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The carbon balance of green biorefineries is significantly impacted by the processing of fibrous side streams

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ABSTRACT

Green biorefineries that produce protein feed from grasses or legumes generate fibrous side streams which can be used to produce biobased products. An analysis was conducted on the net greenhouse gas emissions of five products: (1) transportation fuel (biomethane); (2–3) bioplastics with either a short or long service life; (4) biochar used as a soil amendment; and (5) cellulose products intended for single-use purposes. Analyses consider three land-use scenarios for Sweden, representing different ley (temporary perennial grass-clover crops) cultivation strategies, and include supply-chain emissions, carbon storage in soils and biobased products, and substitution effects from the use of biobased products and N recycling to soils.

Biochar consistently provided the largest emission savings, reaching −39 to −200 t CO_2-eq ha^{-1} over 100 years depending on scenario. The transportation fuel option matched biochar in the short term, reaching −39 to −133 t CO_2-eq ha^{-1} by year 100. Long-lived bioplastics reached −97 t CO_2-eq ha^{-1}, whereas cellulose products and short-lived plastics reached −97 and −45 t CO_2-eq ha^{-1} by year 100 in the most favorable scenario. Carbon storage and fossil fuel substitution were the most important mitigation levers.

In a scenario with expansion of ley cultivation constrained by farmers' preferences, the analyzed options could contribute 10% of the emissions reduction needed for Sweden to meet its 2045 climate target. For the agriculture and LULUCF sectors, some options have an emissions reduction potential exceeding the sectoral target, highlighting that the treatment of residues in green biorefineries can have a significant impact on climate outcomes.

1. Introduction

Agriculture contributes approximately 22% of global net anthropogenic greenhouse gas (GHG) emissions (IPCC, 2023). At the same time, the sector also has significant opportunities for reducing its own emissions as well as supporting emissions reductions in other sectors, for instance by enhancing carbon (C) storage in vegetation and soils and by providing biomass to replace fossil-based resources (Gaffey et al., 2023; IPCC, 2019, 2022). The European Union (EU) supports mitigation and adaptation in the agriculture sector in several ways. The Common Agricultural Policy includes incentives for land management practices aimed at reducing GHG emissions, improving C storage, and promoting bioeconomy (McEldowney and Rossi, 2021; Singh et al., 2021). The EU protein strategy aims to reduce the EU livestock sector's demand for imported protein crops, especially soybeans (EC, 2019b), a key driver of deforestation causing GHG emissions, land degradation, and biodiversity loss outside the EU (Aide et al., 2013; Chan et al., 2024; European Parliament, 2023; Fehlenberg et al., 2017; Khoshnevisan et al., 2023; Pendrill et al., 2019). The European Green Deal (EC, 2019) includes the Circular Economy Action Plan which focuses on the reuse of materials, including improving resource efficiency through the recycling of C and nutrients in biofertilizers, reducing reliance on synthetic inputs (Energimyndigheten, 2024; Singh et al., 2021).

Green biorefineries (GBR) use fresh feedstocks such as grasses and legumes that are high in leaf protein and soluble sugars to produce protein for animal feed along with other biobased products (Andrade and Ambye-Jensen, 2022; Cherubini et al., 2009; Kamm et al., 2016), either through multi-process GBR designs or by directing process side streams to other conversion facilities using anaerobic digestion (AD), pyrolysis (PY) and/or fiber processing (FP) (Bolzonella et al., 2023; Chan et al., 2024; Jørgensen et al., 2022; Ravenni et al., 2024). While protein feed is considered the primary product, the wide range of co-produced products and related applications (Chan et al., 2024; Gaffey et al., 2023; Jørgensen et al., 2022; Sharma et al., 2012) add significant

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value beyond the reduced dependence on imports of plant protein for animal feed, aligning well with circular strategies (EC, 2015; Singh et al., 2021). There are also co-benefits associated with grass cultivation, such as mitigation of soil erosion and nutrient leaching, reduced pesticide use, and increased soil organic carbon (SOC) levels (~0.3–1.1 Mg C ha^{-1} yr^{-1} in Swedish trials (Kätterer and Bolinder, 2023)), improving soil productivity and enhancing the contribution to climate change mitigation (Henryson et al., 2022; Kätterer and Bolinder, 2023; Paustian et al., 2016; Poeplau et al., 2015; Rehn et al., 2024).

After the protein feed concentrate has been extracted (~15% of DM), residual side streams remain in the form of fiber-rich press cake/grass pulp (PC) (~60% of DM), and liquid brown juice (~25% of DM) (Andrade et al., 2025; Chan et al., 2024). These are suitable feedstocks for biogas production through AD. The biogas can be used directly for heat and power or upgraded to methane for use in vehicles or as a chemical feedstock (Bolzonella et al., 2023; Burg et al., 2023; Wall et al., 2013). The AD process also produces residues that can be used as fertilizer in agriculture (EBA, 2020) and biogas upgrading to methane produces a carbon dioxide (CO_2) stream that can be captured and injected into geological reservoirs or used to make new products bioplastics (Mattlar and Ekholm, 2025). The PC can be used to feed ruminants or to produce bioenergy and biomaterials such as cellulose single-use products, which have a smaller net C footprint than traditional products (Andrade et al., 2025; Gaffey et al., 2023; Jørgensen et al., 2022). It can also be used as feedstock in pyrolysis plants to produce biochar (Ravenni et al., 2024), which has many applications. For example, biochar can be used as a feed additive (Jørgensen et al., 2022) and in various industrial applications (Safarian, 2023a). It can also be used as a soil amendment to improve soil structure, water retention, and nutrient availability (Elsgaard et al., 2021; Lehmann et al., 2021). Biochar has shown long-term stability (at least 100 years) when used as soil amendment (Azzi et al., 2023; Rodrigues et al., 2023; Windeatt et al., 2014). Its persistence against decomposition depends on its properties, which are determined by feedstock characteristics and pyrolysis conditions, and the environment in which it is applied (Joseph et al., 2021; Lehmann et al., 2021).

In this study, we examine the net GHG emissions to the atmosphere resulting from the production and use of biobased products using PC in GBR as feedstock in an arable farming system in western Sweden. The purpose is to assess how different PC processing options can contribute to climate change mitigation. Five products are analyzed: (1) transportation fuel; (2–3) bioplastics with either a short or long service life; (4) biochar used as a soil amendment; and (5) cellulose products intended for single-use purposes. The corresponding processing options are: AD followed by biogas upgrading to biomethane for use in transportation or in production of bioplastics (1–3); pyrolysis (4); and FP to produce cellulose products (5). The substitution effect, i.e., the change in GHG emissions resulting from the replacement of alternative products, is quantified based on the adopted substitution pattern associated with the analyzed products, and the estimated GHG emissions associated with the analyzed products and their substituted products. In our method, biochar is treated as a product because it provides useful functions and can be the subject of economic transactions. However, there is no alternative product that provides the identical functions, and the substitution effect is limited to the nitrogen (N) fertilization effect of using biochar as a soil amendment.

The analyses are conducted for three scenarios of including temporary leys in annual crop rotations in agriculture to provide fresh grass-clover biomass for a GBR that produces the PC. The results are compared with the estimated mitigation benefits of replacing imported soy feed with feed from the GBR. The results are also discussed in relation to Sweden's total and sectoral GHG emissions and national climate targets for 2045, which aim to reduce territorial emissions by 85% compared to 1990 levels (Naturvårdsverket, 2022).

2. Materials and method

2.1. Description of system and ley scenarios

Fig. 1 shows the steps considered in the analysis, from agricultural land use providing the grass-clover biomass used as feedstock, via GBR-production of a protein concentrate and processing of side streams, to final end use of products. The grass-clover yield level was set to a fixed value (8 tons dry matter (DM)/ha, (Cederberg and Henriksson, 2020), see Supplementary Material (SM), in SM1), and the protein feed product was not considered in the analysis, as the same amount of protein feed is produced in each case. The C and N flows were modelled based on data and process designs established in previous studies (Andrade et al., 2025; Chan et al., 2024; Santamaría-Fernández and Lübeck, 2020; Zoppi et al., 2023). We assessed (i) emissions (including upstream emissions) from the use of fuels, fertilizers, and other inputs; (ii) SOC changes in agricultural soils; (iii) changes in the amount of C retained in biobased products; and (iv) substitution effects resulting from the use of the biobased products.

2.1.1. Scenarios

The provision of fresh grass-clover biomass to the GBR was calculated for three scenarios for inclusion of temporary leys in a standard crop rotation with annual crops (Rehn et al., 2024), see Table 1. The scenarios cover 100 years to include long-term dynamics and encompass varying frequencies and time periods for ley cultivation in the crop rotation, affecting the SOC dynamics (Kätterer and Bolinder, 2023; Rehn et al., 2024) and biomass supply to the GBR. In all scenarios, there was an adjustment to the original crop rotation in year zero to include 2 years of ley in a 6-year rotation. After 30 years the crop rotations in the three scenarios deviate, as described below.

Scenario 1: Return to the standard arable crop rotation after 30 years, i.e., ley cultivation ends and the system reverts to the baseline rotation typical for western Sweden.

Scenario 2: No change, i.e., the 6-year crop rotation with 2 years of ley was maintained over the 100-year modeling period.

Scenario 3: Change the 6-year crop rotation to include 4 years of ley. This crop rotation was maintained for the rest of the 100-year modelled period.

2.2. Model description

2.2.1. Agricultural land use

We started from an agricultural land-use model (Rehn et al., 2024), (Fig. 1). The crop rotation was modified to include grass-cover leys instead of cereals (see Table 1), providing green biomass to the GBR and subsequent processes. Perennial grass clover cultivation enhances SOC storage by increasing biomass input with larger root systems compared to annual cereals (Kätterer and Bolinder, 2023); the SOC increase was calculated with the Introductory Carbon Balance Model (ICBM) (Andrén and Kätterer, 1997) using the most recently updated parameters (Bolinder et al., 2019), calibrated in long-term Swedish field trials. The ICBM is a well-established soil carbon turnover model that simulates long-term SOC dynamics and has been calibrated in Swedish agricultural conditions. Estimating SOC changes over longer time periods, >30 years, is challenging (Bolinder et al., 2018) and introduces added uncertainty (Andrén and Kätterer, 1997). Therefore, we used ICBM model outputs for the first 30 years and then fitted a logistic growth function (Yu and Ye, 2020) to the ICBM output (from years 10–30) as a post-model curve-fitting step. For years 31 to 100, the SOC dynamics were extrapolated using this logistic curve, creating a continuous estimate of long-term SOC trends. This function was used with the aim to estimate a long-term (100 yrs) SOC development, based on the knowledge that C stocks in soils often plateau after about 20 years of change in C-input (Yang et al., 2019). SOC changes are reported using moving averages.

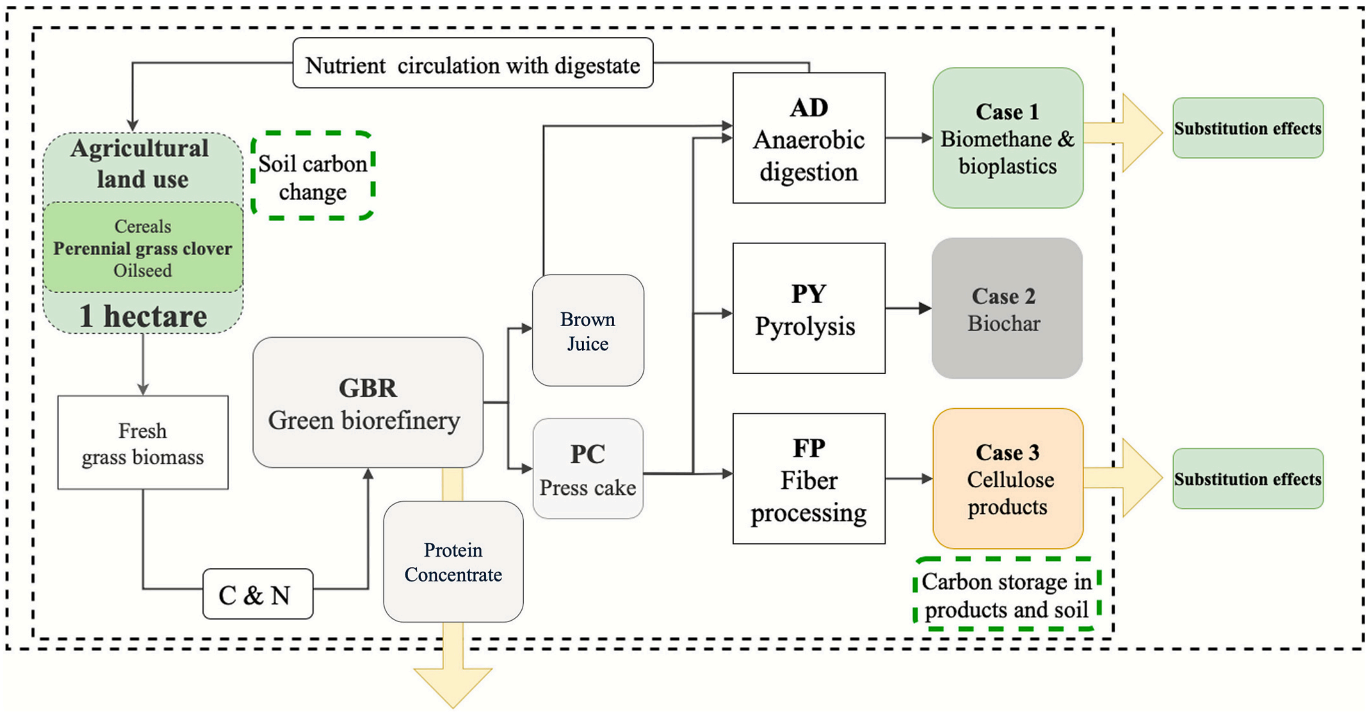

Fig. 1. System overview. Agricultural land-use model and processing steps, including their substitution effects. The GBR generates protein concentrate and the byproducts press cake and brown juice; byproduct C (carbon) and N (nitrogen) content is tracked through bioprocesses. The steps after the GBR—anaerobic digestion, pyrolysis, fiber processing—produce products with varying C-storage durations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Standard crop rotation [baseline], a six-year cereal rotation with rapeseed as a break crop, typical for arable farming systems in western Sweden (Tidåker et al., 2016), and the starting point scenario changes made when introducing ley. Ley = perennial grass clover leys substituting for cereal crops.

	Years in the rotation						Share of cereals
	1	2	3	4	5	6	
Standard crop rotation (baseline)	Winter cereal	Spring cereal	Winter cereal	Spring cereal	Spring cereal	Rapeseed	83%
Crop rotation with 2 years of ley (scenarios 1 & 2)	Winter cereal	Spring cereal	Ley	Ley	Spring cereal	Rapeseed	50%
Crop rotation with 4 years of ley (scenario 3)	Winter cereal	Ley	Ley	Ley	Ley	Rapeseed	17%

All assumptions and details are provided in SM chapter SM2. Temporary leys (i.e., perennial grass-clover ley grown for two up to five years in rotation with annual crops) have been cultivated for a long time in Swedish farming systems and foremost used for cattle feed. Cultivation practices for temporary leys benefit from well-established knowledge and advisory guidance, informing our choices of parameter values for grass-clover ley inputs and emissions, see Table SM1.

2.2.2. *Biomass conversion processes*

The modelled GBR processed fresh grass-clover with an assumed dry matter (DM) yield of 8 tons per hectare (Cederberg and Henriksson, 2020) (Table 2) and an estimated C content of 46.7% (Zoppi et al., 2023) (based on ryegrass). Grass-clover was represented by a typical Swedish forage/ley mixture with an assumed 20% clover content. While the brown juice was always used to produce biogas through AD, the PC was processed into different biobased products, as described in Table 3. Energy demand was calculated for all process steps, including biomass transport from fields. Electricity use was assumed to be from a Nordic electricity mix (Sandgren and Nilsson, 2021). The model assumed declining emission factors for external energy input over time, reflecting both projected reductions in CO_2-equivalent emissions associated with

Table 2
Distribution of dry matter (DM), carbon (C), and nitrogen (N) in the green-biorefinery input and output.

	DM, kg (share [%])	C, kg (share [%])	N, kg (share [%])
Input: grass clover	8000 (100)	3736 (100)	219 (100)
Output: green-protein concentrate	1160 (15)	592 (16)	96 (44)
Press cake	4568 (57)	2395 (64)	114 (52)
Brown juice	2272 (28)	750 (20)	9 (4)

Table 3
Overview of processing options for converting press cake (PC) into different products; anaerobic digestion (AD), pyrolysis (PY), and fiber processing (FP), showing applications and their mitigation effects in terms of C storage and substitution.

Biomass conversion processes after GBR	Products	Application and mitigation effect
AD	Biomethane	Transport Substitution
	Biomethane	Short to long lived bioplastic products C storage + Substitution
PY	Biochar	Soil application in agriculture C storage
FP	Cellulose products	Single use-products C storage + Substitution

electricity use, as well as diesel for tractors. Detailed information and data for each process step are available in the following and in SM 3.

2.2.2.1. Green biorefinery. Data on green biorefining were based on Chan et al. (2024) and complemented with recent data on energy requirements from a demonstration-scale green biorefinery (Andrade et al., 2025). We assumed an average transport distance of 7.5 km for the fresh grass-clover biomass from the field to the GBR (Yilmaz Balaman et al., 2023). Following Chan et al. (2024), 14.5% of the input grass clover biomass (calculated as DM) ends up in the protein feed product, 57% in the PC, and the rest (calculated as residuals) in the brown juice. Based on this, we established mass balances for C and N to follow these elementary substances in the overall model, and the biomass from 1 ha ley generated a yearly input of 3736 kg C into the GBR (Table 2). Chan et al. (2024) do not provide data on C concentrations in the different fractions coming out from the GBR; we derived estimates on these from two pilot-scale studies on GBRs (Santamaria-Fernandez et al., 2020; Zoppi et al., 2023). The elemental composition of PC depends on biomass feedstock, harvest conditions, and processing parameters (Andrade et al., 2025); as these assumptions introduce uncertainty, their impact is assessed in the sensitivity analysis. In accordance with Chan et al. (2024), we applied an average N-content in the grass-clover biomass at 2.75% N of DM, corresponding to an uptake of 219 kg N for 1 ha ley and year, where a relatively large share (44%) was distributed to the protein feed product (see Table 2). Data for the GBR process are shown in Tables SM 3 & 4.

2.2.2.2. Anaerobic digestion. In case 1, the PC was used together with brown juice to produce biogas through AD. The AD process is well documented in previous studies and provides a well-defined basis for modeling (Burg et al., 2023; Chan et al., 2024; Khoshnevisan et al., 2023; Zoppi et al., 2023). The model accounted for leakage of methane from the digester (Møller et al., 2022) and from biofertilizer storage and handling (Feng et al., 2023). Energy use in AD was based on Chan et al. (2024) and it was assumed that 10% of the produced biogas was used for this purpose. However, siting AD plants to utilize heat surplus from other processes could reduce this biogas use. The remaining biogas was upgraded to biomethane by water scrubbing (Angelidaki et al., 2018), which is the most common method in Sweden (SEA, 2022). The residual C and N generated in the AD process were found in the digestate (Santamaria-Fernandez et al., 2020) and considered to be applied to the agricultural land as a biofertilizer in which 65% av N was assumed to substitute for N in synthetic fertilizers (Delin et al., 2012). The residual C in digestate contributes to SOC storage increase according to (Barrios Latorre et al., 2024).

The biomethane was assumed to be used as either transport fuel or as a source for bioplastic production (Ali et al., 2023), in both cases substituting for fossil gas. Additionally, the produced CO_2 from the AD was assumed to be utilized as a product or as industrial feedstock, substituting fossil CO_2 (Cordova et al., 2022, 2023). Further information about product substitution is found in Tables SM 5, 6 & 7.

2.2.2.3. Pyrolysis. In the PY case, the PC was used as feedstock, and the produced biochar was used as a soil amendment. Before entering the pyrolysis chamber, the PC underwent a drying stage, and although drying is an energy-intensive process, efficient combustion of the produced pyrolysis gas can supply enough heat to dry PC feedstock containing up to 80% water content, thereby eliminating the need for external energy (Ravenni et al., 2024). Pyrolysis gas not needed for the drying could instead be used for district heating, but this possibility is not explored further in this study. The stable C content of biochar after 100 years was calculated based on (Azzi et al., 2024); however, pyrolysis of PC is not well investigated. One study has shown PC to yield biochar with high C content (>60 wt%), and N content around 3 wt%, though N can vary due to harvest time and the GBR maceration setting (Ravenni et al., 2024). N retention and bioavailability in the biochar is also sensitive to the pyrolysis temperature; high temperatures drastically reduce the N content (de Oliveira Paiva et al., 2024). Elemental composition and data on pyrolysis and biochar are available in Tables SM 9 & 10.

2.2.2.4. Fiber processing. PC can be processed to enable use of the cellulose fiber, for instance to produce paper and carboard products (Cordis, 2024; Creapaper, 2023; Hermuth-Kleinschmidt, 2021). The main energy use in this process is for drying, pressing, and cleaning the biomass, before forming the product (Hermuth-Kleinschmidt, 2021). Calculations and assumptions are specified in Tables SM 11 & 12. Regarding N, it was assumed to be retained in the final products and not recycled to agriculture. While this may not reflect the actual pathway of N in these processes, the neccesary data for modeling N flows is currently not available (see Section "Future research").

2.2.3. Substitution and C storage

C storage in the biobased products was modelled based on the C content in the biomass feedstock, share of C in the feedstock that is found in biobased product, and product lifespan. To model long-term C release from the products, we applied probability-distribution-based functions, similar to previous approaches for C decay in harvested wood products (Marland et al., 2010; Wei et al., 2023). The function is defined as follows:

$$R(t) = C_{stored}(t-\mu) \bullet \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(t-\mu)^2}{2\sigma^2}}$$

where $R(t)$ is the amount of C released at time t, C_{stored} is the total C initially stored in the products, μ is the mean release time, and σ is the standard deviation. Detailed parameters and input values are provided in Table SM 13, together with a figure shown as an example of this dynamic applied for all products.

In this study, the substitution effect of a biobased product was defined as the net change in CO_2 emissions that arises when it replaces a conventional fossil-based product. The calculations included emissions associated with production, use and end-of-life management of both products.

For fossil methane, the C in the product is emitted to the atmosphere as CO_2 when the product is used and there is no end-of-life treatment. In this case, we assumed that emissions associated with production and use occur simultaneously. For the other alternative products, there are no emissions associated with the use phase, and the C in the product is emitted to the atmosphere at the end of the service life. The biobased and alternative products were assumed to have the same service life and be subject to the same end-of-life treatment. Therefore, possible substitution effects associated with the end-of-life treatment do not need to be considered.

The C storage in biobased products and in SOC is presented separately to show the importance of C storage compared to emission savings through the substitution effect. For alternative products, the temporary storage of fossil C in the products was modelled as a disruption to the linear flow of fossil C from geological reservoirs to the atmosphere, i.e., the fossil C does not enter the atmosphere around the point in time when the fossil resources are extracted and used to produce the alternative products. This delay in emissions is determined by the lifetime of the product.

Data concerning production emissions were obtained from the following sources (Andrade et al., 2025; Chan et al., 2024; Chidambarampadmavathy et al., 2017; Cordis, 2024; Creapaper, 2023; Ortiz et al., 2022; Ravenni et al., 2024; Rise, 2019). Emissions and substitution factors (Delin et al., 2012; Hoxha and Bjarne, 2019; IPPC, 2019) for N in digestate and synthetic fertilizers are found in Table SM 7. All calculations were performed using Python, using *NumPy*, *Pandas*, and *Matplotlib* for data processing, storage, and visualization. Calculations of avoided emissions are available in Table SM 14 and 15.

2.3. Sensitivity analysis

To evaluate the robustness of the results, we performed a sensitivity analysis for Scenario 2. *First*, model runs were carried out to single out the dominant parameters. The dominant parameters were found to be C and N content in the PC, digestate N content, C retention in products, electricity mix, and product lifespan. Based on a literature review, the dominant parameters were assigned individual percentage variations (see Table SM 16) to determine uncertainties concerning parameter values. Uncertainty ranges were on the order of ±5–20% for C and N partitioning parameters and ±30% for the electricity mix. Finally, the influence of each dominant parameter on annual net emissions (t CO_2-eq ha^{-1} yr^{-1}) was quantified using a one-at-a-time approach, in which the value of one parameter was varied while the values of all other parameters were kept constant.

3. Results and discussion

3.1. Model assumptions and process uncertainties

To properly frame the interpretation of the results, it is important to first outline the key methodological considerations and assumptions. We use a yield level of 8 t DM ha^{-1} yr^{-1} grass-clover leys as the basis for biomass input in the GBR, matching yield statistics for southern Sweden. However, yield quantity and quality can vary significantly due to seasonal conditions, species composition, and harvest timing. Grass-clover mixtures show high variability in DM content and composition, affecting both protein yield and downstream processing and energy consumption (Andrade et al., 2025; Zoppi et al., 2023). As the newly harvested biomass is transported fresh to the GBR (typically around 80% water), the transport distance is a make-or-break factor. A too great distance can undermine biorefinery profitability. The assumption of an average 7.5 km transport from field to GBR is found to be reasonable from an economic perspective (Yilmaz Balaman et al., 2023).

The ICBM model and the logistic growth function model introduce uncertainty in the SOC stock calculations. Extending the ICBM trajectory with a logistic model after the first 30 years suggests that, in Scenario 2, SOC will increase by 2 Mg C ha^{-1} (95% CI 1.2–3.2 Mg C ha^{-1}) and plateau. We also assume that the baseline SOC increases with time. This is due to the relatively high residue and root C input from cereals and cover crops in the agricultural land-use model, reflecting the current cultivation patterns and yields in annual crop rotations in Swedish agriculture (Rehn et al., 2024).

The GBR is the starting point of the biomass processing steps; we use recent studies of green biorefining process trials for protein yields, fractioning of side-streams through the processes as well as energy demand (Andrade et al., 2025; Chan et al., 2024; Zoppi et al., 2023). However, C and N content pathways to PC, brown juice, and protein feed product are uncertain; we source these values from multiple GBR experiments of different size and character (Santamaría-Fernández and Lübeck, 2020; Zoppi et al., 2023). The sensitivity analysis shows that C content in the PC and, for plastics, the N content of the digestate, stand out as the largest contributing parameters (Table 4).

The AD enables the production of transport fuel, bioplastics, and a nutrient-rich digestate assumed to be applied to agricultural land as a substitute for synthetic N fertilizer. This study does not consider practical field application of the digestate amounts, which has been discussed as a transportation constraint (Santamaría-Fernández and Lübeck, 2020). However, our sensitivity analysis shows that the N content in the digestate is one of the most important determinants of the results for the bioplastics option, indicating that using the digestate as fertilizer in agriculture is an important factor for climate mitigation strategies.

For the pyrolysis process and biochar production temperature, this study uses 400 °C. Pyrolysis temperature plays a key role in determining biochar yield and long-term C stability (Azzi et al., 2024; Lehmann et al., 2021; Zhang et al., 2020). The effects of using biochar as a soil amendment are associated with uncertainties; quantifying the yield-effects is challenging due to the heterogeneity of both biochar and soils (Tsolis and Barouchas, 2023). The temperature setting of the pyrolysis should be appropriate for the intended utilization; we find significant N emissions to air (as ammonia and N oxides) when relatively N-rich feedstocks such as PC are pyrolyzed even at 400 °C (de Oliveira Paiva et al., 2024). This is an environmental drawback that should be further investigated. Another drawback of the pyrolysis option is the substantial need for drying PC prior to pyrolysis. This is a particularly energy-demanding step, and feedstock biomass DM directly influences energy demand (Ravenni et al., 2024). An important system setting to consider is the extent to which drying relies on surplus heat (which would otherwise be wasted), reducing the need for other energy inputs (see Future research).

This study focused on CO_2, as initial calculations showed that it is the most important GHG; other GHGs were converted to CO_2-eq using GWP100 factors. This means that the net CO_2-eq emissions we find cannot be used to directly model global average temperature changes. In particular, near-term temperature effects will be especially underestimated if a substantial portion of the CO_2-eq emissions is due to methane.

3.2. SOC storage changes in scenarios for ley implementation

The impact of including ley in the crop rotation is illustrated in Fig. 2. The SOC storage trends are represented by smoothed moving averages derived from the ICBM model simulations and post-model curve fitting extrapolation. The starting point SOC storage (topsoil 0–20 cm) for all scenarios is 67.7 Mg C ha^{-1}, representing a mean for fields in west Sweden without leys (Rehn et al., 2024) (see SM6). A baseline scenario shows an increase of SOC in the first decades, followed by a gradual stabilization, even though no changes to the crop rotation are applied (see Discussion). Over the first 30 years, the integration of leys in the three scenarios leads to an additional SOC gain of 1.6 Mg C ha^{-1}. In Sc 1, which reverts to the original crop rotation after 30 years, SOC levels gradually decline after the reversion and approach the baseline level. In contrast, Sc 2 and Sc 3 show further increases, reaching stabilization at higher SOC levels, suggesting new equilibrium levels where annual SOC losses balance C inputs from the additional perennial ley roots. Sc 2

Table 4
Results of sensitivity analysis for each case and product and for the largest contributing parameters. Changes (%) indicate the model variation for each parameter, and the % under each product is the resulting deviation from the Sc2 results.

Parameter	Changes	Short plastic	Long plastic	Transportation fuel	Cellulose product	Biochar
Baseline	(%)	0.64 t CO_2-eq ha^{-1} y^{-1} (%)	0.73 t CO_2-eq ha^{-1} y^{-1} (%)	0.74 t CO_2-eq ha^{-1} y^{-1} (%)	0.276 t CO_2-eq ha^{-1} y^{-1} (%)	0.91 t CO_2-eq ha^{-1} y^{-1} (%)
C input	±15	±0	±2	±12	±1	±7
N input	±5	±5	±2	±1	±0	±1
Digestate N	±15	±16	±10	±5	±1	±0
Electricity mix	±30	±18	±16	±2	±8	±2
Product lifetime	±20	±0	±1	±0	±1	−9 + 0
Share of C to biobased product	±10	±0	±1	±8	±0	±5

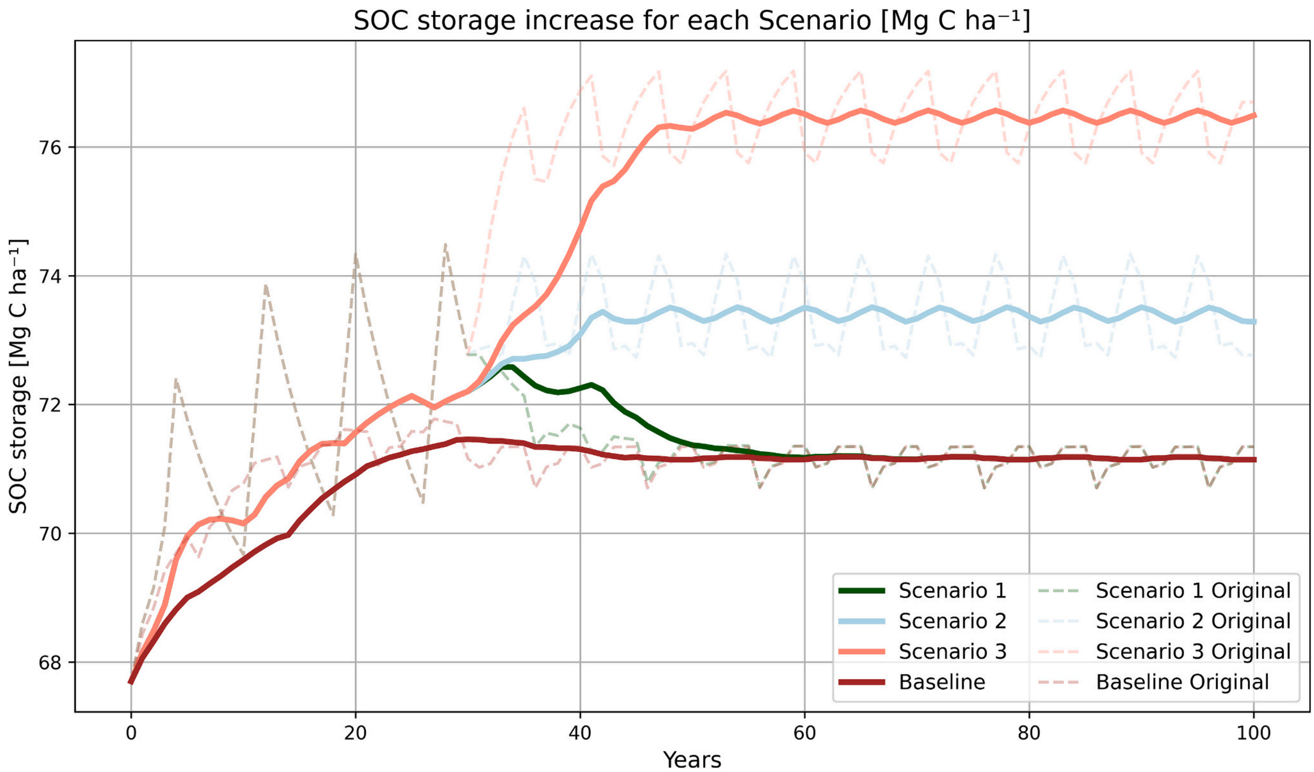

Fig. 2. SOC storage changes for a baseline scenario and for the three grass-clover scenarios [Mg C in SOC ha^{-1}]. Results based on individual ICBM model runs and post-model curve fitting, where the share of perennial leys within the crop rotation is changed according to the scenario description. Filled lines show the smoothed moving average, while the dashed lines show the original data.

stabilizes at a SOC storage level of 2.4 Mg C ha^{-1} above baseline, while Sc 3, with twice the amount of grass-clover, achieves a higher level of 5.4 Mg C ha^{-1}.

3.3. C storage in products and SOC

Fig. 3 shows the changes in C storage over a 100-year period, capturing both near-term and long-term storage for all cases and scenarios, with storage separated into the product pool (blue) and SOC pool (dark and light brown). Biochar has the largest long-term C storage potential, due to its high recalcitrance. In Sc 3 for the pyrolysis case, the C storage reaches 198 t CO_2-eq ha^{-1} in year 100, of which 84% is stored within the biochar itself. Following biochar, long-lived bioplastics store the most C, with storage reaching 55 t CO_2-eq ha^{-1} (47% Product C, 53% SOC) after 100 years in Sc3. Cellulose products and short-lived plastics show small product C storage potentials. After 100 years, about 81–95% of the stored C is in SOC in Sc3. Biomethane as transportation fuel substituting for fossil fuels generates no C storage, by definition, so all storage increase is associated with increases in the agricultural soil. Except for biochar and long-lived bioplastics, additional SOC is the dominant contributor to total C storage.

These results clarify the inherent trade-off in product choice. Pyrolysis achieves the greatest C removal because of the recalcitrant biochar, with only a small share due to SOC storage increase. Long-lived bioplastics retain a smaller yet significant biogenic C stock in the product itself, while, as for the other options, increased SOC remains the dominant C sink. Our results clarify that product lifetime needs to be considered along with the substitution effect: The conversion of PC into long-lived products (biochar, durable plastics) contributes significantly to the net emissions reduction. Products with a short service life mainly contribute to net reductions through the substitution effect, unless the end-of-life treatment keeps the C out of the atmosphere for longer periods of time. Across all scenarios, the substitution effects outweigh production-stage emissions (Fig. 5). The biochar option performs the best because of its high recalcitrance. Biomethane as transportation fuel stands out as an attractive option for short-term mitigation targets, on par with biochar production.

3.4. Emissions and avoided emissions

Fig. 4 shows the cumulative GHG emissions associated with the production of biobased products (red) and avoided emissions resulting from substitution (green) over the 100-year period, for all product types and scenarios. The dashed lines show the cumulative net emissions to the atmosphere, where negative values indicate net emission savings. As can be seen, there are net emission savings in all scenarios and cases. The small reduction in emissions associated with biochar in all scenarios is due to the assumption that biochar applied to agricultural fields has a small substitution effect associated with N input, which reduces the need for synthetic fertilizers. In Sc1, the emission curves level off because ley cultivation—and therefore the supply of biomass to the GBR and the production of biobased products—ends after 30 years. After 30 years of ley cultivation (around 2055), replacing fossil fuels with biomethane and substituting synthetic fertilizers with digestate from the AD has reduced net emissions by 26 t CO_2-eq ha^{-1}. Using PC to produce cellulose products and short−/long-lived plastics results in reductions of around 6–8 t CO_2-eq ha^{-1}. In Sc2, the production and use of transportation reduces net emissions by 64 t CO_2-eq ha^{-1} over 100 years. Net emission reductions are 19 and 18 t CO_2-eq ha^{-1} for cellulose and long-lived plastics, respectively, while they are 7 and 2 t CO_2-eq ha^{-1} for short-lived plastics and biochar. In Sc3, production and use of biomethane as transportation fuel reduces the net emissions by 101 t CO_2-eq ha^{-1} over 100 years, driven by fossil-fuel substitution (3.8 t CO_2-eq ha^{-1} yr^{-1} ha^{-1}) and N substitution (0.3 t CO_2-eq ha^{-1} yr^{-1} ha^{-1}) of digestate application. Long-lived bioplastics reduces net emissions by 53 t CO_2-eq ha^{-1}.

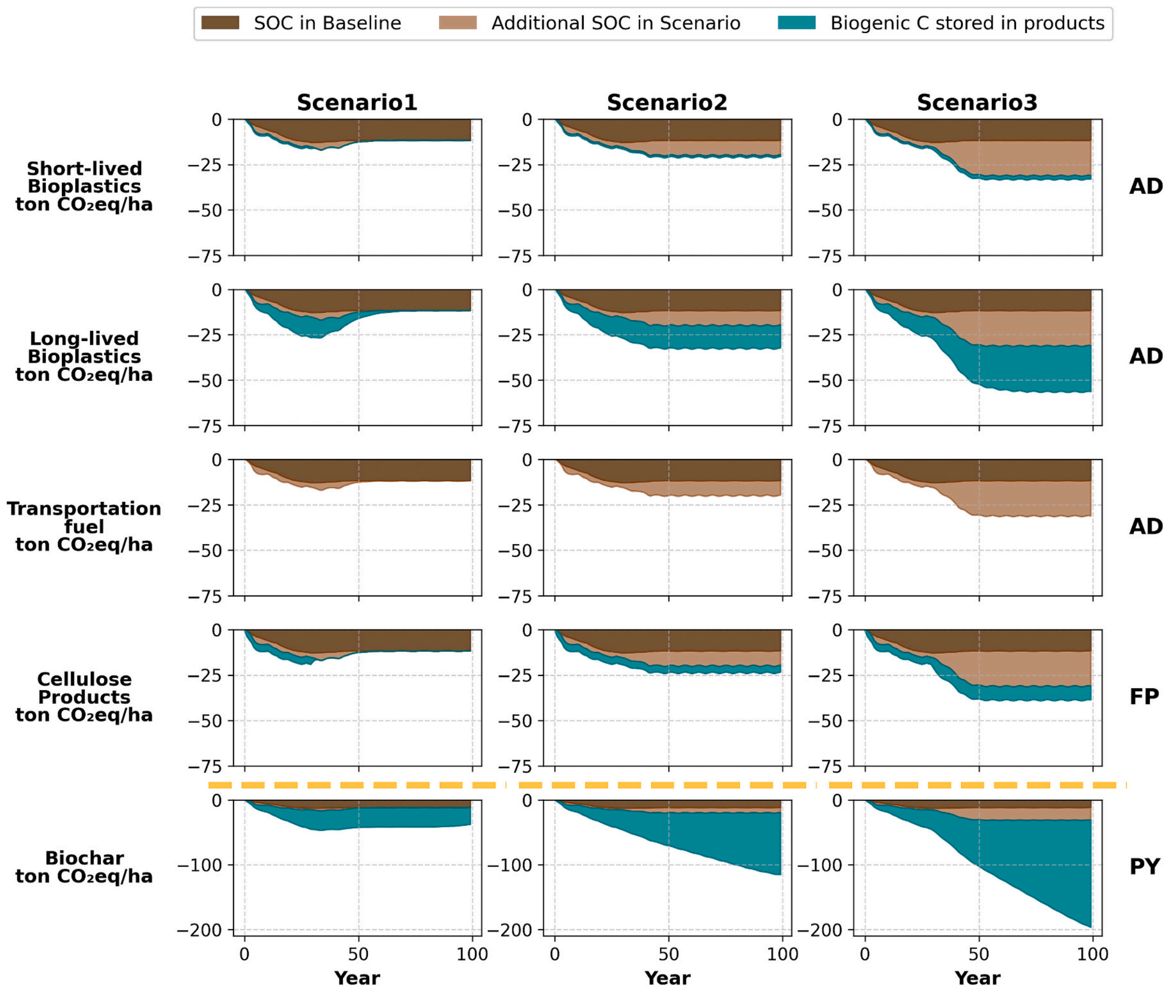

Fig. 3. Cumulative C storage of each product for each scenario for the complete 100 years of modeling. The figure includes soil organic (SOC) storage in the baseline scenario (dark brown), additional SOC storage increase (light brown), and biogenic C storage in the final products. Note the difference in y-axis scale in diagrams above and below the orange dashed line. AD = anaerobic digester, FP = fiber processing, PY = pyrolysis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

These emission patterns are shaped by how nitrogen moves through the system. N has an important effect on the net GHG savings, because the option chosen for the PC processing determines how much N stays within the system. If both the PC and the brown juice go to the AD case, the digestate returns N to the soil with a substitution effect of −195 kg CO_2-eq ha^{-1} ley^{-1} yr^{-1}. By contrast, routing the PC to pyrolysis or fiber processing leaves only the brown juice to the AD, with a smaller amount of digestate N returned to the soil. This entails a smaller substitution effect at the same time as the N bound to products effectively leaves the system. The choice between PC processing options is therefore a critical design variable that directly controls N retention and climate mitigation performance.

The process energy demand matters: Manufacturing long-lived rather than short-lived bioplastics emits ~40% more CO_2 (2.29 vs 1.64 t CO_2-eq ha^{-1}), partially offsetting the benefit of their longer lifetime. Biochar has the smallest process emissions, but this is due to its assumed internal utilization of pyrolysis gas for energy recirculation for the drying stage of the process (Ravenni et al., 2024). The Nordic electricity mix results in relatively low GHG emissions, so it has a small impact on results for the biochar or transportation fuel options but still matters for bioplastics and cellulosic products. These latter cases stay climate-positive only with a similarly clean electricity mix, whereas biochar and transportation fuel are more robust across a range of electricity mixes.

3.5. Changes in net GHG emissions over 100 years

In all cases, the changes in land use and production and use of biobased products contribute to net emission savings throughout the modeling period (Fig. 5). The cases with biochar and transport fuel achieve the largest savings in all scenarios and in both the short and long term. By year 30, the net emission savings are −47 and −43 t CO_2-eq ha^{-1}, respectively, for biochar and transport fuel, followed by cellulose and long-lived plastics (−29 to −27 t CO_2-eq ha^{-1}), and short-lived plastics (−20 t CO_2-eq ha^{-1}). After ley cultivation, and thereby biomass production, ceases (Sc 1), cumulative net emission savings plateau, sustained primarily by additional SOC accumulation. However, after about 60 years, the SOC C storage level is similar to the level in the baseline, i.e., cumulative additional SOC C increases during the first 30 years are lost in the following 30 years. The remaining climate benefit is associated with C storage in biobased products and avoided emissions resulting from substitution effects. Over 100 years in Sc1, biochar and transportation fuel both deliver −39 t ha^{-1} CO_2-eq. In Sc2, biochar and transport fuel show rather similar paths, however after 100 years, biochar delivers −118 t ha^{-1} compared with −84 t ha^{-1} for biomethane as transportation fuel replacing fossil fuels. In the short term, biomethane for transportation performs very close to biochar in terms of net emission savings (−33 t CO_2-eq at year 20 compared to −34 t CO_2-eq for biochar).

The large difference happens in Sc3, where biomass input doubles

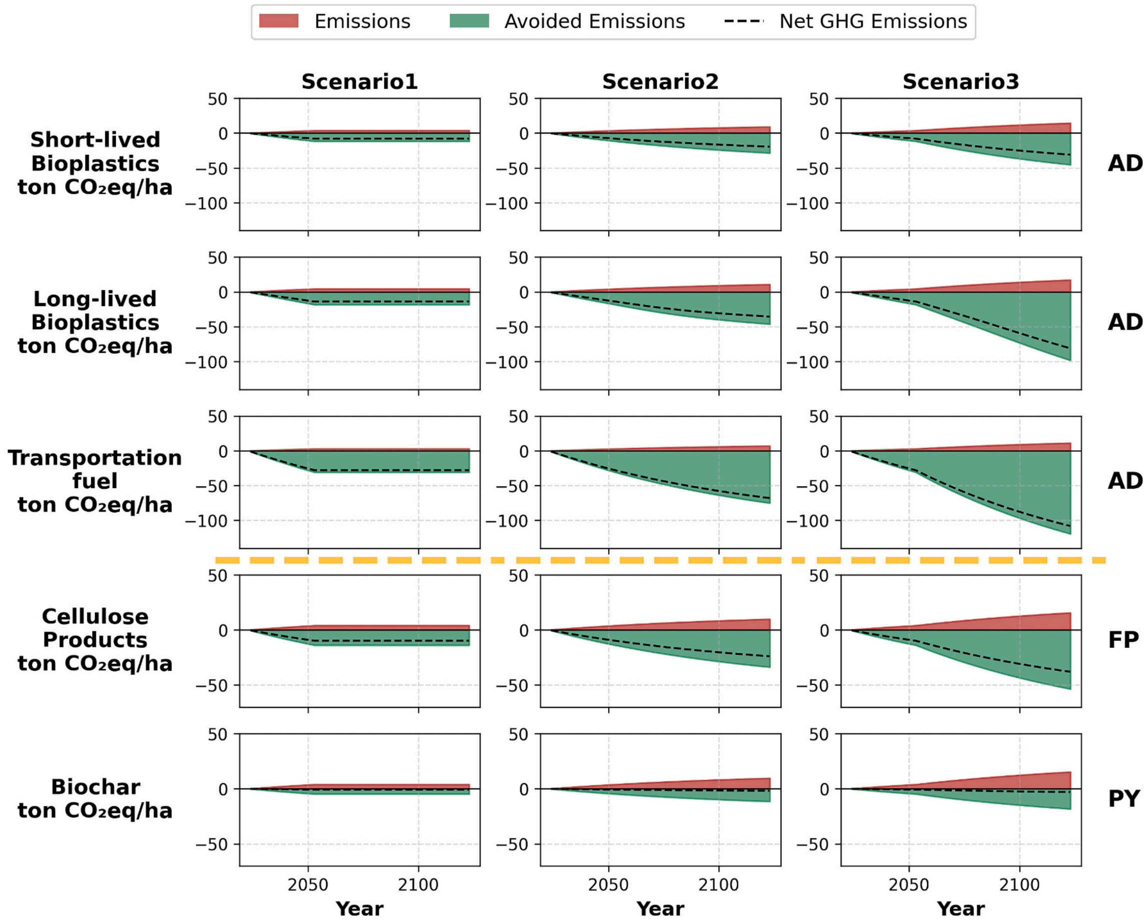

Fig. 4. Cumulative GHG emissions and avoided emissions for all cases across all scenarios over the full 100-year modeling period. The figure shows cumulative emissions associated with production of biobased products (red), as well as cumulative avoided emissions (green) resulting from substitution of alternative products. The black dashed lines show the cumulative net GHG emissions, where negative values indicate net emission savings. Note that the orange dashed line indicates a change in y-axis scale. AD = anaerobic digester, FP = fiber processing, PY = pyrolysis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

after 30 years when the rotation shifts to 4 years of ley. The biochar option results in the largest net emission savings, reaching 200 t CO_2-eq ha^{-1} after 100 years, where 16% is associated with the increased C storage in soils. Biomethane used as transportation fuel, lacking in-product storage, relies on SOC increase and on substituting for fossil-fuels and for synthetic fertilizers N, ultimately reaching −133 t CO_2-eq ha^{-1} (Sc 3). Short-lived plastic remains the weakest option, with a modest annual C input into the product pool and short product lifetime. Cellulose fibers and long-lived plastics provide similar mid-range benefits, despite their different product-C retention times. Cellulose products have a rather large C input, but short retention time (assumed to be used within a year), and long-lived plastics have a smaller carbon input, but an assumed long retention time and larger avoided emissions.

This study does not consider the protein feed product because every PC conversion option is associated with the same protein feed output. But the benefit of substituting imported soymeal is still noteworthy. As shown in Table 3, each hectare of ley yields about 1160 kg DM protein feed, which roughly corresponds to 1.2 t protein feed product at 10% moisture, before the PC and brown juice enter the processing routes. If this protein replaces imported soymeal in pig or poultry feed, and we use the Escobar et al. (2020) average footprint for Brazilian soymeal exported to the EU (0.77 t CO_2-eq t^{-1}), Sc1 would gain an additional −28 t CO_2-eq ha^{-1} over 30 years—savings on par with the transport fuel substitution credit. Accounting for such co-products attributes additional climate benefit to the GBR concept.

All cases contribute to emission reductions throughout the century (Fig. 5). In Sc3, the biochar option delivers the largest effect, followed by biomethane for transportation. Short-lived bioplastics are the weakest option, whereas cellulose fibers and long-lived bioplastics provide intermediate mitigation. The contrast between the two bioplastics options shows a wider trade-off: Long-lived bioplastics keep the biogenic C stored in polymers which is good for climate mitigation, but it could also increase the amount of long-lived waste (Mattlar and Ekholm, 2025). Short-lived plastics reduce the amount of waste, while offering a more modest climate benefit. Biomethane for transportation matches biochar closely during the first two decades, indicating that for near-term climate targets, these cases have equal potential.

These results point toward different possible options as strategies to consider when aiming for different climate goals. Near-term climate goals, such as those set for the EU 2030 (EC, 2020) or for Sweden 2045 (Naturvårdsverket, 2022), for example, could potentially benefit most from rapidly deployable solutions like transportation fuel or biochar, whereas biochar also can act as a C sink on a longer timescale. Durable bioplastics offer a middle ground, pairing moderate near-term gains with possible long-term C storage.

3.6. *Contribution to Swedish 2045 climate goals*

Table 5 compares mitigation potentials for the products with the required emission reductions for achieving sector-specific targets in the Swedish 2045 climate goals (Naturvårdsverket, 2022). The comparison assumes that crop rotations are changed to include grass-clover leys on

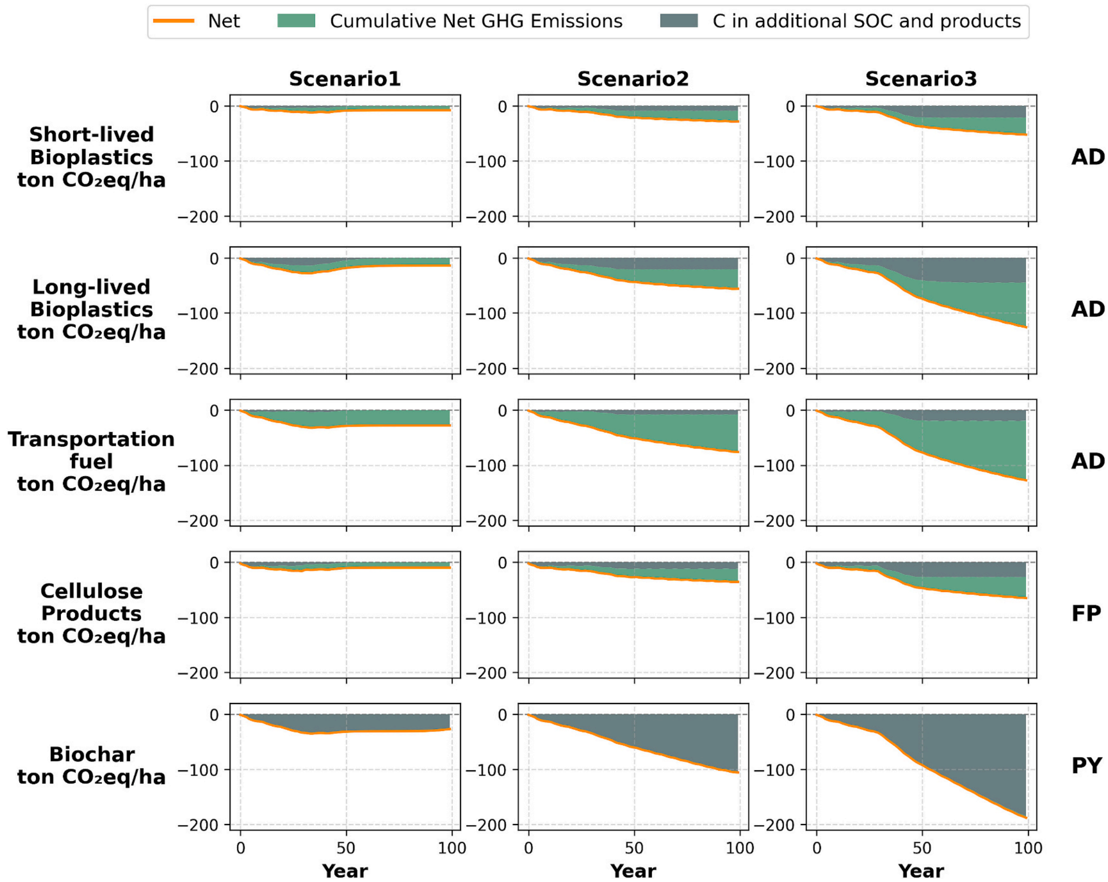

Fig. 5. Changes in net GHG emissions (CO_2-eq) per hectare for all cases across all scenarios over the 100-year modeling period. The figure shows the combined result of C storage in products and soil (Fig. 3) and the cumulative GHG emissions and avoided emissions (Fig. 4). AD = anaerobic digester, FP = fiber processing, PY = pyrolysis.

100,000 ha to support deployment of GBR. This corresponds to a 10 % increase of ley cultivation in Swedish agriculture (perennial leys are currently cultivated on 1 million ha arable land, which is 39% of total arable land). This is in line with farmers' views on possible and interesting land-use change options (Rehn et al., 2024) as ley cultivation provides several agronomy benefits when included in cereal-dominated rotation (Bossio et al., 2020; Paustian et al., 2019; Rumpel et al., 2022; Wiesmeier et al., 2019). This increase in ley cultivation for GBR processing would produce approximately 120,000 ton protein feed and thus have the potential to substitute for close to half of Sweden's soymeal import (IDH, 2023).

As can be seen in Table 5, the required reduction in emissions from the agriculture & LULUCF sector (1.5 Mt CO_2-eq) could be achieved if the PC were used to produce biochar for use as a soil amendment. The net GHG savings for the other options correspond to 70% of the required reductions for the agriculture sector, although all savings would not occur in the agriculture & LULUCF sector. Other sectors have larger emissions reduction targets, and the percentage contribution is therefore smaller. This holds especially for the industry and transport sectors, with their significantly larger reduction targets of 12.9 and 13.5 Mt CO_2-eq, respectively. Among all products assessed, biomethane used in the transport sector stands out.

The total estimated mitigation potential of 3.3 Mt CO_2-eq over 20 years covers 15% of the transport sector's target and 11% of Sweden's overall reduction goal for 2045. This result suggests that biomethane used for transport (i.e., assumed that biomethane, instead of fossil methane is used to replace diesel or petrol) represents the most impactful alternative overall for Sweden. The bioplastics created are assumed to replace normal plastic production, so they are sorted with petrochemistry in the industrial sector. Biomethane for energy refers to the use of biomethane as a fuel in district heating systems.

3.7. Sensitivity analysis

Increasing or decreasing the C content of the PC feedstock by 15% changes the results for biochar by ±7% and for transport fuel by ±12%. Altering product lifetime by 20% has an asymmetric effect: Shortening lifetime reduces the biochar benefit by 9%, whereas lengthening it provides virtually no further gain. Varying the electricity mix ±30% is important for cellulose (±8%) and for long- and short-lived plastics (±16–18%) but has only a small effect on biochar (±2%) and transport fuel (±2%). Varying the N concentration in the digestate by 15% changes the results for transport fuel by about ±5% and for long- and short-lived plastics by ±10% and ±16%, respectively. Taken together, these results show that the model's overall behavior is governed mainly by three parameters—the carbon content of the PC, assumed product lifetime, and electricity mix used in production—with the N content of the digestate also important for the plastics cases (Table 4).

3.8. Future research

This work assumes that pyrolysis gas is used at the drying stage before the pyrolysis process. How much gas is produced is regulated with heat, heating rate, and retention time (Fambri et al., 2024; Thomsen, 2022). However, the gas produced could also be used for drying the protein concentrate (Jørgensen et al., 2022), district heating, or for energy provision elsewhere in a more integrated system. Such energy utilization could improve energy efficiency at the wider system

Table 5
Estimated contribution toward Sweden's 2045 climate goals in the 100,000 ha scenario, allocate to major emission sectors. Values indicate the estimated emission reduction [Mt CO_2-eq] and percentage contribution to each sector's reduction target. Each sector's reduction target and percentage of Sweden's overall target (31 M CO_2-eq) are shown in the bottom row.

Sector	Agriculture & LULUCF (soil C and N_2O)	Industry	Transport	Electricity and DH	Total and share of 2045 target
Product	[Mt CO_2-eq] (%)	[Mt CO_2-eq] (%)	[Mt CO_2-eq] (%)	[Mt CO_2-eq] (%)	[Mt CO_2-eq] (%)
Cellulose products	1 (70)	1.1 (8)	–	–	2.1 (7)
Biochar soil	2.3 (153)	–	–	–	2.3 (7)
Biomethane for energy	1 (70)	0.1 (1)*	–	1.4 (47)	2.6 (8)
Biomethane for transport fuel	1 (70)	0.1 (1)*	2 (15)	–	3.3 (11)
Plastics long term	1 (70)	1.3 (10)*	–	–	2.4 (8)
Plastics short term	1 (70)	0.7 (5)*	–	–	1.8 (6)
Sectoral emissions reduction goal for 2045	1.5 (5)	12.9 (39)	13.5 (41)	3.1 (9)	31 (93)

* Emission reductions from avoided mineral fertilizer production are shown under Industry, but since production takes place abroad these do not contribute to Sweden's territorial climate targets. However, they are relevant in sectoral discussions of agricultural climate strategies, where upstream production of inputs is often included.

level considerably and should be further investigated. We assume some internal energy recovery, with associated C emissions, in AD (10% biogas) and the PY (pyrolysis gas for drying). This is a sensible strategy; however, this C might achieve a better climate effect elsewhere. This should be investigated further in a wide integrated-system optimization model.

In our product C model, the C is assumed to be stored in products during their service life; material recycling or energy recovery at the end of a product's service life is not considered. Plastic products with a long service life might be considered representative of plastic products with short service life and high material recycling potential. However, more careful consideration is warranted where material recycling and/or energy recovery is modelled explicitly to consider energy use, material losses, and quality degradation in recycling processes, as well as additional substitution effects. Biochar may also substitute for synthetic fertilizers because of its N content. In this study, we assumed that 50% of the N present in the biochar can replace conventional fertilizers, but this estimate carries significant uncertainty. N retention in biochar is highly dependent on the pyrolysis temperature. Lower temperatures (~300–400 °C) preserve more bio-available N structures, while higher temperatures (>600 °C) result in stable but less available aromatic N compounds (de Oliveira Paiva et al., 2024). Future work should aim to better quantify the long-term bioavailability of N in biochar and its actual substitution value in agricultural systems.

Case construction and product selection are based on previous research (Gaffey et al., 2023; Jørgensen et al., 2022). Other potential industry sectors and materials could also utilize the PC stream, such as the textile industry (Gaminian et al., 2024), or biochar, for instance in construction (Senadheera et al., 2023) or in the steel industry (Safarian, 2023b). If applied in steel production, as a substitute for coal in blast-furnace technology, the quantified impact could have the potential of 1.3 Mt CO_2-eq, based on data from Safarian (2023b).

Grass fiber application remains rather understudied, with companies producing cardboard boxes (Creapaper, 2023) and insulation sheets (Gramitherm, 2024), and with new experiments on grass to textiles (Cid Gomes et al., 2025)—but, overall, systemic studies are still lacking. The long-lived alternatives, such as insulation sheets where the biogenic C is stored for decades in buildings, show a significant potential for long-term CO_2 storage and large climate benefit. Future work should aim to investigate more product streams from the GBR residues, and how the post-GBR processing steps can be integrated in agricultural systems.

4. Conclusion

The climate benefits of GBR are significantly influenced by the way lignocellulosic side streams are used. Across three land-use scenarios, the biochar option shows the greatest reduction in cumulative net GHG emissions almost exclusively through C storage in the biochar. Biomethane as transport fuel matches biochar in the first decades via fossil-fuel substitution and nutrient recycling. Long-lived bioplastics contribute significantly, while short-lived plastics and cellulose products offer more modest benefits.

Two factors prove critical in our study: nutrient recycling from digestate when producing biogas, and the service life of products, with more durable carbon pools (biochar and long-lived plastics) enhancing net removals. Scaled to 100,000 ha of additional leys—within the preferences of Swedish farmers—the concept could deliver substantial reductions for the agricultural sector, meet 15% of the transport sector's 2045 climate target, and supply up to half of Sweden's imported soymeal. Using processing side streams to produce biobased products can significantly improve the climate benefits of GBR and help national climate mitigation targets.

CRediT authorship contribution statement

Andreas Rehn: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Göran Berndes:** Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Christel Cederberg:** Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biteb.2026.102606.

Data availability

The input data of this study are available by following the respective references. Code availability: https://github.com/climate-carbonlanduse/carbonmodelling_agrisystem_biobased_products

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