regression model was finally used to estimate the share of land available for IC cultivation in each individual SKO, which was then used to calculate the total IC cultivation area.

2.2.3. Estimation of IC biomass

The aboveground (shoot) biomass potential of oilseed radish was calculated directly using the OR yields and the estimated available area. Belowground (root), stubble, and harvestable fractions of total biomass were also estimated. A constant average shoot:root ratio of 8.36 (Prade et al., 2022) was used to calculate the belowground biomass. It is worth noting that factors such as the establishment date, growing days, and fertilization can significantly affect shoot:root ratios as evidenced by Prade et al. (2022). Given the considerable variation in shoot:root ratios, this became one of the selected variables considered in the sensitivity analysis detailed below. The harvestable fractions dependent on yields were calculated based on the observations of Prade et al. (2022), falling somewhere between 0.68 for the lowest yield (498 kg ha^{-1}) and 0.81 for the highest (3449 kg ha^{-1}). Additionally, to maintain consistency with the previous assumptions for residual crop biomass, a recoverable potential of 80% was assumed.

2.3. Contributions to soil organic carbon

Based on the total biomass obtained from different fractions of oilseed radish and their carbon content, we estimated potentially stabilized soil carbon from intermediate crops in arable land. This was then contrasted with the potential loss of stabilized soil carbon resulting from the complete removal of recoverable crop residues. The carbon content in dry biomass for crop residues (consisting mainly of cereal straw) and intermediate crops was assumed to be 42.3% and 43.6%, respectively (Ma et al., 2018). A humification coefficient (h-value) of 0.35 for IC root biomass was used for a simplified estimation of carbon contribution as the fraction of C that can be potentially stabilized (Kätterer et al., 2011). Exudates were assumed to have an additional contribution of 65% respective to the roots (Bolinder et al., 2007). The humification coefficient for aboveground biomass was calculated for each SKO as a function of clay content (Poeplau et al., 2015). Average clay content values for each district were calculated by extracting the information from a digital soil map (Piikki and Söderström, 2019) and using the Zonal Statistics at Table tool from ArcMap 10.8.1 (Appendix C). The analysis of potential compensation for stable carbon loss from residue removal due to the inclusion of intermediate crops considered two scenarios: one in which the IC was incorporated into the soil and one in which the IC aboveground biomass was harvested.

The C/N ratio was on average 18 for OR, 22 for perennial ryegrass, and 20 for grass in mixture with clover, at sampling in late autumn. Different C/N ratios will affect mainly mineral N dynamics in the soil after incorporation (Constantin et al., 2023), while the amount of biomass will be most important for C sequestration, which was the main focus of this study. As these C/N ratios were similar between the ICs, using the same humification coefficient for the OR and grass-clover in the sensitivity analysis was deemed appropriate.

2.4. Sensitivity analysis

The sensitivity of the results was tested for variables that showed high variation and/or uncertainty. Using residue removal and IC biomass harvesting as base scenario, the effects on SOC inputs of varying humification coefficient for IC biomass, clay content, shoot:root ratio, and a different IC species were evaluated in one or two alternative scenarios per variable (Table 3). The humification coefficient function for litter developed by Poeplau et al. (2015) was based on experimental stabilization values for incorporated aboveground residues (mainly cereal straw but also oilseed, sugar beet, tomato, potato, and soybean residues). However, humification coefficients are also affected by the source of carbon input, as is evidenced by Kätterer et al. (2011). Therefore, the tested alternative scenario to the humification coefficient dependent on clay content was a constant value of 0.12 for aboveground biomass (Kätterer et al., 2011).

The clay content in agricultural land can vary significantly across the landscapes of a single yield survey district (Piikki and Söderström, 2019). Similarly, the shoot:root ratios for oilseed radish show a high variability (Prade et al., 2022). Therefore, for these two latter variables, alternative scenarios plus and minus one standard deviation were developed (Table 3). Additionally, a final scenario considering an undersown grass–clover mixture as IC was included as part of the sensitivity analysis. This last scenario makes generalized assumptions about a hypothetical undersown IC mixture based on the data from Prade et al. (2022) and Aronsson et al. (2023), to offer some insights on how a different crop species could affect the outcome (Table 3). Since there were no significant differences between different regions in grass-clover mixtures yields (Aronsson et al., 2023), a constant value of 917 kg ha^{-1} was assumed, using the same area allocated for the production of OR.

Table 3
Description of variables selected for sensitivity analysis and alternative scenarios (SD = standard deviation).

	Input variable	Base scenario	Sensitivity analysis	
			Alternative 1	Alternative 2
A	h-value of IC shoot biomass	h = −0.044 + 0.0036*Clay(%)	Constant: h = 0.12	–
B	Clay content	Average per yield survey district	Average−1 SD	Average+1 SD
C	Shoot:root ratio	8.36	4.20 (−1 SD)	12.52 (+1 SD)
D	IC species	Oilseed radish	Clover–grass mixture Yield: 917 kg ha^{-1} Shoot:root =4 Harvestable =73%	–

3. Results

3.1. Residual biomass availability

The annual recoverable amount of residual crop biomass for Sweden was estimated at 2139 kt DW, meaning an average yield of 837 kg DW ha^{-1} on arable land or a normalized value of 4.9 t DW km^{-2} of total land area. Also, 84% of total residues corresponded to cereal straw. However, as shown in Fig. 1, the amounts across the yield survey districts vary greatly, both in total residual biomass and crop origin. Although the contribution from cereal straw dominates the residual biomass in the whole country, there are important amounts of residue left over from sugar beets and other crops (mainly rapeseed) in the southernmost regions (Fig. 1a). Moreover, residue composition affects the percentage of recoverable biomass, with the highest values being associated with higher shares of cereal straw. Among all SKOs, the recoverable residual biomass of the main crops constituted between 38.9% and 48.7% of the total theoretical potential, with an average of 46.4%. Also, the highest amounts of recoverable residual biomass per unit of total area were registered in the southernmost region with values up to 158 t DW km^{-2} (Fig. 1b). This is in contrast to the results obtained in more than half of the districts (52%), where the recoverable biomass is <5 t DW km^{-2}, while only 26% of districts show values higher than 30 t DW km^{-2}, and only 13% show a recoverable biomass >55 t DW km^{-2}.

3.2. IC biomass

3.2.1. Oilseed radish yields

Oilseed radish yields exhibit a latitudinal gradient with the highest values in the southernmost part of the country, which is associated with earlier sowing dates, warmer conditions, and later potential harvest dates. The values range from <500 kg ha^{-1} up to nearly 3500 kg ha^{-1}. However, values over 1800 kg ha^{-1} are only found in <20% of the districts, >2300 kg ha^{-1} in only 7%, while for the majority (>70%) the average yields are below 1500 kg ha^{-1}. More detailed information can be found in Appendix A.

3.2.2. Area available for intermediate crops and biomass production

The hierarchical cluster analysis resulted in 10 clusters following a spatial distribution that aggregates neighboring districts. However, in some cases, distant districts were grouped together, reflecting similar cultivation patterns across distant regions of the country. The generated clusters are presented in Appendix B.

The design of alternative crop rotations for each cluster is exemplified in Fig. 2. This example illustrates the restricting effect that some crops, such as ley, have on opportunities to include IC in crop rotations. Moreover, the relative area covered by each rotation and the established frequency of intermediate crops allowed for calculation of the area available for IC cultivation. The information on the average relative cultivation areas for various crop groups within each cluster, along with the estimated area available for IC establishment can be consulted in Appendix B. The mathematical model formulated to calculate the IC area at each individual SKO is found in Appendix D. Among the variables

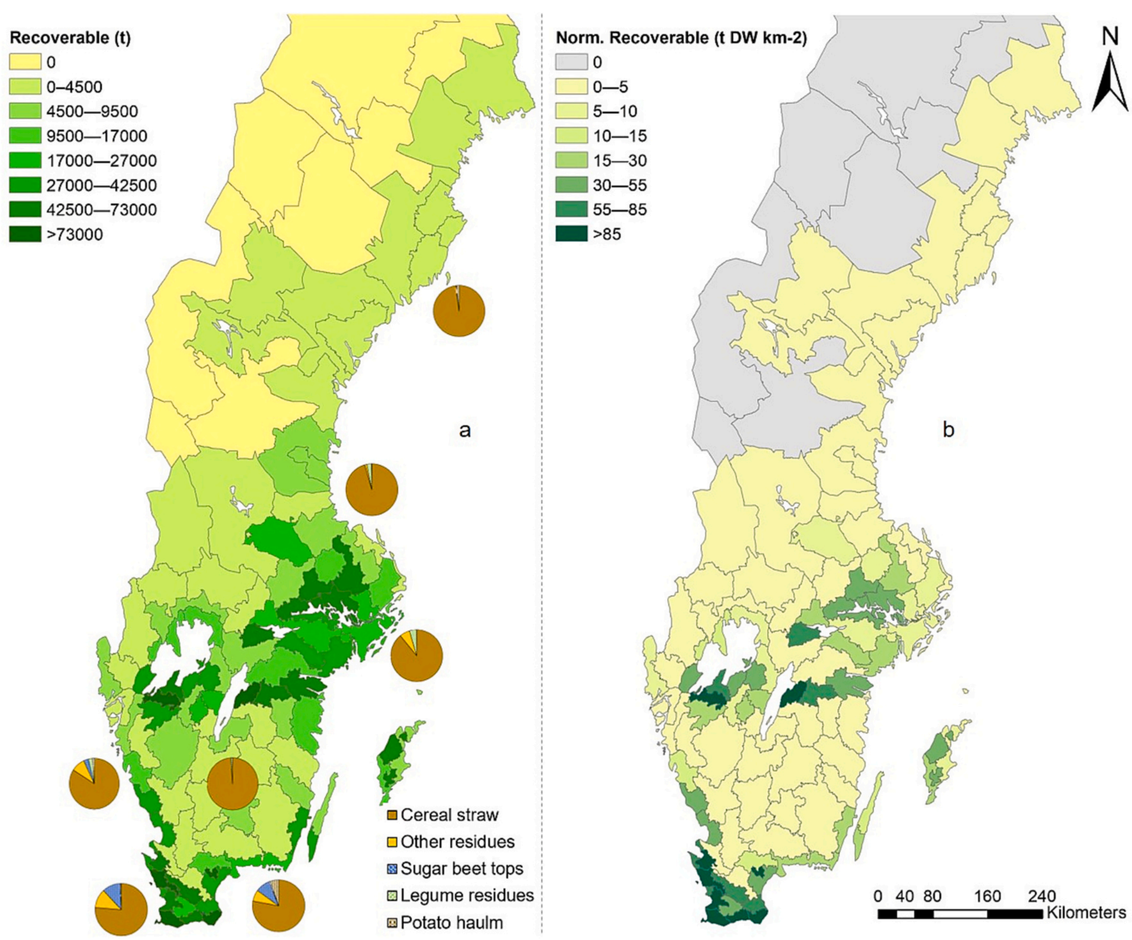


Fig. 1. Recoverable residual biomass potential of main crop groups per yield survey district in Sweden: (a) total biomass [t] and the relative regional amounts of different types of crop residues (circle diagrams) and (b) values normalized by total area of each yield survey district [t DM km^{-2}].

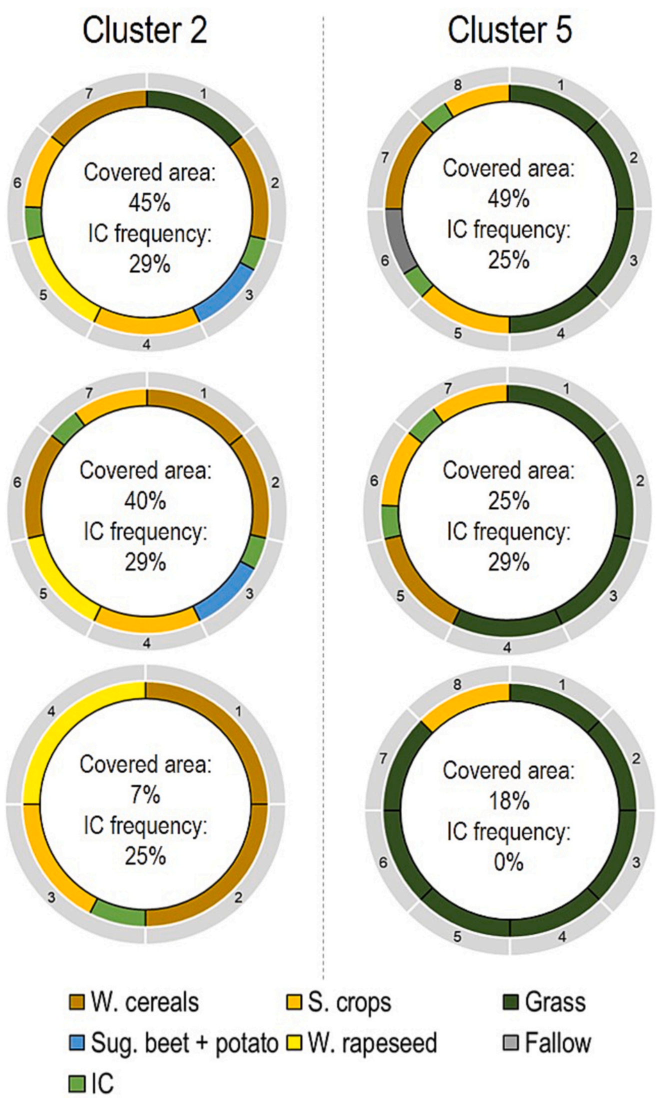


Fig. 2. Rotation alternatives designed for cluster 2 and cluster 5 with respective area coverage and estimated IC frequency within each rotation sequence (classification of crops as presented in Table 2).

considered in the analysis, the proportions of land allocated for spring crops and winter cereals were the two factors that exhibited a significant effect (*p*-value <0.05) on area availability for intermediate crops. These variables accounted for 94% of the observed variability (R^2), indicating a strong influence of the two factors in IC area estimation.

The total available area calculated for each yield survey district is presented in Fig. 3 along with the total estimated recoverable biomass potential from oilseed radish harvesting. There is a great variability in these results throughout the country: on average, the area available for IC in the selected SKOs is 21% of arable land, with a maximum of 50% in SKOs with prevalence of spring crops and no land available when the system is dominated by ley grass. The total annual area estimated for IC cultivation in the country is 542,852 ha. More than half of this land is located in 19 SKOs, which comprise only about 32% of total arable land of the country.

Total recoverable biomass production from oilseed radish was estimated at 383 kt with an average normalized amount of 4.6 t km^{-2}. This, to some extent, reflects the area available for IC cultivation; however, the total biomass production from oilseed radish is also influenced by OR yields. The OR biomass production per unit area is still highest on Sweden's southern coast, reaching a maximum of 27.6 t km^{-2}. The spatial variability of potential OR production is evidenced in the fact that only 11 SKOs have production values over 10 t km^{-2}, accounting for 32% of the total production (121 kt). When considering arable land, about 30% of the area can produce as much IC biomass as the remaining 70% of arable land considered in this study.

3.3. Effects on organic carbon contribution

When considering incorporation into the soil, the total input of organic carbon from the cultivation of oilseed radish was estimated at 344 kt for the area analyzed. The results of potentially stabilized carbon in the soil were 30.5 kt, meaning that the average fraction of potentially stabilized carbon is 9% (Fig. 4). Nevertheless, there is a degree of variability which is strongly affected by the value of the humification coefficient for the shoot biomass, dependent on clay content. Up to 16% of total carbon is potentially stabilized in soils with >40% clay content (Appendix B).

The carbon inputs from IC reflect, to some extent, the results presented in Fig. 3. However, the carbon contribution from stubble and root biomass modifies the overall results. The total carbon inputs from intermediate crops seem to be especially significant in the southernmost SKOs. A slightly different pattern was observed when only considering the carbon that can be stabilized in the soil through humification. Peak values are reached in the northern parts of the study region, where higher clay content in the soil results in higher C stabilization of aboveground biomass. Due to variations in clay content, the contribution from shoot and root biomass varies and affects total stabilized carbon, showing an uneven distribution throughout the country (Fig. 4b).

In contrast, the total carbon contribution of recoverable crop residues (calculated for the same area as IC cultivation) was estimated at 897 kt, of which 4% or 36.6 kt are potentially stabilized. This is a relatively low fraction of stabilized carbon, which is mainly affected by the calculated clay-content–dependent h-values. The top 8 SKOs contributing to total residual biomass (32% of total carbon inputs) show humification coefficients between 0.01 and 0.06 due to lower clay content. Only six SKOs showed h-values over 0.10, and they contributed <1% of total carbon inputs. Moreover, there is a significant area where the average values of clay content are under 10%, meaning that there is virtually no stabilization of the carbon inputs from recoverable residues in nearly 27% of the total arable land.

By subtracting the values of the potential organic carbon contribution loss due to the complete removal of recoverable crop residues, we obtained the results presented in Fig. 5. The overall balance of potentially stabilized carbon in both cases—whether the IC is incorporated in the soil or harvested—are negative, with values of −6.1 kt and − 12.4 kt, respectively, resulting in a net emission of carbon into the atmosphere. However, for the majority of yield survey districts, the inclusion of intermediate crops resulted in a positive carbon input balance when combined with the removal of residual biomass. Although there is reduced carbon contribution when harvesting the OR, only a few districts experience a shift from a positive to a negative carbon balance (Figs. 5). For areas with predominantly low-clay soils (<10%), the stable carbon contribution from both aboveground IC biomass and residual crop biomass is negligible, due to the low stabilization of carbon. Therefore, the resulting balance is positive due mainly to the contribution of IC root biomass. In contrast, for soils with higher clay content (>35%), the carbon contribution from both IC aboveground biomass and residual biomass takes on more relevance. Since the contribution to potentially stabilized carbon from crop residues is higher in these types of soils, the required compensation from IC when considering a total removal of residues is also higher. Due to this effect, although the carbon contribution from IC shoot biomass is also higher in clay soils (Fig. 5b), the overall balance in districts with higher clay contents is negative.

Based on the previous results, Fig. 6 shows recommended actions when combining residue removal and cultivation of oilseed radish as an

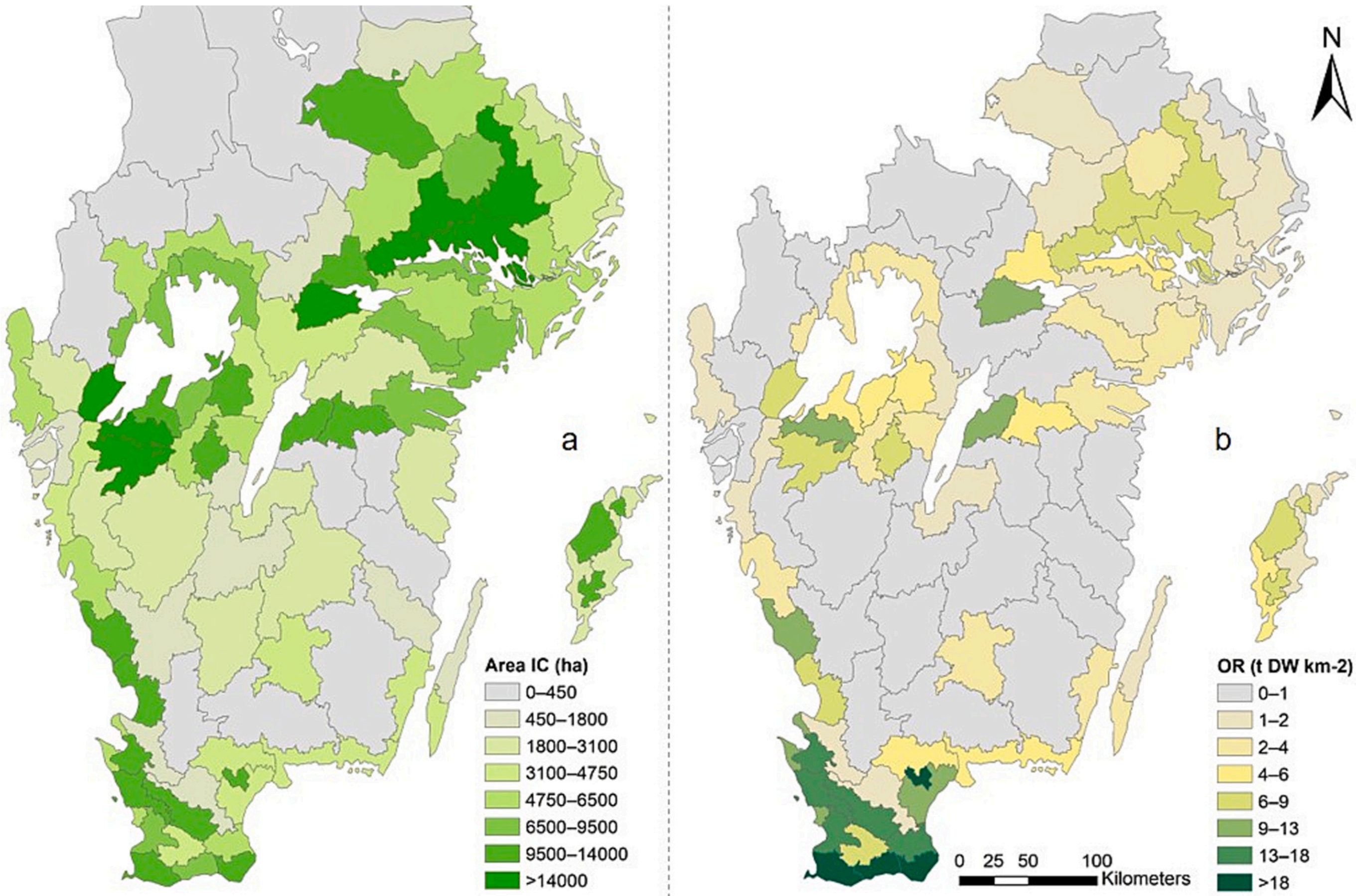


Fig. 3. Potential for intermediate crop cultivation in Sweden: (a) estimated area available for IC [ha] and (b) estimated OR recoverable biomass [t DW km^{-2}] for oilseed radish.

intermediate crop. The only criterion for this analysis is a positive balance in carbon contribution when combining the cultivation of IC and complete removal of the recoverable fraction of crop residue. When considering the incorporation of IC in the soil, it is possible to completely remove recoverable crop residue biomass for 55% of the total arable land. Considering harvest of OR biomass, 51% of the total arable land still allows for complete residue removal. For the remaining area, removal restrictions of crop residue harvest are recommended. However, these results are derived from large spatial units, and a final assessment should be performed for each individual field. Moreover, this analysis does not intend to offer definitive recommendations but rather to provide an initial understanding of the implications of combining residues removal and intermediate crop cultivation.

3.4. Sensitivity analysis

The results of the sensitivity analysis with removal of residues and harvest of OR biomass as a base-line scenario are depicted in Fig. 7. The figure shows the resulting values of potentially stabilized carbon for each of the 84 SKOs, ordered according to total stable carbon input in the base-line scenario (from highest to lowest). They are also compared with the alternative scenarios described in Table 3.

A constant humification coefficient (h-value) for the IC aboveground biomass increases the estimations of total stable carbon input in the majority of cases by a median value of 74%, although only in a few districts (7) the value changes from a negative to a positive balance (Fig. 7a). A higher shoot:root ratio of OR decreases the carbon contribution by a median of 33%, while a lower shoot:root increases the balance by 100%, which reflects the importance of roots in contributing to organic soil carbon (Fig. 7c). When the shoot:root ratio is reduced, 10 districts switched from a negative to a positive carbon input balance, while the opposite happened in 5 districts when increasing the shoot:root value.

The variability in soil clay content showed the greatest impact on the results. With a median reduction of 79% in carbon inputs, higher values of clay shifted the balance from positive to negative in 19 districts (Fig. 7b). With lower clay content values, a median increase of 44% was obtained and the carbon inputs changed from negative to positive in 15 districts. This accounts for the relevance and impact of the natural soil type variability within each yield survey district on the potential to stabilize organic carbon.

Finally, the selection of a grass–clover mixture instead of OR resulted in an overall increase in the contribution to stable carbon for the majority of districts (Fig. 7d). This phenomenon is related with a lower shoot:root ratio, meaning a higher contribution of root biomass in contrast to OR, despite the higher yields of the latter. There was a shift from a negative carbon balance to a positive one in 9 districts.

4. Discussion

This study examined the removal of crop residues in combination with a widespread cultivation of intermediate crops as a sustainable intensification strategy that enhances the provisioning of feedstock for the bioeconomy in the Northern European context. By harnessing carbon sequestration as an ecosystem service derived from temporal diversification (Tittonell, 2014; Poeplau and Don, 2015; Jian et al., 2020; Aronsson et al., 2023), the establishment of ICs in crop rotation sequences can improve the overall sustainability and resilience of

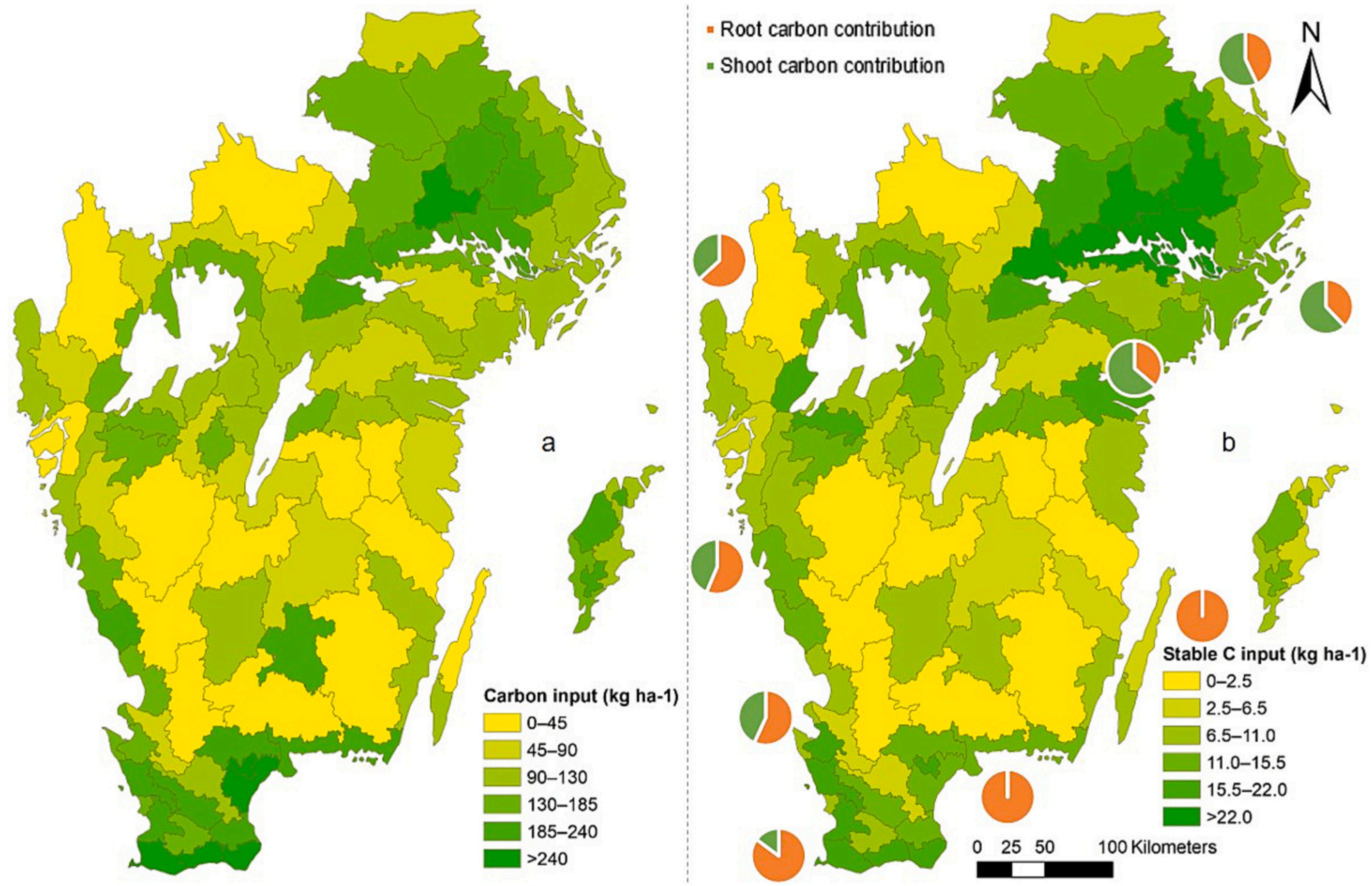


Fig. 4. Estimated carbon inputs derived from incorporated intermediate crop biomass in arable land [kg ha^{-1}]: (a) total carbon input and (b) potentially stabilized carbon illustrating relative shoot and root contributions. (Note the difference in scale between maps).

agroecosystems (Aronsson et al., 2016; Abdalla et al., 2019; Jensen et al., 2022; Hao et al., 2023). By boosting biobased production, this sustainable intensification strategy aligns with the EU bioeconomy strategy (European Commission, 2018) and, therefore, the agricultural practice proposed in this study harmonizes with European Green Deal initiatives which aim to reach climate neutrality by 2050, and in the implementation of the United Nations' 2030 Agenda (UN General Assembly, 2015; European Commission, 2019).

However, counteracting effects and conflicting targets have previously been identified between several Sustainable Development Goals, especially in the food–energy–climate nexus (Pham-Truffert et al., 2020). Competition over water and land has resulted in trade-offs between food production and the availability of biomass, while potentially increasing emissions due to indirect land use change (Prade et al., 2017; Lantz et al., 2018; Pham-Truffert et al., 2020). In this context, the suggested use of IC has the potential to address multiple targets while avoiding constraining, counteracting, or cancelling effects between goals (Pham-Truffert et al., 2020; Jensen et al., 2022). This practice also aligns with the package of policy initiatives of the European Green Deal and the 'Fit for 55' proposals that deal with the reduction of GHG emissions (European Commission, 2019; European Council, 2023). The results presented here show how the inclusion of IC cultivation in crop rotation sequences is a means of offsetting detrimental effects on SOC stocks due to the large-scale removal of residue, which can lead to an overall reduction in carbon emissions.

Several studies have highlighted the importance of residual agricultural biomass as a bioeconomy feedstock in Northern Europe (Nilsson and Bernesson, 2009; Hamelin et al., 2019; Björnsson and Prade, 2021; de Toro et al., 2021; Broberg et al., 2022; Jensen et al., 2022). Previous estimates have suggested that the potential energy derived from total residual streams could account for 20–30% of Sweden's total energy consumption (Hamelin et al., 2019). A regional study on the southwestern coast of the country acknowledged the role of crop residues as potential substrates for the production of biogas, the largest contributor among different potential substrates (Broberg et al., 2022). Moreover, straw comes in second in total theoretical residual biomass potential (after residues from forestry), as the primary source of non-food biomass in Sweden's southernmost region (Hamelin et al., 2019). Consequently, accurate and reliable quantification of available biomass and an analysis of environmental effects are both required.

It has been suggested that the use of functional multipliers or algorithms for the calculation of residual biomass offers good estimations that reflect the effect of yield on straw biomass production (Bentsen et al., 2014; Hamelin et al., 2019). However, functions developed for Europe have been considered inadequate for Swedish conditions (Björnsson and Prade, 2021), where the use of constant values for straw: grain ratios are deemed a better alternative (Bentsen et al., 2014). Following IPCC guidelines for good practice (IPCC, 2019), we used specific straw:grain ratios that have been developed for several crops of major importance in the country, simplifying the calculation of harvestable potentials (Nilsson and Bernesson, 2009). The results presented here are consistent with recent estimations for some regions in Southern Sweden (Broberg et al., 2022). Residue:product ratios used in this study were also somewhat more conservative for most crop types analyzed in comparison to the factors used in the Swedish national GHG inventory (Naturvårdsverket, 2023). Furthermore, our results for available crop residues show slightly lower values, due to the use of recovery coefficients as suggested by de Toro et al. (2021). They emphasized the importance of considering the technical limitations imposed by climatic conditions in specific regions of Sweden and

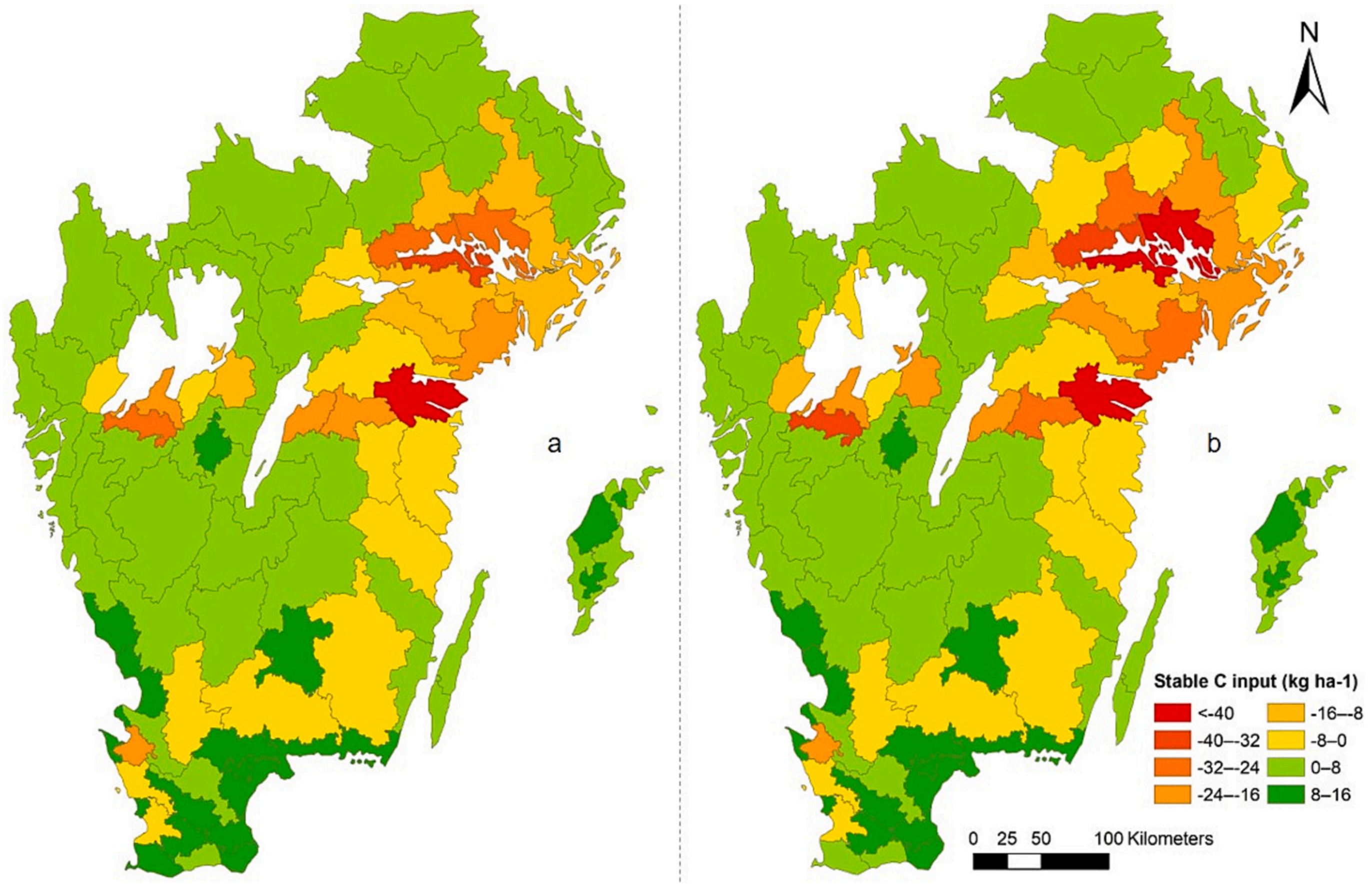


Fig. 5. Estimated change in potentially stabilized carbon inputs when removing the recoverable fraction of residual biomass and including oilseed radish as intermediate crop: (a) incorporation of OR in soil, and (b) removing the recoverable OR fraction.

proposed recovery coefficients to estimate technical potentials. This approach was deemed to result in more accurate estimations.

Although major attention has been paid to straw as a principal contributor of crop residue, other crop residues, from crops such as sugar beets (Kreuger et al., 2014), rapeseed (Maravić et al., 2022), and potatoes (Kaplan et al., 2018), have the potential to provide important volumes of biomass, especially in the southern regions of Sweden. Here we stress the relevance of sugar beet and rapeseed residues along the southern coast of Sweden. Such crop residues have also been recognized as a valuable resource for multiple applications within the bioeconomy (Kreuger et al., 2014; Torma et al., 2018), from the production of biogas (Kreuger et al., 2014) to the extraction of compounds of interest, such as proteins and phenolic compounds (Tamayo Tenorio et al., 2018; Maravić et al., 2022). Furthermore, there is a growing interest in the use of horticultural crops that typically leave fresh residue at harvest that can be used for different applications (Prade et al., 2021). Although a more detailed assessment of these crops was outside the scope of this study, the analysis of potential biomass provisioning and their role in IC rotation sequences could contribute to current research on bioeconomy feedstock.

In our estimation of potential IC production, a simplified multiple regression model was developed to estimate IC area availability related to IC frequency within a rotation system. The results were consistent with previous findings from Johnsson et al. (2022), who simulated the possibility of growing catch crops for larger catchment areas to calculate nutrient leakage. For the analysis of IC yields, we used oilseed radish (OR) sown after harvest of the main crop as a model IC to simplify and generalize the system. The main reason was that OR is commonly used as a cover crop in south Sweden, and there is a larger data availability from different sites in the country than for other crops. We included the geographical aspect in the estimation of biomass production of ICs (Fig. 3), but did not directly consider the effect of sowing time, partly due to insufficient data. Both climate and sowing time will affect the number of days with sufficient temperature for growth, which is a factor that determines biomass production of both OR and other IC (Lehrke, 2000). In this study, we indirectly included the time of sowing, since we restricted the inclusion of ICs in crop rotations to only after main crops were harvested in August or earlier, with the assumption that ICs were sown no later than August.

In practice, there would be a diversity of ICs used in the different crop rotations and regions. For example, OR is not recommended for use in crop rotations with other *Brassica* species due to the risk of propagation of the club root disease (*Plasmodiophora brassicae)* (Wallenhammar et al., 2012). Other ICs currently in use in Sweden, sown after harvest of the main crop, include, for example, different clovers (*Trifolium* spp.), hairy vetch (*Vicia villosa*), phacelia (*Phacelia tanacetifolia*), winter rye (*Secale cereale*), as well as grasses (e.g., *Lolium* spp., *Festuca rubra* and *Phleum pratense)*. Mixtures of two species, or even multi-species mixtures, are commonly used according to practitioners, but this is not captured by agricultural statistics. In the more northern districts included in our study, ICs of grasses or grass–clover mixtures, under-sown in the main crop in spring, would likely comprise the main practice. These ICs are robust and have long been used under Nordic conditions, where the climate constrains the timeframe for cover crops and ICs (Aronsson et al., 2016). Different IC species and mixtures will produce different amounts of shoot and root biomass, as well as be be of different quality. For biomass production, which is of most concern for effects on SOC, the time available for growth, i.e. time of sowing, will be the most important factor. The quality of the IC shoots and roots, as C/N ratio, will affect degradation processes in the soil, N release and

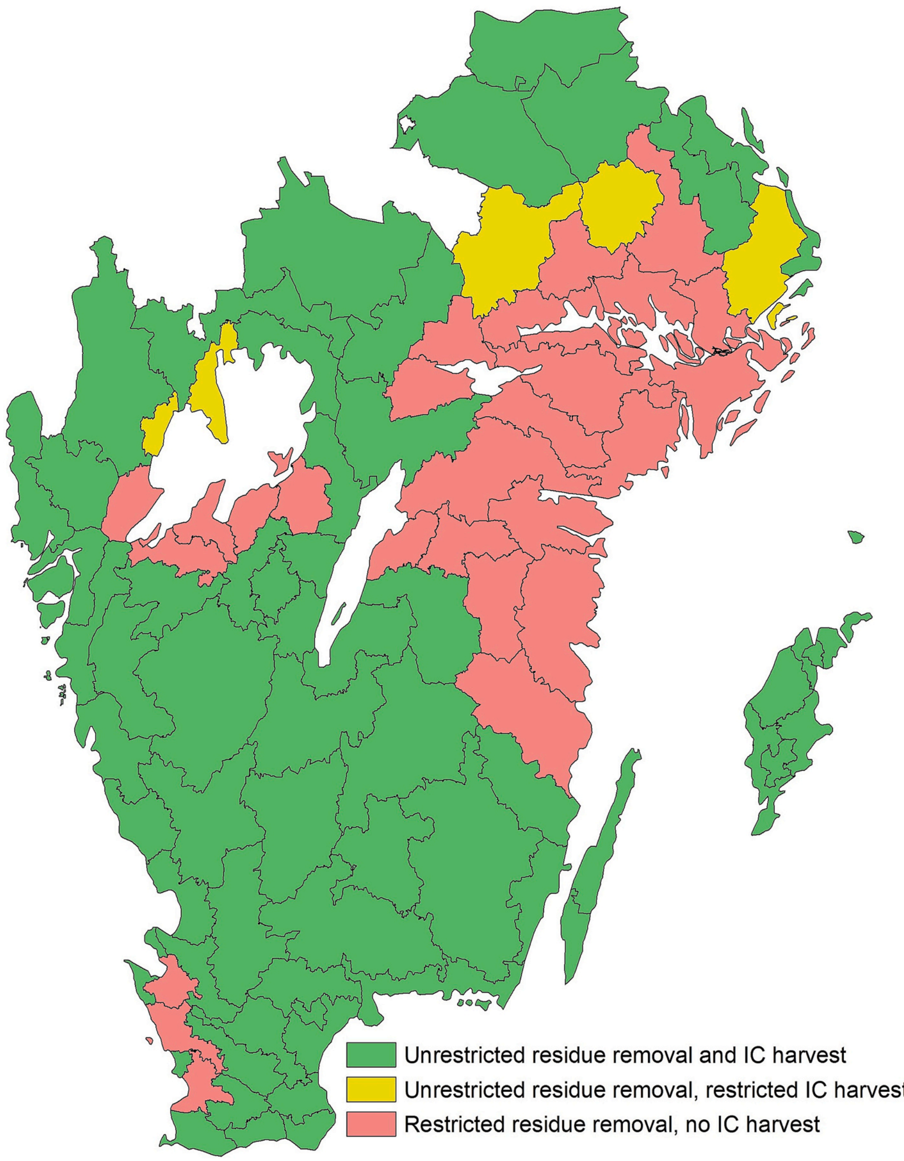


Fig. 6. Recommendation based on potential of IC to compensate for the effect of residue removal on potentially stabilized organic carbon inputs.

stabilization of C. Especially N mineralization and fertilizer effect on the following crop will be affected by the C/N ratio of the IC, where legume species in general result in larger N mineralization than species from Brassicaceae, Hydrophyllaceae and Poaceae (Constantin et al., 2023). However, there is still a knowledge gap about the effect of C/N ratio on C stabilization in the soil (Poirier et al., 2018; Kallenbach et al., 2019). Further development of tools for IC strategies in the Nordic countries would preferably include growth models for different types of ICs, which in turn require better regional field data.

The above-proposed sustainable intensification practice for the increased production of biomass does not negatively alter the current level of food production resulting from competition for land. However, in this study, we did not consider the effects of the IC on nitrogen availability for the following crop, which can be either slightly negative or slightly positive (green manure effect), depending on factors like the time of incorporation of IC material, plant C/N ratio, N uptake, and climate (Thorup-Kristensen et al., 2003). Residual effects of cover crops on crop yield are often zero or slightly negative for non-legume cover crops, according to a meta-study by Tonitto et al. (2006). Efficient soil N depletion in combination with slow remineralization seemed to be the explanation. Adding legumes to cover crop mixtures generally improves N dynamics and results in more reliable green manure effects of the cover crops (Wallgren and Linden, 1994; Dabney et al., 2010). Conversely, under certain circumstances, the establishment of ICs can pose a risk of decreasing yields for the main crop due to phenomena related to pre-emptive competition (Thorup-Kristensen et al., 2003; Dabney et al., 2010) and the potential of the IC to become a weed in subsequent seasons (Aronsson et al., 2016; Abdalla et al., 2019). These effects were not accounted for in this study, and could be a matter of investigation in future research.

Our results suggest that there is a net carbon emission from the combination of residue removal and IC for the area of study, independent of the IC being incorporated in the soil or being harvested. Nevertheless, there is a spatial differentiation showing a net carbon sequestration in the majority of yield survey districts analyzed, meaning that for a large share of the territory the inclusion of OR as intermediate crop can offset the negative effects of residue removal on SOC stocks. In contrast, the locations where the overall balance was negative are related to higher clay content and lower yields of OR, indicating that the combined effects of crop yields and soil texture result in different outcomes depending on the location. Low stabilization of C in soils with low clay content resulted in negligible contribution of OR aboveground

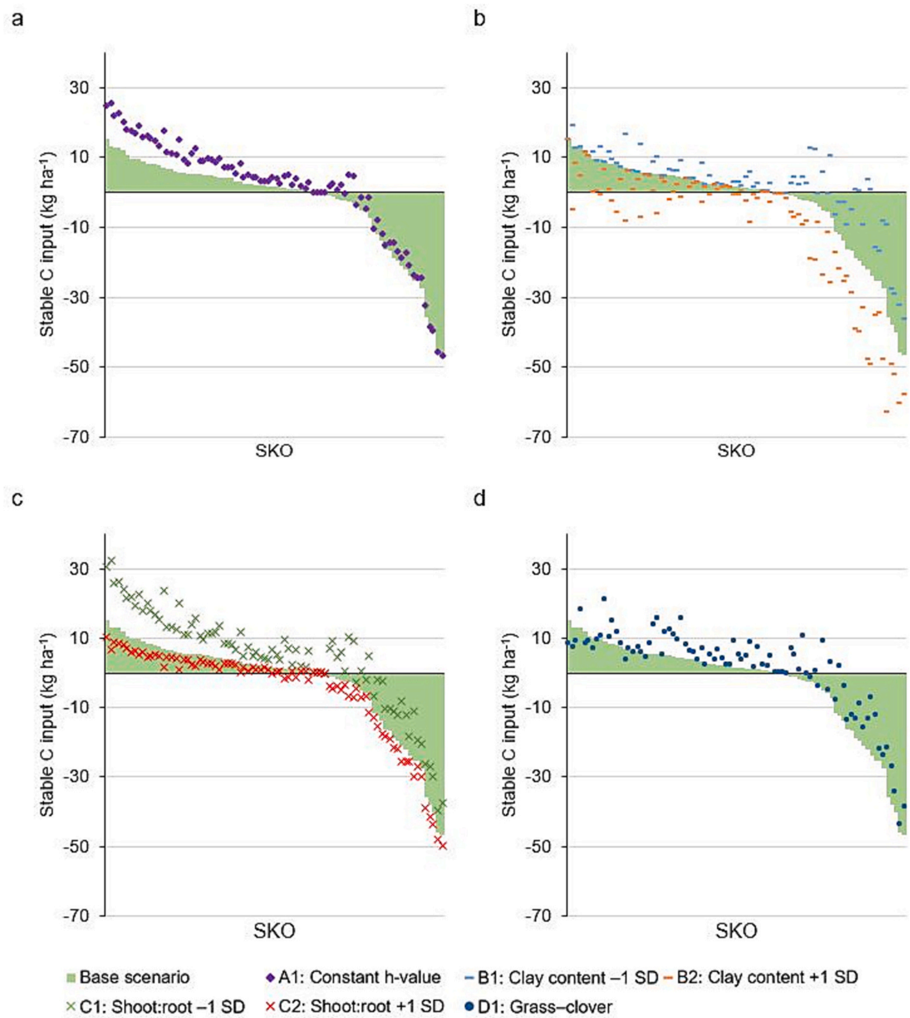


Fig. 7. Sensitivity analysis comparing base scenario (harvest of IC) to alternative scenarios with results from 84 SKOs ordered from left to right according to total stable carbon input in the base-line scenario: (a) change in humification coefficient, (b) change in clay content, (c) change in shoot:root ratio, and (d) use of grass-clover mixture as IC. Bars represent base SKO carbon input values ordered from highest to lowest.

biomass to SOC in these soils. This confirms other observations indicating that the long-term maintenance of soil carbon stocks by the incorporation of crop residues is spatially differentiated (Andrade Díaz et al., 2023). Our results also illustrate how soil texture plays an important role when analyzing the effect of incorporation of litter biomass, as was previously indicated by Poeplau et al. (2015), and that the variation in the clay content within single spatial units can lead to notable differences in the resulting stable carbon inputs. This study also supports the claims of other studies that challenge the vision of fixed sustainable harvesting restrictions for crop residues as a measure for SOC preservation (Poeplau and Don, 2015; Björnsson and Prade, 2021; Andrade Díaz et al., 2023).

This research shows how the use of intermediate crops can be an effective measure to preserve and increase soil carbon stocks, and a way to promote sustainable or ecological intensification of agricultural systems, as has been suggested in previous studies (Aronsson et al., 2016; Wittwer et al., 2017; Abdalla et al., 2019; Herbstritt et al., 2022). Adequate land use, soil management, and a set of agricultural practices that preserve SOC are not only desirable from the perspective of soil quality maintenance and enhancement but can be a key strategy in regulating greenhouse gas emissions at the global scale (FAO and ITPS, 2015; Prade et al., 2017; Lantz et al., 2018; Björnsson and Prade, 2021; Olofsson, 2021). Furthermore, it is important to note that this study does not consider the bioeconomy pathway for which the harvesting of straw and IC is intended or the return of any type of product to the soil. As indicated by Andrade Díaz et al. (2023), when removing residues as feedstock for the bioeconomy, the effects on maintaining long-term SOC stock are dependent on the conversion pathway. Different co-products returning to the soil exhibit various degrees of recalcitrance, which would affect the long-term effects on SOC, total carbon sequestration, and estimations of the availability of sustainable straw. Among different biomass utilization scenarios—including pyrolysis, gasification, hydrothermal liquefaction, and lignocellulosic fermentation (Andrade Díaz et al., 2023)—a process that has gained special attention in Sweden is anaerobic digestion (AD) for biogas production (Kreuger et al., 2014; Lantz et al., 2018; Broberg et al., 2022; Gustafsson and Anderberg, 2023). The resulting digestate from the AD process is not only interesting due to its potential contribution to SOC, but also for its value as organic fertilizer (Andrade Díaz et al., 2023; Gustafsson and Anderberg, 2023). This study therefore offers insights into the effects of the inclusion of IC and removal of crop residues and points out the opportunity to develop further research in modelling SOC dynamics when coupling transformation pathways within the bioeconomy. This can lead to a more comprehensive evaluation of sustainable intensification strategies considering the 4 per 1000 program objectives (Minasny et al., 2017) and the fulfilment of Fit for 55 carbon sequestration targets (European Council, 2023).

5. Conclusion

This study examined how the cultivation of intermediate crops in crop rotation sequences could offset detrimental effects of crop residue removal on soil organic carbon stocks in Sweden. Although the overall potentially stabilized carbon input balance was negative when considering the entire country, on 54% of arable land the inclusion of intermediate crops can offset the negative effect of residue removal on organic carbon input. Estimations on total residue availability for major crops allowed us to establish the theoretical loss of stable carbon from arable land due to their complete removal. Assessment of the total carbon contribution from intermediate crop establishment was possible, thanks to the development of a regression model based on potential crop rotations. This model allowed us to determine frequencies or relative areas for the establishment of intermediate crops in single spatial units. The net effects on soil organic carbon inputs were proven to be spatially differentiated and affected by factors like soil clay content and the yields of intermediate crops, which show spatial gradients.

CRediT authorship contribution statement

Barrios Latorre: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sergio Alejandro:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aronsson Helena:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Data curation, Conceptualization. **Björnsson Lovisa:** Writing – review & editing, Validation, Supervision, Conceptualization. **Viketoft Maria:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Prade Thomas:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

The data is available in the following permanent link: https://doi.org/10.5878/t9ey-ac36.

Acknowledgements

This work was supported by the Swedish Research Council for Environment Agricultural Sciences and Spatial Planning (FORMAS) [project number 2021-01090] under the project name "Removing agricultural residues as feedstock for the growing bioeconomy – efficiency of intermediate crops to minimize negative environmental consequences" and the Swedish University of Agricultural Sciences (SLU).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.103873.

References

Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., Truu, J., Rees, R.M., Smith, P., 2019. A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. Glob. Chang. Biol. 25 (8), 2530–2543. https://doi.org/10.1111/gcb.14644.

Andrade Díaz, C., Clivot, H., Albers, A., Zamora-Ledezma, E., Hamelin, L., 2023. The crop residue conundrum: maintaining long-term soil organic carbon stocks while reinforcing the bioeconomy, compatible endeavors? Appl. Energy 329, 120192. https://doi.org/10.1016/j.apenergy.2022.120192.

Aronsson, H., Hansen, E.M., Thomsen, I.K., Liu, J., Ogaard, A.F., Kankanen, H., Ulen, B., 2016. The ability of cover crops to reduce nitrogen and phosphorus losses from arable land in southern Scandinavia and Finland. J. Soil Water Conserv. 71 (1), 41–55. https://doi.org/10.2489/jswc.71.1.41.

Aronsson, H., Ernfors, M., Kätterer, T., Bolinder, M.A., Svensson, S.-E., Hansson, D., Prade, T., Bergkvist, G., 2023. Mellangrödor i växtföljden – för kolinlagring och effektivt kväveutnyttjande. Uppsala: Sveriges lantbruksuniversitet. Ekohydrologi, p. 179.

Basche, A.D., Miguez, F.E., Kaspar, T.C., Castellano, M.J., 2014. Do cover crops increase or decrease nitrous oxide emissions? A meta-analysis. J. Soil Water Conserv. 69 (6), 471–482. https://doi.org/10.2489/jswc.69.6.471.

Bennich, T., Belyazid, S., Kopainsky, B., Diemer, A., 2018. Understanding the transition to a bio-based economy: exploring dynamics linked to the agricultural sector in Sweden. Sustainability 10 (5), 1504. https://doi.org/10.3390/su10051504.

Bentsen, N.S., Felby, C., Thorsen, B.J., 2014. Agricultural residue production and potentials for energy and materials services. Prog. Energy Combust. Sci. 40, 59–73. https://doi.org/10.1016/j.pecs.2013.09.003.

Björnsson, L., Prade, T., 2021. Sustainable cereal straw management: use as feedstock for emerging biobased industries or cropland soil incorporation? Waste Biomass Valoriz. 12 (10), 5649–5663. https://doi.org/10.1007/s12649-021-01419-9.

Bolinder, M.A., Janzen, H.H., Gregorich, E.G., Angers, D.A., VandenBygaart, A.J., 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. Agric. Ecosyst. Environ. 118 (1–4), 29–42. https://doi.org/10.1016/j.agee.2006.05.013.

Bolinder, M.A., Crotty, F., Elsen, A., Frac, M., Kismányoky, T., Lipiec, J., Tits, M., Tóth, Z., Kätterer, T., 2020. The effect of crop residues, cover crops, manures and nitrogen fertilization on soil organic carbon changes in agroecosystems: a synthesis of reviews. Mitig. Adapt. Strateg. Glob. Chang. 25 (6), 929–952. https://doi.org/10.1007/s11027-020-09916-3.

Broberg, K., Lindahl, L., Tamm, D., 2022. Potentialstudie för biogassubstrat i Västra Götaland, Halland och Skåne, 2022. RISE, p. 58.

Brunner, T., Nowak, P., Mandl, C., Obernberger, I., 2021. Assessment of Agrobiomass Combustion in State-of-the-art Residential Boilers, p. 10.

Chen, Q., Zhang, T.C., Ouyang, L., Yuan, S., 2022. Single-step hydrothermal synthesis of biochar from H3PO4-activated lettuce waste for efficient adsorption of cd(II) in aqueous solution. Molecules 27 (1), 269. https://doi.org/10.3390/molecules27010269.

Constantin, J., Minette, S., Vericel, G., Jordan-Meille, L., Justes, E., 2023. MERCI: a simple method and decision-support tool to estimate availability of nitrogen from a wide range of cover crops to the next cash crop. Plant Soil. https://doi.org/10.1007/s11104-023-06283-1.

Dabney, S.M., Delgado, J.A., Collins, F., Meisinger, J.J., Schomberg, H.H., Liebig, M.A., Kaspar, T., Mitchell, J., Reeves, W., 2010. Using Cover Crops and Cropping Systems for Nitrogen Management. In: Advances in Nitrogen Management, pp. 230–281.

Dudarev, I., 2020. A Review of Fibre Flax Harvesting: Conditions, Technologies, Processes and Machines. J. Nat. Fibers 0 (0), 1–13. https://doi.org/10.1080/15440478.2020.1863296.

European Commission, 2018. A Sustainable Bioeconomy for Europe: Strengthening the Connection between Economy, Society and the Environment - Updated Bioeconomy Strategy. Publications Office of the European Union, Luxembourg.

European Commission, 2019. The European Green Deal. https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF.

European Commission, 2021. Communication from the Comission to the European Parlament and the Council: Sustainable Carbon Cycles. https://doi.org/10.1163/2210-7975_HRD-4679-0058.

European Commission, 2022. Commission proposes certification of carbon removals [Text], European Commission - European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7156.

European Council, 2023. Fit for 55. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/.

FAO & ITPS, 2015. Status of the World's Soil Resources (SWSR) – Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome.

Gruver, L.S., Weil, R.R., Zasada, I.A., Sardanelli, S., Momen, B., 2010. Brassicaceous and rye cover crops altered free-living soil nematode community composition. Appl. Soil Ecol. 45 (1), 1–12. https://doi.org/10.1016/j.apsoil.2009.11.007.

Gustafsson, M., Anderberg, S., 2023. Great expectations—future scenarios for production and use of biogas and digestate in Sweden. Biofuels 14 (1), 93–107. https://doi.org/10.1080/17597269.2022.2121543.

Hamelin, L., Borzęcka, M., Kozak, M., Pudełko, R., 2019. A spatial approach to bioeconomy: quantifying the residual biomass potential in the EU-27. Renew. Sust. Energ. Rev. 100, 127–142. https://doi.org/10.1016/j.rser.2018.10.017.

Hao, X., Abou Najm, M., Steenwerth, K.L., Nocco, M.A., Basset, C., Daccache, A., 2023. Are there universal soil responses to cover cropping? A systematic review. Sci. Total Environ. 861 https://doi.org/10.1016/j.scitotenv.2022.160600.

Herbstritt, S., Richard, T.L., Lence, S.H., Wu, H., O'Brien, P.L., Emmett, B.D., Kaspar, T. C., Karlen, D.L., Kohler, K., Malone, R.W., 2022. Rye as an energy cover crop: management, forage quality, and revenue opportunities for feed and bioenergy. Agriculture 12 (10), 1691. https://doi.org/10.3390/agriculture12101691.

Yang, J.Y., Drury, C.F., Yang, X.M., De Jong, R., Huffman, E.C., Campbell, C.A., Kirkwood, V., 2010. Estimating biological N2 fixation in Canadian agricultural land using legume yields. Agric. Ecosyst. Environ. 137 (1), 192–201. https://doi.org/10.1016/j.agee.2010.02.004.

Yetimwork, G.G., Awet, E.G., Solomon, M., 2014. Crop–Livestock Interaction for Improved Productivity: Effect of Selected Varieties of Field Pea (Pisum sativum L.) on Grain and Straw Parameters. In: Vanlauwe, B., van Asten, P., Blomme, G. (Eds.), *Challenges and Opportunities for Agricultural Intensification of the Humid Highland Systems of Sub-Saharan Africa*. Springer International Publishing, pp. 137–148. https://doi.org/10.1007/978-3-319-07662-1_12.

IPCC (2019). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4 - Agriculture, Forestry and Other Land Use. E. Calvo Buendia, K. Tanabe, A. Kranjc et al. Switzerland.

Högy, P., Fangmeier, A., 2009. Atmospheric CO2 enrichment affects potatoes: 1. Aboveground biomass production and tuber yield. European J. Agron. 30 (2), 78–84. https://doi.org/10.1016/j.eja.2008.07.007.

Jensen, J.L., Eriksen, J., Thomsen, I.K., Munkholm, L.J., Christensen, B.T., 2022. Cereal straw incorporation and ryegrass cover crops: the path to equilibrium in soil carbon storage is short. Eur. J. Soil Sci. 73 (1), e13173 https://doi.org/10.1111/ejss.13173.

Jian, J., Du, X., Reiter, M.S., Stewart, R.D., 2020. A meta-analysis of global cropland soil carbon changes due to cover cropping. Soil Biol. Biochem. 143, 107735 https://doi.org/10.1016/j.soilbio.2020.107735.

Johnsson, H., Mårtensson, K., Lindsjö, A., Persson, K., Blombäck, K., 2022. NLeCCS - a System for Calculating Nutrient Leakage from Arable Land. (Ekohydrologi, 177). SLU - Institutionen för mark och miljö, Uppsala.

Jordbruksverket, 2022. Jordbruksverkets statistikdatabas. https://statistik.sjv.se/PXWeb/pxweb/sv/Jordbruksverkets%20statistikdatabas/?rxid=5adf4929-f548-4f27-9bc9-78e127837625.

Kallenbach, C.M., Wallenstein, M.D., Schipanksi, M.E., Grandy, A.S., 2019. Managing agroecosystems for soil microbial carbon use efficiency: ecological unknowns, potential outcomes, and a path forward. Front. Microbiol. 10 https://doi.org/10.3389/fmicb.2019.01146 [2023-11-28].

Kaplan, M., Ulger, I., Kokten, K., Uzun, S., Oral, E.V., Ozaktan, H., Temizgul, R., Kale, H., 2018. Nutritional composition of potato (*Solanum tuberosum* L.) haulms. Prog. Nutr. 20 (1–S), 90–95. https://doi.org/10.23751/pn.v20i1-S.5541.

Kätterer, T., Bolinder, M.A., Rumpel, C., 2022. Agriculture practices to improve soil carbon storage in upland soil. In: CNRS, France (Eds.), Burleigh Dodds Series in Agricultural Science. Burleigh Dodds Science Publishing. https://doi.org/10.19103/AS.2022.0106.15.

Kätterer, T., Bolinder, M.A., Andrén, O., Kirchmann, H., Menichetti, L., 2011. Roots contribute more to refractory soil organic matter than above-ground crop residues, as revealed by a long-term field experiment. Agric. Ecosyst. Environ. 141 (1), 184–192. https://doi.org/10.1016/j.agee.2011.02.029.

Kludze, H., Deen, B., Weersink, A., van Acker, R., Janovicek, K., De Laporte, A., McDonald, I., 2013. Estimating sustainable crop residue removal rates and costs based on soil organic matter dynamics and rotational complexity. Biomass Bioenergy 56, 607–618. https://doi.org/10.1016/j.biombioe.2013.05.036.

Kluts, I., Wicke, B., Leemans, R., Faaij, A., 2017. Sustainability constraints in determining European bioenergy potential: A review of existing studies and steps forward. Renew. Sust. Energ. Rev. 69, 719–734. https://doi.org/10.1016/j.rser.2016.11.036.

Kreuger, E., Prade, T., Björnsson, L., Lantz, M., Bohn, I., Svensson, S.-E., Lindkvist, A., Hörndahl, T., 2014. Biogas från Skånsk betblast - potential, teknik och ekonomi, 93. Miljö-och Energisystem, LTH, Lunds Universitet, Lund.

Lantz, M., Prade, T., Ahlgren, S., Björnsson, L., 2018. Biogas and ethanol from wheat grain or straw: is there a trade-off between climate impact, avoidance of iLUC and production cost? Energies 11 (10), 2633. https://doi.org/10.3390/en11102633.

Lehrke, U., 2000. Frühe Ernte schafft optimale voraussetzungen für den Zwischenfruchtanbau. Zuckerrube 49, 204–207.

Li, L., Yang, S., Li, X., Zhang, F., Christie, P., 1999. Interspecific complementary and competitive interactions between intercropped maize and faba bean 212, 105–114.

Liu, C., Lu, M., Cui, J., Li, B., Fang, C., 2014. Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis. Glob. Chang. Biol. 20 (5), 1366–1381. https://doi.org/10.1111/gcb.12517.

Locker, C.K., 2021. *Residual biomass utilisation in the potato and sugar beet processing industry: evaluation from a circular perspective*. Wageningen (MSc Thesis).

Ma, S., He, F., Tian, D., Zou, D., Yan, Z., Yang, Y., Zhou, T., Huang, K., Shen, H., Fang, J., 2018. Variations and determinants of carbon content in plants: a global synthesis. Biogeosciences 15 (3), 693–702. https://doi.org/10.5194/bg-15-693-2018.

Maravić, N., Teslić, N., Nikolić, D., Dimić, I., Šereš, Z., Pavlić, B., 2022. From agricultural waste to antioxidant-rich extracts: green techniques in extraction of polyphenols from sugar beet leaves. Sustain. Chem. Pharm. 28, 100728 https://doi.org/10.1016/j.scp.2022.100728.

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Hong, S.Y., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.-C., Vågen, T.-G., van Wesemael, B., Winowiecki, L., 2017. Soil carbon 4 per mille. Geoderma 292, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002.

Montanarella, L., Panagos, P., 2021. The relevance of sustainable soil management within the European green Deal. Land Use Policy 100, 104950. https://doi.org/10.1016/j.landusepol.2020.104950.

Munkholm, L.J., Hansen, E.M., 2012. Catch crop biomass production, nitrogen uptake and root development under different tillage systems. Soil Use Manag. 28 (4), 517–529. https://doi.org/10.1111/sum.12001 Naturvårdsverket (2023). National Inventory Report Sweden 2023. Naturvårdsverket. https://unfccc.int/documents/627663.

Naturvårdsverket, 2023. *National Inventory Report Sweden 2023*. Naturvårdsverket. https://unfccc.int/documents/627663.

Nichols, V., English, L., Carlson, S., Gailans, S., Liebman, M., 2020. Effects of long-term cover cropping on weed seedbanks. Front. Agron. 2, 591091 https://doi.org/10.3389/fagro.2020.591091.

Nilsson, D., Bernesson, S., 2009. Halm som bränsle: Del 1: Tillgångar och skördetidpunkter. (011). Institutionen för energi och teknik, SLU, Uppsala. https://pub.epsilon.slu.se/4854/1/nilsson_d_et_al_100630.pdf [2022-06-27].

Olofsson, J., 2021. Time-dependent climate impact of utilizing residual biomass for biofuels—the combined influence of modelling choices and climate impact metrics. Energies 14 (14), 4219. https://doi.org/10.3390/en14144219.

Pellicanò, A., Romeo, M., Pristeri, A., Preiti, G., Monti, M., 2015. Cereal-pea intercrops to improve sustainability in bioethanol production. Agronomy for Sustain. Develop. 35 (2), 827–835. https://doi.org/10.1007/s13593-015-0294-1.

Pham-Truffert, M., Metz, F., Fischer, M., Rueff, H., Messerli, P., 2020. Interactions among sustainable development goals: knowledge for identifying multipliers and virtuous cycles. Sustain. Dev. 28 (5), 1236–1250. https://doi.org/10.1002/sd.2073.

Piikki, K., Söderström, M., 2019. Digital soil mapping of arable land in Sweden – validation of performance at multiple scales. Geoderma 352, 342–350. https://doi.org/10.1016/j.geoderma.2017.10.049.

Pinto, M. de C.E., David da Silva, D., Amorim Gomes, A.L., Menezes dos Santos, R.M., Alves de Couto, R.A., Ferreira de Novais, R., Leopoldo Constantino, V.R., Tronto, J., Pinto, F.G., 2019. Biochar from carrot residues chemically modified with magnesium for removing phosphorus from aqueous solution. J. Clean. Prod. 222, 36–46. https://doi.org/10.1016/j.jclepro.2019.03.012.

Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. Agric. Ecosyst. Environ. 200, 33–41. https://doi.org/10.1016/j.agee.2014.10.024.

Poeplau, C., Kätterer, T., Bolinder, M.A., Börjesson, G., Berti, A., Lugato, E., 2015. Low stabilization of aboveground crop residue carbon in sandy soils of Swedish long-term experiments. Geoderma 237–238, 246–255. https://doi.org/10.1016/j.geoderma.2014.09.010.

Poirier, V., Roumet, C., Munson, A.D., 2018. The root of the matter: linking root traits and soil organic matter stabilization processes. Soil Biol. Biochem. 120, 246–259. https://doi.org/10.1016/j.soilbio.2018.02.016.

Prade, T., Björnsson, L., Lantz, M., Ahlgren, S., 2017. Can domestic production of iLUC-free feedstock from arable land supply Sweden's future demand for biofuels? J. Land Use Sci. 12 (6), 407–441. https://doi.org/10.1080/1747423X.2017.1398280.

Prade, T., Muneer, F., Berndtsson, E., Nynäs, A.-L., Svensson, S.-E., Newson, W.R., Johansson, E., 2021. Protein fractionation of broccoli (Brassica oleracea, var. Italica) and kale (Brassica oleracea, var. Sabellica) residual leaves — A pre-feasibility assessment and evaluation of fraction phenol and fibre content. Food Bioprod. Process. 130, 229–243. https://doi.org/10.1016/j.fbp.2021.10.004.

Prade, T., Hansson, D., Svensson, S.-E., 2022. Etableringstidpunktens inverkan på sommarmellangrödors markkolsbidrag och ogräsbekämpande egenskaper. (Landskapsarkitektur, trädgård, växtproduktionsvetenskap: rapportserie, 2022:1). Institutionen för biosystem och teknologi - SLU, Alnarp.

Ramirez-Cando, L., Spugnoli, P., Matteo, R., Bagatta, M., Tavarini, S., Foschi, L., Lazzeri, L., 2017. Environmental assessment of flax straw production for non-wood pulp mills. Chem. Eng. Trans. 58, 787–792. https://doi.org/10.3303/CET1758132.

Ruiz, P., Nijs, W., Tarvydas, D., Sgobbi, A., Zucker, A., Pilli, R., Jonsson, R., Camia, A., Thiel, C., Hoyer-Klick, C., Dalla Longa, F., Kober, T., Badger, J., Volker, P., Elbersen, B.S., Brosowski, A., Thrän, D., 2019. ENSPRESO - an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. Energ. Strat. Rev. 26, 100379 https://doi.org/10.1016/j.esr.2019.100379.

Shams Esfandabadi, Z., Ranjbari, M., Scagnelli, S., 2022. The imbalance of food and biofuel markets amid Ukraine-Russia crisis: a systems thinking perspective. Biofuel Res. J. 9 (2), 1640–1647. https://doi.org/10.18331/BRJ2022.9.2.5.

Sharma, R., Malaviya, P., 2023. Ecosystem services and climate action from a circular bioeconomy perspective. Renew. Sust. Energ. Rev. 175, 113164 https://doi.org/10.1016/j.rser.2023.113164.

Soltaninejad, A., Jazini, M., Karimi, K., 2022. Biorefinery for efficient xanthan gum, ethanol, and biogas production from potato crop residues. Biomass Bioenergy 158, 106354. https://doi.org/10.1016/j.biombioe.2022.106354.

Tamayo Tenorio, A., Kyriakopoulou, K.E., Suarez-Garcia, E., van den Berg, C., van der Goot, A.J., 2018. Understanding differences in protein fractionation from conventional crops, and herbaceous and aquatic biomass - consequences for industrial use. Trends Food Sci. Technol. 71, 235–245. https://doi.org/10.1016/j.tifs.2017.11.010.

Thorup-Kristensen, K., Magid, J., Jensen, L.S., 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. In: Advances in Agronomy. Elsevier, pp. 227–302. https://doi.org/10.1016/S0065-2113(02)79005-6.

Tittonell, P., 2014. Ecological intensification of agriculture—sustainable by nature. Curr. Opin. Environ. Sustain. 8, 53–61. https://doi.org/10.1016/j.cosust.2014.08.006.

Tomei, J., Helliwell, R., 2016. Food versus fuel? Going beyond biofuels. Land Use Policy 56, 320–326. https://doi.org/10.1016/j.landusepol.2015.11.015.

Tonitto, C., David, M.B., Drinkwater, L.E., 2006. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: a meta-analysis of crop yield and N dynamics. Agric. Ecosyst. Environ. 112 (1), 58–72. https://doi.org/10.1016/j.agee.2005.07.003.

Torma, S., Vilček, J., Lošák, T., Kužel, S., Martensson, A., 2018. Residual plant nutrients in crop residues – an important resource. Acta Agricult. Scandin., Sect. B — Soil Plant Sci. 68 (4), 358–366. https://doi.org/10.1080/09064710.2017.1406134.

de Toro, A., Gunnarsson, C., Jonsson, N., Sundberg, M., 2021. Effects of variable weather conditions on baled proportion of varied amounts of harvestable cereal straw, based on simulations. Sustainability 13 (16), 9449. https://doi.org/10.3390/su13169449.

UN General Assembly, 2015. Transforming our world: The 2030 Agenda for Sustainable Development. https://sdgs.un.org/sites/default/files/publications/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf.

Wallenhammar, A.-C., Almquist, C., Söderström, M., Jonsson, A., 2012. In-field distribution of Plasmodiophora brassicae measured using quantitative real-time PCR. Plant Pathol. 61 (1), 16–28. https://doi.org/10.1111/j.1365-3059.2011.02477.x.

Wallgren, B., Linden, B., 1994. Effects of catch crops and ploughing times on soil mineral nitrogen, 24 (2), 67–75.

Wegi, T., Tolera, A., Wamatu, J., Animut, G., Rischkowsky, B., 2018. Effects of feeding different varieties of faba bean (Vicia faba L.) straws with concentrate supplement on feed intake, digestibility, body weight gain and carcass characteristics of Arsi-Bale sheep. Asian-Australasian J. Animal Sci. 31 (8), 1221–1229. https://doi.org/10.5713/ajas.17.0736.

Wezel, A., Soboksa, G., McClelland, S., Delespesse, F., Boissau, A., 2015. The blurred boundaries of ecological, sustainable, and agroecological intensification: a review. Agron. Sustain. Dev. 35 (4), 1283–1295. https://doi.org/10.1007/s13593-015-0333-y.

Wittwer, R.A., Dorn, B., Jossi, W., van der Heijden, M.G.A., 2017. Cover crops support ecological intensification of arable cropping systems. Sci. Rep. 7 (1), 41911. https://doi.org/10.1038/srep41911.