Original Article

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Towards multifunctional landscapes coupling low carbon feed and bioenergy production with restorative agriculture: Economic deployment potential of grass-based biorefineries

Sebnem Yilmaz Balaman, **Göran Berndes**, **Christel Cederberg**, Division of Physical Resource Theory, Department of Space, Earth and Environment, Chalmers University of Technology, Göteborg, Sweden

Håkan Rosenqvist, Independent Researcher, Billeberga, Sweden

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Abstract: Grass-based biomass from grasslands can be used as feedstock in green biorefineries (GBs) that produce a range of biobased products. In addition, adjustments made as part of crop rotation to increase areas under temporary grasslands can yield benefits such as carbon sequestration, increased soil productivity, reduced eutrophication and reduced need for pesticides. In this paper, a flexible modeling framework is developed to analyze the deployment options for GBs that use grass–clover to produce protein feed and feedstock for bioenergy. The focus is placed on optimal deployment, considering system configuration and operation, as well as land use changes designed to increase grass–clover cultivation on cropland. A case study involving 17 counties in Sweden showed that the deployment of GB systems could support biomethane and protein feed production corresponding to 5–60 and 13–154%, respectively, of biomethane and soybean feed imports to Sweden in 2020. © 2022 Society of Chemical Industry and John Wiley & Sons, Ltd.

Supporting information may be found in the online version of this article.

Key words: green biorefinery; circular bio-economy; bioenergy; land use change; modeling and optimization

Introduction

Biorefineries can produce a broad range of products from a variety of biomass resources.[1–3] Green biorefineries (GBs) can utilize grass (e.g. biomass from cultivated grasslands, closure fields and nature reserves), green crops (e.g. lucerne and clover), and immature cereals from extensive land cultivation[4,5] to produce soluble sugars, proteins, lipids, inorganics, active natural components and a fiber fraction. These can be used as intermediates in various

Correspondence to: Division of Physical Resource Theory, Department of Space, Earth and Environment, Chalmers University of Technology, Göteborg, Sweden.
E-mail: sebnem@chalmers.se

production processes or sold directly,[5] e.g. extracted protein is suitable for animal feed.[6–8] While commercial GBs are not yet deployed, pilot and demonstration plants showing that the production of high-value products from grass is technically, economically and environmentally feasible[9,10] have been constructed in Germany,[11,12] Denmark[6,13,14] (Corona *et al.,*[15,16]), Ireland,[17,18] and Austria.[19]

The introduction of temporary grasslands as part of crop rotations dominated by annual crops can enhance biodiversity[20,21] and carbon sequestration into soils, thereby improving soil structure and fertility, as well as water storage capacity.[22–26] It can also reduce nitrogen (N) and phosphorus (P) losses, mitigating eutrophication in aquatic ecosystems[27] and reducing fertilizer use with associated reductions in greenhouse gas (GHG) emissions.[26,28–30] Mixed grass and clover cultivation produces good yields with a relatively low demand for synthetic N-containing fertilizers owing to clover's biological capacity for nitrogen fixation. Besides biogas, anaerobic digestion of the harvested biomass produces N-rich digestates that can substitute for mineral fertilizers, enhancing GHG savings.[31]

Apart from the benefits described above, Tidåker *et al.*[31] reported that Swedish farmers' profits increased when crops with low-level profitability were replaced with grass–clover in cereal-dominated crop rotations, mainly because the rotation resulted in increased crop yields and reduced costs for pesticides and fertilizers. Furthermore, in the overall crop rotations, protein production increased 29–44% when a grass–clover crop was introduced. Positive economic and environmental effects of GB deployment have been reported also in other studies,[32,33] although the outcomes were sensitive to crop prices[34] and transport costs.[17,18,35]

Building on the above-mentioned studies and other studies related to the production efficiency, environmental impacts and economics of GBs,[6–8,13,15,36] an analytical framework was developed in the present study that allows investigations of GB systems that use mixed grass and clover crops to produce protein feed and bioenergy in the Swedish context. The framework builds on a generalized and flexible methodology for the modeling and optimization of GB production chains, including land use change (LUC) to increase the cultivation of mixed grass–clover crops, transport logistics, biomass conversion and end uses. The framework can be used to determine how interactions between agricultural farms and GBs influence system configuration and operational decisions, as well as to quantify deployment potentials for GBs.

The applicability of the framework is tested in a case study of southern and central Sweden that quantifies the protein feed and bioenergy supply potentials and analyzes the effects of different LUC patterns and price settings on the GB configuration and economic performance of supply chains. The implications of the modeling results are discussed from the perspective of the climate policy framework adopted by the Swedish Parliament, including the goal that Sweden should have net-zero emissions by Year 2045, and as part of the realization of this vision, that all energy gases used in Sweden should be completely fossil-free. According to Sweden's National Energy and Climate Plan (2020), bioenergy is expected to play an important role in reaching that target, and Sweden's energy supply security should be increased through the domestic production of biogas. Here, a specific focus is placed on the potential for increasing the domestic production levels of biogas and protein feed, so as to reduce dependency on natural gas and soybean meal imports.

Materials and methods

System description

GBs use a fractionation technology as the first step to separate the biomass into the economically valuable fractions of a fiber-rich press cake and a nutrient-rich green juice. The green juice can be processed to obtain a protein concentrate (hereinafter referred to as 'protein feed') and a residual brown juice, through coagulation and decanting. The press cake can be used as: feed for ruminant animals[6]; a fermentation feedstock;[37,38] feedstock for biogas and bioethanol production[13,39,40]; and as a solid fuel.[41] Alternatively, it can be dried and used as a structural material.[9,18,19] Feed protein separated from the green juice has a protein content of approximately 46–50% dry matter (DM)[47]; and can be used as feed for monogastric animals substituting for other protein-rich feeds, such as soybean meal,[14,32,42,43] which has similar protein composition and content.

Modeling framework

A mixed integer linear programming model was developed that comprises four interconnected modules: (1) configuration and network design of GBs; (2) LUC to increase the cultivation of mixed grass–clover crops; (3) GB production planning; and (4) procurement and allocation of biomass resources. Appendix A depicts the main modules of the model, links these modules with the corresponding decisions made in each module and explains the notations for decision variables and parameters used in the formulas. The formulations representing objective function and system constraints are

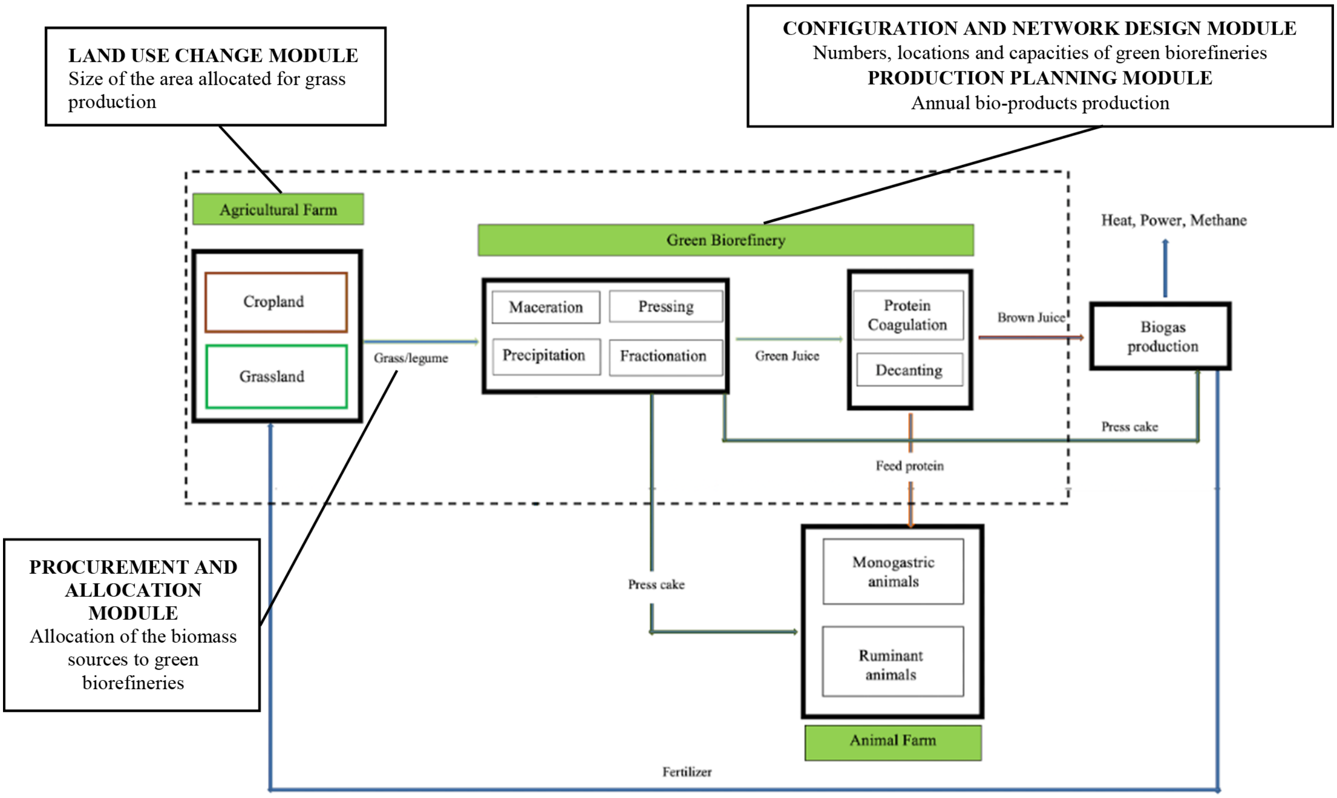


Figure 1. Green biorefinery (GB) supply chain and system boundary (indicated by dashed line).

also indicated in Appendix A. Figure 1 illustrates the GB supply chain with mass flows and how the respective modeling modules cover the specific parts of the chain.

Case study

The model is demonstrated in a case study of 17 counties in southern and central Sweden (Fig. 2), using county-specific data. The center-point of each county is assumed to be a candidate location for biorefineries, i.e. the coordinates of the center-points of the counties are used to calculate the geographic distances between the GB and the locations for grass–clover cultivation.

Agricultural production

Most of Sweden's cereal cultivation takes place in southern and central Sweden, where cereal-based rotations dominate the arable cropping systems used on farms that are widely dispersed across the regions. Here, the areas used to cultivate the three major cereals – winter wheat, spring oats and spring barley – are considered to be potentially available for the cultivation of grass and clover. It is assumed that mixed grass–clover cultivated as a two-year temporary ley is introduced into the cereal-based crop rotations, and that the harvested fresh grass–clover is transported to biorefineries. As an example, Fig. 3 illustrates how a typical 6-year crop rotation in Västra Götaland County changes when grass–

Figure 2. The map of counties.

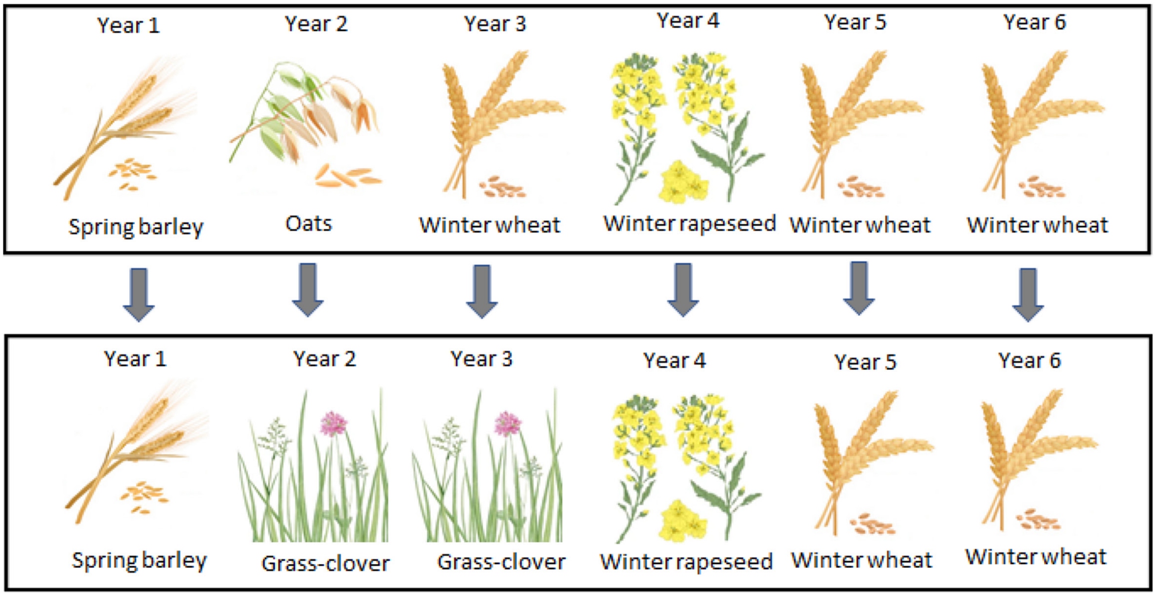


Figure 3. A typical six-year crop rotation in Västra Götaland County and change after introducing a 2 year grass–clover ley.

clover cultivation is introduced. The cereal growth areas and yields in each region are set based on the agricultural statistics in Statistics Sweden (SCB).[44] Data on grass–clover yields and increases in cereal yields after grass–clover introduction are based on the work of Tidåker *et al.*,[31] who calculated the yield increases for four regions in Sweden. The yield increases reported by Tidåker *et al.*[31] were assigned to the 17 counties based on their respective associations with production regions included in the reporting of agricultural statistics in Sweden.[44]

Agricultural costs and prices

Cultivation costs comprise area- and yield-related costs. Area-related cultivation costs are calculated based on the size of the agricultural area, and are associated with mainly preparing the soil for cultivation, e.g. the costs for the land, materials, energy, machinery and labor for seeding, fertilizers, liming, the use of pesticides and lubricants. Yield-related cultivation costs are calculated based on the volume of crop/biomass production and include costs for energy and labor and machinery costs to harvest, load and unload the crops. Data on the area- and yield-related cultivation costs for different types of crops are derived from Tidåker *et al.*[31]

We set the price levels for autumn 2020, adopted from Lantmännen[45], as the base prices for the cereals. The base price for grass–clover mixture is set at 1.25 SEK/kg DM based on the previous report.[31] As cereal prices fluctuate significantly and market conditions for grass–clover are uncertain (a commercial market associated with GB in Sweden does not yet exist), sensitivity analyses were made in which the prices were varied. Two agricultural subsidies are taken into account: the single farm payment (2122 SEK/ha); and the environmental subsidy for grass cultivation (500 SEK/ha).

Green biorefinery data

The data related to the conversion of grass–clover to GB outputs (protein feed, press cake and brown juice), protein feed-soybean meal substitution factors and methane yields from press cake and brown juice are primarily based on the experimental studies reported by Corona *et al.*[15,16] and Santamaría-Fernández *et al.*[13] (Appendix B).

Press cake and brown juice from GB are assumed to be converted into biogas that has 65% methane content, based on wet mesophilic anaerobic digestion.[46] In Sweden, soybean meal prices exhibit an upward trend, with the highest and lowest prices being 4.66 and 3.2 SEK/t, respectively, between January 2020 and April 2021. We assumed that the price of protein feed was 3.97 SEK/t, which is slightly higher than the April 2021 price of soybean meal at 3.92 SEK/t.[47] The prices for press cake and brown juice are set based on Martinsen and Andersen.[48]

Three levels of GB processing capacity are included, corresponding to annual biomass processing levels of 20 000 t DM (small), 70 000 t DM (medium), and 120 000 t DM (large). The capital investment and operational (energy, labor and maintenance) costs are assumed to decrease with higher GB capacities owing to economies of scale, and are calculated according to the paper of Martinsen and Andersen.[48] The investment costs are updated based on current land prices[44] for each county.

Biomass supply area and transportation

The cost of fresh grass–clover transport from agricultural farms to GBs exerts a strong influence on the economic performance, as the water content of fresh grass is high (typically around 80–84%).[35,48] Therefore, particular attention is paid to the transport distance and area of biomass supply in the calculations, and how the interrelationship between transport costs and raw material costs results in trade-offs. The transport costs are calculated based on Gunnarsson *et al.*,[49] who divided the area of substrate supply around a biogas plant fed with grass biomass into six zones (hereinafter referred to as $Z_m = Z_1, Z_2,\ldots, Z_6$) with transport distances of 0–5, 5–10, 10–15, 15–30, 30–50 and 50–100 km, in order to calculate the transport costs for different substrates. Gunnarsson *et al.*[49] stated that the transport cost of fresh grass–clover biomass varied between 0.028 and 0.093 SEK/kg among these zones. Adopting the approach of Gunnarsson *et al.*[49] implies modification of Eq. (3) in Appendix A as follows:

$$\text{if } k = i \Rightarrow \text{Transport cost} = \sum_{b=1}^{B}\left[\left(\sum_{i=1}^{I}\sum_{k=1}^{K} Y_{ikb} * \left(1/DM_b\right) * FT\text{Cost}_{bz_m}\right)\right] \tag{1}$$

$$\begin{aligned}\text{if } k \neq i \Rightarrow \text{Transport cost} &= \sum_{b=1}^{B}\left[\left(\sum_{i=1}^{I}\sum_{k=1}^{K} Y_{ikb} * \left(1/DM_b\right) * FT\text{Cost}_{bz_6}\right)\right.\\ &\left.+\left(\sum_{i=1}^{I}\sum_{k=1}^{K} Y_{ikb} * \left(1/DM_b\right) * \left(\text{dist}_{ik} - 100\right) * \text{VTCost}_b\right)\right]\end{aligned} \tag{2}$$

where Eqs. (1) and (2) relate to the transport cost for fresh grass–clover produced within the same county as the GB and in other counties, respectively. DM_b denotes the DM content of fresh biomass, and FTCost_{bz} denotes the fixed transportation cost of biomass supplied from zone Z_m, which has different values for each zone as stated above. It is assumed that the maximum radius for supply from the same county is 50–100 km (refers to Z_6). The inter-county (center-to-center) distance is greater than 100 km for most counties. Hence, the cost formulation for inter-county transport involves a variable transportation cost defined for each unit distance exceeding 100 km.

Results and discussion

County-wise expansion and configuration of green biorefineries: Biomass price and supply volumes

This section focuses on how varying grass–clover prices and upper boundaries for LUC trigger LUC to supply feedstock to the GB, and accordingly affect GB profitability, deployment potential, GB output and substitution potential. We explore the following aspects:

- the economically optimal investment decision for each county (whether to invest in GB in a county or not);
- county-specific GB capacity, considering profitability; and
- LUC to grass–clover cultivation in each county (within a pre-specified limit) to support the operational stability of the GB.

Figure 4 illustrates that optimal expansion (county-wise location and total number) and configuration of GB supply chains, along with the related transport and LUC patterns, are significantly affected by biomass price and LUC limits. Owing to the increased raw material cost and low GB profitability at high grass prices, there is a tendency to construct fewer biorefineries, and for lower grass prices the opposite tendency holds true, confirming that the model replicates the expected real-world dynamics. For the scenario with base grass price and LUC limited to 10%, the model suggests constructing only two large biorefineries in two counties that have large, continuous cropland areas cultivated with cereals. LUC occurs only in these two counties (with 7.6 and 8.6% changes in winter wheat and oat acreages, respectively), and inter-county transport does not take place. A significant increase in the number of biorefineries is observed when the grass price is 20% lower than the base price. In this case, two large, three medium, and eight small biorefineries are constructed (Fig. 4(a)). In 15 out of the 17 counties, LUC is close to the upper limit (10%) and biomass transport between neighboring counties occurs, along with local transport (Fig. 4(b)). As shown in Fig. 4, the transportation pattern is shaped by the grass price rather than the extent of LUC, i.e. inter-county biomass transport is feasible at low grass prices, regardless of the LUC limit.

When higher shares of current cereal acreage are allowed to be converted to mixed grass–clover leys, the number of biorefineries increases for all grass price-levels. In this case,

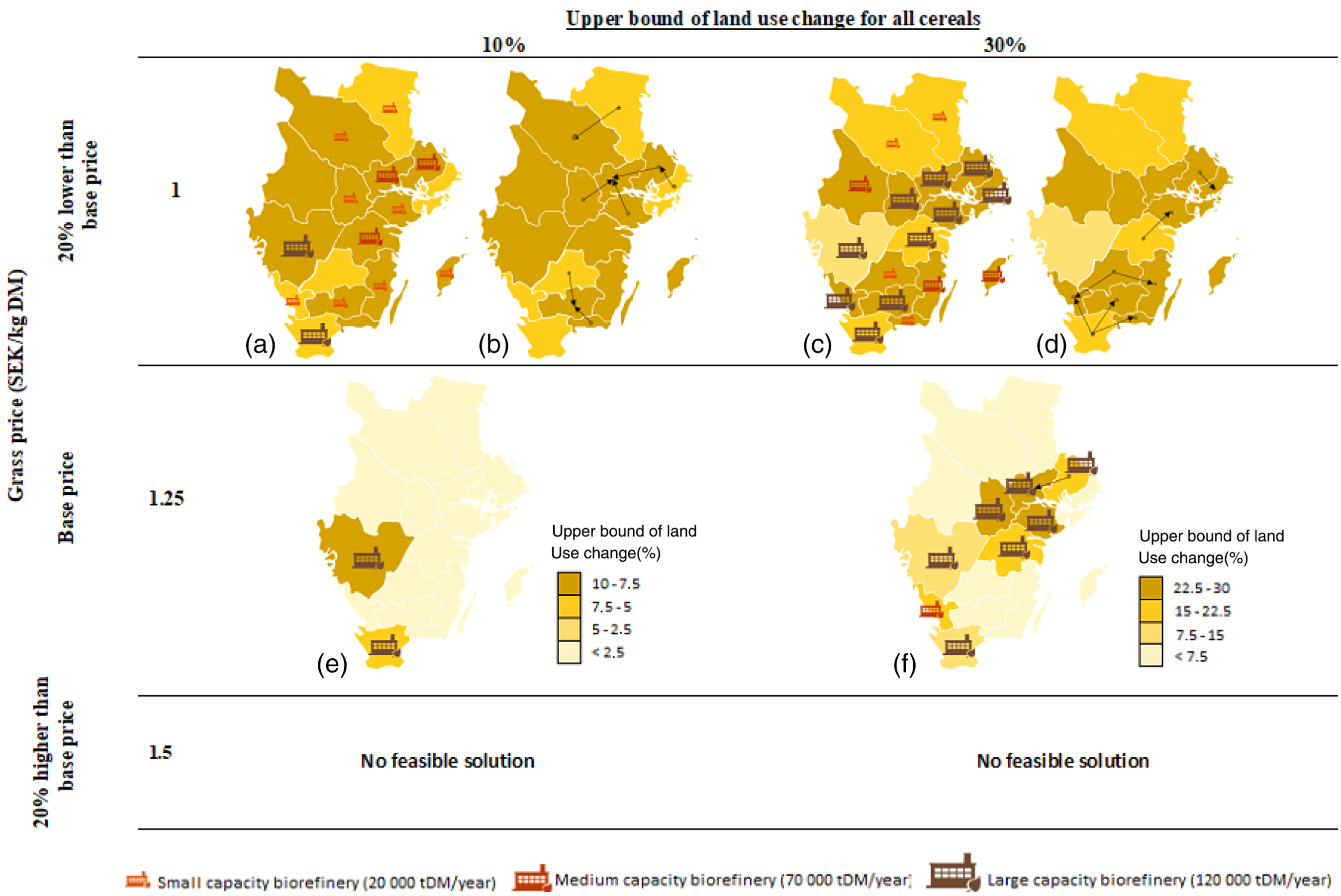


Figure 4. The optimized county-wise expansion and configuration of green biorefineries, with related transport and land use change (LUC) patterns. Three grass–clover prices (base, 20% higher and 20% lower) and two upper bounds for LUC (10 and 30%) are considered. The radius of the preferred (or available) biomass supply zone is assumed to be 15–30 km in each region, which refers to the fourth zone (Z_4), and the associated transport cost is 50 SEK/t fresh grass–clover.[49]

large biorefineries outweigh small and medium biorefineries in the optimal configuration, which implies that large biorefineries can capitalize on more extensive biomass procurement without relying on increased inter-county transport (Fig. 4(c)). At higher grass prices, the raw material cost increases to the extent that the additional transport cost cannot be counterbalanced by benefits of scale and GB profitability decreases considerably. In this case, LUC takes place only in the counties where biorefineries are built (Fig. 4(f)).

When the grass–clover price increases by 20%, only short-distance (3–4 km) local transport takes place and only one large GB is constructed (Västra Götaland) if the LUC limit is set to 10%. The transport cost and distance remain the same in the case of a higher LUC limit (30%), although three large GBs are then built in three counties (Uppsala, Östergötlands and Västra Götaland, with LUC at 21, 20 and 8.6% of the cereal areas, respectively).

The selection of counties for GB deployment reflects a number of factors, including biomass cultivation potential, which depends on the size of the current agricultural area assigned to cereal cultivation and the yield levels of grass–clover, investment costs (which depend on land prices) and transport costs. Regardless of the biomass price and the upper limit set for LUC, the preferred counties are those with the largest areas under cereal production and, thus, with the largest potential for grass–clover cultivation. The county with the highest capital expenditure cost (owing to high land prices) remains attractive for GB deployment because of its high potential for grass–clover cultivation, in terms of both the size of the area and yield level. Owing to the availability of large areas for cereal cultivation, regions such as Uppsala and Östergötlands are preferred as GB locations in most of the settings (Fig. 4(a), (c), (f)). Västmanlands is chosen for a centralized GB owing to its central position (in comparison with other regions that have high potential for

  |

grass cultivation), which leads to lower inter-regional transport costs (Fig. 4(b)). Blekinge is an example of a region with low GB deployment potential owing to limited cereal cultivation and high land costs. GB localization in Blekinge only happens in the case with the lowest grass price and highest upper boundary for LUC. Deployment in a region also depends on the conditions in surrounding regions. This is exemplified by the deployment of a large GB in the Kronoberg region, which has a low potential for grass cultivation but has low land prices and proximity to regions with high potentials for grass cultivation (Fig. 4(c)).

Green biorefinery output and substitution potential

Table 1 indicates the GB outputs, as well as the protein balances (protein loss owing to displaced cereal cultivation relative to new protein output from GBs), with the different county-wise expansion and configuration settings, as illustrated in Fig. 4.

The net protein output after LUC is always positive, i.e. the total protein output *via* grass–clover harvest is larger than the protein loss owing to the displacement of cereal cultivation (in some cases, the protein output more than doubles; see Table 1). The potential for substitution of imported soybean meal can be significant; the configuration with the highest number of biorefineries (Fig. 4(c)) has a protein feed production that is about 1.5 times the current level of soybean meal imports to Sweden (European Commission, 2021), indicating a significant protein feed export potential. However, the variation in protein feed production is large, corresponding to 13–154% of soybean meal imports to Sweden.

The GB deployment would also present an opportunity to increase domestic biomethane production and reduce Sweden's dependency on imported natural gas. In 2020, almost 764.5 million cubic meter (MCM) of natural gas were imported into Sweden. The calculated biomethane production from GB outputs (8.31–99.7 MCM; see Table 1) corresponds to 1–13% of the total natural gas import. The Swedish gas network is connected to the European gas network, has 14 injection sites, and currently covers the south-western part of Sweden, including the counties of Västra Götaland and Skåne, which are identified here as having significant GB deployment potential. A planned regional gas network[50] also extends into counties with significant GB deployment potential (Stockholm and Örebro).

Table 1. Green biorefinery (GB) output potential and protein balance*

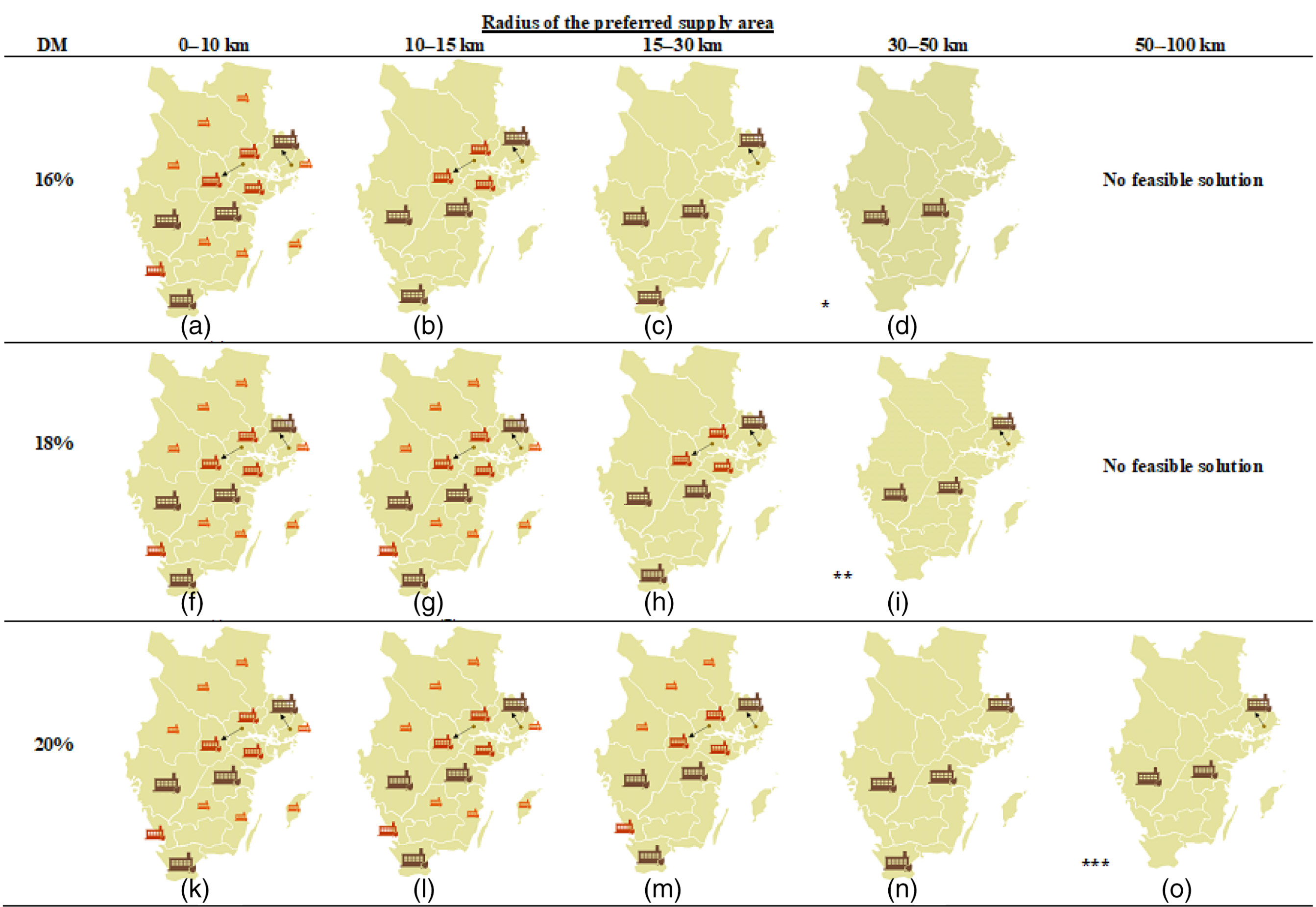
	Grass price (SEK/t DM)					
	1		1.25		1.5	
Upper bound of land use change	10%	30%	10%	30%	10%	30%
Biorefinery Output						
Total protein concentrate (t/year)	111 522	267 990	44 640	164 085	22 320	66 960
Soybean meal substitution potential (t/year)	107 061	257 271	42 854	157 522	21 427	64 282
Imported soy meal substitution (%)	64	154	26	94	13	38
Total press cake (t/year)	400 519	962 459	160 320	589 294	80 160	240 480
Total brown juice (t/year)	87 539	210 358	35 040	128 798	17 520	52 560
Total biomethane potential (MCM/year)*	41.5	99.7	16.6	61.1	8.31	24.9
Protein Balance						
Total protein loss (t)	57 881	138 767	25 283	90 262	12 220	39 405
Total harvested protein from changed area (t)	129 509	311 214	51 840	190 550	25 920	77 760
Net protein harvest (t)	71 628	172 447	26 557	100 288	13 700	38 355
Total harvested protein from per ha of changed area (t/ha)	1.72	1.72	1.79	1.68	1.70	1.64
Protein output from biorefinery per ha of changed area (t/ha)	1.72	1.72	1.79	1.69	1.70	1.64

Abbreviation: DM, dry matter; MCM, million cubic meter.
*The radius of the preferred/available supply zone is assumed to be 15–30 km in each county, for the base price and the 20% lower grass price. As local transport for 15–30 km cannot be compensated if the grass price is 20% higher than the base price, the results for GB output in the last two columns of the table are presented for local transport of 3–4 km.

County-wise expansion and configuration of green biorefineries: Biomass supply area

We conducted analyses of the economically reasonable distances to biomass supply area for introducing grass–clover leys that would feed the GBs. These were based on the variations in DM content of the grass–clover determining the extent to which the distance to the supply area influences the transportation cost. Figure 5 illustrates how the radius of the preferred/available supply area and the DM content of the grass influence the levels of profitability and GB deployment patterns and configurations in the different counties.

It is clear that GB deployment is more widespread when the distance-wise probability of reaching suitable agricultural farms to introduce grasslands, and/or DM content of the biomass, increases. For the lowest transport cost scenario, assuming all the biomass supply is available within 10 km, the model suggests a multi-regional deployment that favors small-scale biorefineries, irrespective of the DM content of the biomass (Fig. 5(a), (f), (k)). The lower the DM content of the biomass is, the higher the tendency to construct fewer biorefineries (Fig. 5(a–d)), even allowing for a slight increase in transport distance. For example, if the maximum distance to a supply of biomass of 16% DM content increases to 15 km, the economically viable deployment comprises fewer biorefineries, while medium- and large-scale GBs are preferred over small-scale GBs. However, in the case of transporting biomass of higher DM content, the model suggests relatively wider expansion of GBs, even with higher



* Atmost 36 km local transport can be tolerated
** Atmost 45 km local transport can be tolerated
*** Atmost 55 km local transport can be tolerated

Figure 5. The optimized expansion and configuration of green biorefineries for different values of the dry matter (DM) content and radius for the preferred/available supply area. The DM content of biomass resources varies in the range of 16–20% (Corona *et al*, 2018). The grass price and LUC limit are set to their respective base values (1.25 SEK/kg DM and 20%). As the results for Z_1 (0–5 km) are the same for each value of DM content as those for Z_2, they are combined and indicated as 0–10 km. The arrows represent the transport of biomass between counties.

transport distances. A total of 11 biorefineries with varying capacities can be operated economically across counties if biomass resources of at least 20% DM content can be supplied within a 15–30 km radius (Fig. 5(m)). When the radius increases to 30–50 km, the number of biorefineries decreases significantly.

For lower DM contents (16 and 18%), even a distance of 50 km to the biomass suppliers cannot be tolerated. The distance to the supply area has to be at most 36 km (with transport cost of 55 SEK/t) to transport biomass of 16% DM content to the GB. For transport distances longer than 36 km, the increase in transport cost cannot be counterbalanced, which means that the GB investment is not economically viable. The maximum distance to the biomass supply increases to 45 km (with transport cost of 62 SEK/t) when the DM content is up to 18%. The model opts for large-capacity biorefineries in the case of a wider supply area, i.e., *Z4* (15–30 km) for the transport of biomass with DM content <18%, and *Z5* (30–50 km) regardless of DM content. Thus, the higher output levels and higher income levels from biorefineries that result from economies of scale counterbalance the higher costs incurred by transport over longer distances, to the extent that the GB sustains profitability. Biomass supply from *Z6* (50–100 km transport distance) is not feasible when the DM content of the biomass is <20%, as the model cannot produce a feasible solution. Nonetheless, a maximum transport distance of 55 km can be tolerated (with cost of 69 SEK/t) if the DM content of the biomass is at least 20%.

By increasing the radius of the preferred/available supply area, a point is reached after which the model is unable to produce a solution with at least one GB, owing to excessive transport costs. This point can be considered as the maximum radius of the supply area that is economically acceptable for GBs to process fresh biomass and the changes that occur in the price of biomass related to the trade-off between raw material cost and transport cost in the profitability function. The profitability-lowering effect of the transport cost owing to a wider supply area can be compensated by a decrease in the raw material cost. When the biomass price is high, the GB tends to procure less feedstock, so as to avoid excess raw material cost, or chooses a supplier that is closer in distance, so as to keep the transport cost lower and counterbalance the high raw material cost. Therefore, to ensure maximum profitability, the model constitutes a balance between raw material cost and transport cost based on the grass price, level of supply and transport distance. Figure 6 illustrates how GB profitability changes with regards to grass price for six supply zones. Figure 7 indicates the grass price that can be tolerated for each supply zone, the so-called 'break-even point' of the grass price for each supply zone.

From a different perspective, Figs 6 and 7 indicate the maximum radius of the supply area that is economically reasonable for GB. Figs 6 and 7 demonstrate that if the biomass supply requires long-distance transport (50–100 km), i.e. the agricultural farms that are suitable for the introduction of grassland for GB are available within *Z6*, the GB remains profitable only for grass prices up to 1.17 SEK/kg DM. When the supply radius is decreased to 30–50 km, the purchasing price of grass–clover can be increased to 1.22 SEK/kg DM. This can also be interpreted as meaning that the maximum transport distance for grass–clover prices in the range of 1.17–1.22 SEK/kg DM is 50 km. Likewise, if a sufficient amount of grass–clover can be procured from the area within

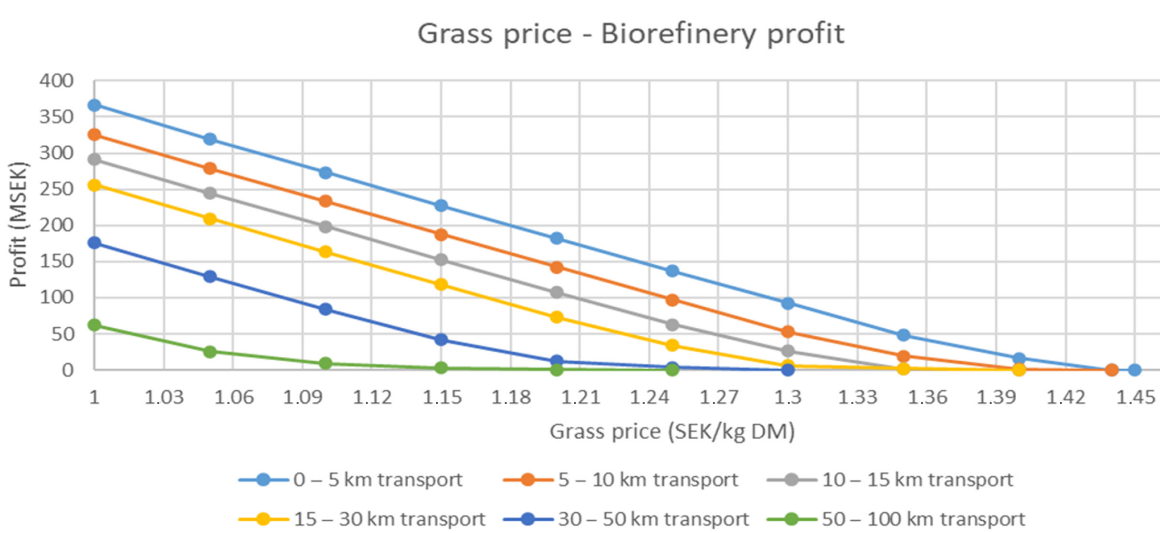


Figure 6. Grass price vs. GB profit for different supply zones (LUC is limited to 20%).

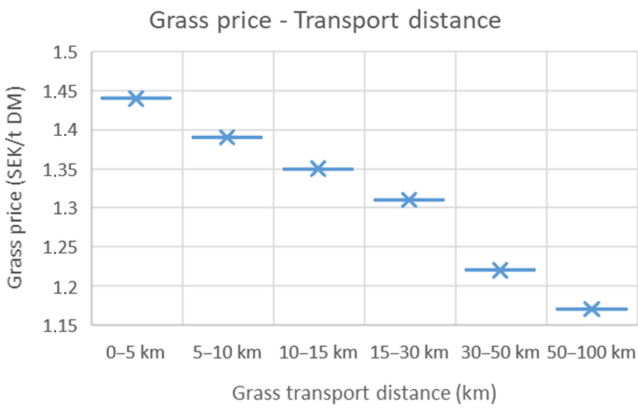


Figure 7. Maximum grass price that can be tolerated for each supply zone.

a 15–30 km radius, then a grass price of up to 1.31 SEK/kg DM can be offered to suppliers to ensure the profitability of GB. The price goes up to 1.35 SEK/kg DM and 1.39 SEK/kg DM when the suppliers are at distances of 10–15 and 5–10 km from the GB, respectively. Finally, if the grass price is as high as 1.44 SEK/kg DM, the suppliers located within 0–5 km of the GB should be reached. In other words, the maximum supply distance should be 5 km if the grass price is in the range of 1.39–1.44 SEK/kg DM, for the model to suggest the construction of at least one GB.

System dynamics and economic interactions based on grass biomass and cereal prices

Profitability can be improved at the farm level when temporary grasslands are introduced into the annual crop rotations through a combination of increased harvests, reduced costs for inputs and through crops with lower profitability in the crop rotation being replaced with grass.[31] However, wide-scale deployment of GBs requires functioning supply chains that impose interactions and tradeoffs between the economical situations of agricultural farms and GBs. The market price of biomass has a strong influence on both farm and GB profits, albeit in opposite directions. Biomass demand at the GB level increases with decreasing biomass prices and – conversely – farmers' interest in shifting from cereal to grass cultivation increases with increasing biomass prices. Thus, there will be a break-even biomass price level at which the farmers' and GB profit margins are balanced. Here, the system dynamics and interactions are analyzed and discussed based on three critical levels of biomass price: (1) the break-even price for the farmer (BEP-F); (2) the price ensuring maximum profit for the farmer (PMP-F); and (3) the break-even price for the GB (BEP-B). Figures 8 and 9 show how the LUC patterns and farmers' and GB profit levels change when the biomass prices change, for three different cereal prices (base, 20% lower, 20% higher) and two different limits on LUC.

BEP-F refers to the biomass price at which the profit made by the farm begins to exceed that of the current situation with only cereal cultivation, which can be considered as the minimum price that the farmer would like to be offered to avoid a decrease in profit. For grass prices lower than BEP-F, LUC induces unfavorable effects on the economics of the farm. As a consequence, farmers may be discouraged from introducing grass into the crop rotations. Figure 8 delineates that for the base scenario of cereal prices, BEP-F is 0.97 SEK/kg DM grass–clover. In a case in which cereal prices increase by 20%, the farmer needs an 18.5% higher grass–clover price (1.15 SEK/kg DM) to compensate for the economic loss induced by changing some cereal cultivation into grass–clover, whereas a grass–clover price of 0.76 SEK/kg DM (21% less than that of the base scenario) would be sufficient in the case of a 20% decline in cereal prices (Fig. 8(a–d)).

Farm profit reaches a maximum at PMP-F (depicted by the yellow dots in Figs 8 and 9), which refers to the price for biomass that the farmer probably wants to be offered. The PMP-F is 1.22 SEK/kg DM regardless of changes in cereal price settings (Fig. 8(a–c)). Prices that exceed the PMP-F lead to a rapid decrease in farm profitability because, as a consequence of the too-high feedstock price, the GB tends to buy less grass to maintain profitability. Consequently, LUC decreases, in detriment to the farm economy. Figure 9 clearly indicates that the share of current cultivation to be converted to grass cultivation drops rapidly just after the PMP-F for each cereal. The orange lines in Fig. 8(a–d) indicate that an increase in biomass price implies a downward trend in GB profitability, which causes a reduction in GB deployment. Thus, LUC is less triggered with increasing biomass price. On the other hand, up to the PMP-F, the effect of an increase in biomass price dominates the effect of a decrease in LUC on farm profits. Farm profit (represented by the blue line in Fig. 8) shows an upward trend to the PMP-F, after which the decrease in LUC, correspondingly to the decreased amount of biomass purchased by the GB, dominates the biomass price increase and farmer profits start to decline.

Figure 8(c) shows that a LUC pattern that makes agricultural production profitable cannot be proposed for any grass–clover price, given a scenario in which cereal prices are 20% lower than the base price and LUC is limited to 20%. However, increasing the limitation imposed on LUC to 30% eventuates positive farm profits in those cases in which the grass–clover price is in the range of 1.1–1.24 SEK/kg DM, with the highest profit being obtained at a price of 1.2 SEK/kg

Figure 8. Change in farmer and GB profits with varying biomass prices [the break-even price for the farmer (BEP-F), the price ensuring maximum profit for the farmer (PMP-F) and the break-even price for the GB (BEP-B) are shown with red, yellow and dark-blue dots, respectively].

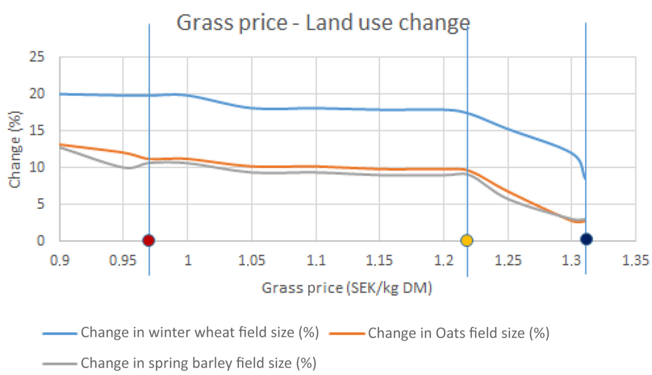


Figure 9. Changes in LUC pattern with varying biomass prices (BEP-F, PMP-F and BEP-B are shown with red, yellow and dark-blue dots, respectively).

DM (Fig. 8(d)). It also evident that the PMP-F is not affected by the cereal price and only slightly by the extent of LUC.

BEP-B represents the break-even point for the GB, which is the maximum biomass price that the GB can offer to the farmer above which the GB investment would not be reasonable. Figure 8(a–d) shows that the BEP-B is 1.31 SEK/kg DM for all settings and that the levels of GB profitability (both the trend and values at different grass prices) do not change according to variations in the cereal prices. This is expected because the objective function is formulated around the maximization of GB profitability, so cereal prices do not have a direct impact from the modeling perspective.

The introduction of a grass–clover ley into annual crop rotations reduces the area used for cultivation of annual crops. However, the displacement effect, i.e. expansion and/or intensification of annual crop production elsewhere, is moderated in several ways and in some instances the need for annual crop production elsewhere can even be reduced[51]. First, improved soil quality owing to soil organic carbon (SOC) increases, enhanced disease control and improved supply of nitrogen and water can lead to a 3–20% increase in yields of annual crops following ley in modified rotations.[31,52] Second, when the biomass is used in GBs to produce protein feed that replaces soybean meal there will be a reduced need for soy cultivation.[36] Given average soybean yields at 2.8 t ha^{-1} in Europe (IDH and IUCN NL, 2019) and 2.8–3.5 t ha^{-1} in Brazil (SIDRA, 2020), and assuming that 80% of the soybean is used for soymeal, each hectare in Sweden that is used for ley instead of annual crops reduces the need for soybean cultivation by approx. 0,8 ha in the EU or 0,64–0.8 ha in Brazil. Finally, displacement effects can be mitigated through targeting abandoned or low-productivity cropland where the yields are most negatively affected by historic land use and accumulated SOC losses. Indicative of the potential for this strategy, Naess *et al.*[53] identified 50 Mha of abandoned cropland outside biodiversity hotspots from 1992 to 2015 out of which 20% was found in Europe.

Conclusions

The present study indicates a strong potential for GBs in Sweden. It is estimated that protein feed and biomethane production from the expansion of GBs can be up to 154% of soybean meal import and 13% of the natural gas import to Sweden, respectively. However, successful deployment will require that farmers within a region perceive incentives for making significant changes to their land use. These incentives could include payments for carbon removal in agricultural practice, which is a topic that is attracting interest from both the private sector and EU policymakers, as well as benefits associated with changes in land use, e.g. improved soil health, reduced nutrient leaching, lower use of pesticides and increased crop diversity. New opportunities for payments may incentivize farmers to engage in a transition towards increased grass–clover cultivation in cereal-dominated agricultural landscapes.

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References

1. Cherubini F, The biorefinery concept: using biomass instead of oil for producing energy and chemicals. *Energ Conver Manage* **51**(7):1412–1421 (2010).
2. Hess JR, Lamers P, Stichnothe H, Beermann M and Jungmeier G, Bioeconomy strategies, in *Developing the Global Bioeconomy*. Academic Press, Cambridge, MA, pp. 1–9 (2016).
3. Meyer R, Bioeconomy strategies: contexts, visions, guiding implementation principles and resulting debates. *Sustainability* **9**(6):1031 (2017).
4. Kamm B, Gruber PR and Kamm M eds, *Biorefineries-Industrial Processes and Products (No. 1)*. Wiley-VCH, Weinheim (2006).
5. Kamm B and Kamm M, Biorefineries–multi product processes. *Adv Biochem Eng Biotechnol* **105**:175–204 (2007).
6. Hermansen JE, Jørgensen U, Lærke PE, Manevski K, Boelt B, Jensen SK and Fog E, Green biomass-protein production through bio-refining. DCA-Nationalt Center for Fødevarer og Jordbrug. (2017).
7. Santamaría-Fernández M, Schneider R, Lübeck M and Venus J, Combining the production of L-lactic acid with the production of feed protein concentrates from alfalfa. *J Biotechnol* **323**:180–188 (2020).
8. Stødkilde L, Ambye-Jensen M and Krogh Jensen S, Biorefined grass-clover protein composition and effect on organic broiler performance and meat fatty acid profile. *J Anim Physiol Anim Nutr* **104**(6):1757–1767 (2020).
9. Mandl MG, Status of green biorefining in Europe. *Biofuel Bioprod Biorefin* **4**(3):268–274 (2010).
10. Xiu S and Shahbazi A, Development of green biorefinery for biomass utilization: a review. *Tr Ren Energy* **1**(1):4–15 (2015).
11. Kamm B, Hille C, Schönicke P and Dautzenberg G, Green biorefinery demonstration plant in Havelland (Germany). *Biofuel Bioprod Biorefin* **4**(3):253–262 (2010).
12. Papendiek F and Venus J, Cultivation and fractionation of leguminous biomass for lactic acid production. *Chem Biochem Eng Q* **28**(3):375–382 (2014).
13. Santamaría-Fernández M, Molinuevo-Salces B, Lübeck M and Uellendahl H, Biogas potential of green biomass after protein extraction in an organic biorefinery concept for feed, fuel and fertilizer production. *Renew Energy* **129**:769–775 (2018).
14. Santamaría-Fernández M and Lübeck M, Production of leaf protein concentrates in green biorefineries as alternative feed for monogastric animals. *Anim Feed Sci Technol* **268**:114605 (2020).
15. Corona A, Parajuli R, Ambye-Jensen M, Hauschild MZ and Birkved M, Environmental screening of potential biomass for green biorefinery conversion. *J Clean Prod* **189**:344–357 (2018a).
16. Corona A, Ambye-Jensen M, Vega GC, Hauschild MZ and Birkved M, Techno-environmental assessment of the green biorefinery concept: combining process simulation and life cycle assessment at an early design stage. *Sci Total Environ* **635**:100–111 (2018b).
17. O'Keeffe S, Schulte RPO, Sanders JPM and Struik PC, I. Technical assessment for first generation green biorefinery (GBR) using mass and energy balances: scenarios for an Irish GBR blueprint. *Biomass Bioenergy* **35**(11):4712–4723 (2011a).
18. O'Keeffe S, Schulte RPO, Lalor STJ, O'Kiely P and Struik PC, Green biorefinery (GBR) scenarios for a two-cut silage system: investigating the impacts of sward botanical composition, N fertilisation rate and biomass availability on GBR profitability and price offered to farmers. *Biomass Bioenergy* **35**(11):4699–4711 (2011b).
19. Kromus S, Wachter B, Koschuh W, Mandl M, Krotscheck C and Narodoslawsky M, The green biorefinery Austria-development of an integrated system for green biomass utilization. *Chem Biochem Eng Q* **18**(1):8–12 (2004).
20. Hoeffner K, Beylich A, Chabbi A, Cluzeau D, Dascalu D, Graefe U *et al*., Legacy effects of temporary grassland in annual crop rotation on soil ecosystem services. *Sci Total Environ* **780**:146140 (2021a).
21. Hoeffner K, Hotte H, Cluzeau D, Charrier X, Gastal F and Pérès G, Effects of temporary grassland introduction into annual crop rotations and nitrogen fertilisation on earthworm communities and forage production. *Appl Soil Ecol* **162**:103893 (2021b).
22. An H, Wu X, Zhang Y and Tang Z, Effects of land-use change on soil inorganic carbon: a meta-analysis. *Geoderma* **353**:273–282 (2019).

23. Kautz T, Stumm C, Kösters R and Köpke U, Effects of perennial fodder crops on soil structure in agricultural headlands. *J Plant Nutr Soil Sci* **173**(4):490–501 (2010).
24. Mukumbuta I, Shimizu M and Hatano R, Short-term land-use change from grassland to cornfield increases soil organic carbon and reduces total soil respiration. *Soil Tillage Res* **186**:1–10 (2019).
25. Panettieri M, Courtier-Murias D, Rumpel C, Dignac MF, Almendros G and Chabbi A, Land-use perturbations in ley grassland decouple the degradation of ancient soil organic matter from the storage of newly derived carbon inputs. *Soil* **6**(2):435–451 (2020).
26. Santos RS, Oliveira FC, Ferreira GW, Ferreira MA, Araujo EF and Silva IR, Carbon and nitrogen dynamics in soil organic matter fractions following eucalypt afforestation in southern Brazilian grasslands (pampas). *Agr Ecosyst Environ* **301**:106979 (2020).
27. Reay DS, Davidson EA, Smith KA, Smith P, Melillo JM, Dentener F *et al*., Global agriculture and nitrous oxide emissions. *Nat Clim Change* **2**(6):410–416 (2012).
28. Krol DJ, Jones MB, Williams M, Choncubhair ON and Lanigan GJ, The effect of land use change from grassland to bioenergy crops Miscanthus and reed canary grass on nitrous oxide emissions. *Biomass Bioenergy* **120**:396–403 (2019).
29. Li S, Xu J, Tang S, Zhan Q, Gao Q, Ren L *et al*., A meta-analysis of carbon, nitrogen and phosphorus change in response to conversion of grassland to agricultural land. *Geoderma* **363**:114149 (2020).
30. Obermeier MM, Gnädinger F, Raj ACD, Obermeier WA, Schmid CA, Balàzs H *et al*., Under temperate climate, the conversion of grassland to arable land affects soil nutrient stocks and bacteria in a short term. *Sci Total Environ* **703**:135494 (2020).
31. Tidåker, P., Rosenqvist, H., Gunnarsson, C., Bergkvist, G. 2016. Räkna med vall. Hur påverkas ekonomi och miljö när vall införs i spannmålsdominerade växtföljder? Rapport 445, Lantbruk & Industri. JTI – Institutet för jordbruks- och miljöteknik, Uppsala.
32. Cong RG and Termansen M, A bio-economic analysis of a sustainable agricultural transition using green biorefinery. *Sci Total Environ* **571**:153–163 (2016).
33. Parajuli R, Dalgaard T and Birkved M, Can farmers mitigate environmental impacts through combined production of food, fuel and feed? A consequential life cycle assessment of integrated mixed crop-livestock system with a green biorefinery. *Sci Total Environ* **619**:127–143 (2018).
34. Papendiek F, Tartiu VE, Morone P, Venus J and Hönig A, Assessing the economic profitability of fodder legume production for green biorefineries–a cost-benefit analysis to evaluate farmers profitability. *J Clean Prod* **112**:3643–3656 (2016).
35. O'Keeffe S, Schulte RP, Sanders JP and Struik PC, II. Economic assessment for first generation green biorefinery (GBR): scenarios for an Irish GBR blueprint. *Biomass Bioenergy* **41**:1–13 (2012).
36. Njakou Djomo S, Knudsen MT, Martinsen L, Andersen MS, Ambye-Jensen M, Møller HB *et al*., Green proteins: an energy-efficient solution for increased self-sufficiency in protein in Europe. *Biofuels Bioprod Biorefin* **14**(3):605–619 (2020).
37. Kamm B, Schönicke P and Kamm M, Biorefining of green biomass–technical and energetic considerations. *Clean–Soil, Air Water* **37**(1):27–30 (2009).
38. Leiß S, Venus J and Kamm B, Fermentative production of L-lysine-L-lactate with fractionated press juices from the green biorefinery. *Chem Eng Technol* **33**(12):2102–2105 (2010).
39. Molinuevo-Salces B, Larsen SU, Ahring BK and Uellendahl H, Biogas production from catch crops: increased yield by combined harvest of catch crops and straw and preservation by ensiling. *Biomass Bioenergy* **79**:3–11 (2015).
40. Parajuli R, Kristensen IS, Knudsen MT, Mogensen L, Corona A, Birkved M *et al*., Environmental life cycle assessments of producing maize, grass-clover, ryegrass and winter wheat straw for biorefinery. *J Clean Prod* **142**:3859–3871 (2017).
41. Richter, F., Fricke, T., & Wachendorf, M. (2010). Influence of cutting date and pre-conditioning on the energy production from grassland through the integrated generation of solid fuel and biogas from biomass (IFBB). Grassland in a changing world, 172.
42. Kamp A, Ambye-Jensen M and Østergård H, Modelling matter and energy flows of local, refined grass-clover protein feed as alternative to imported soy meal. *Ecol Model* **410**:108738 (2019).
43. Stødkilde L, Damborg VK, Jørgensen H, Lærke HN and Jensen SK, White clover fractions as protein source for monogastrics: dry matter digestibility and protein digestibility-corrected amino acid scores. *J Sci Food Agric* **98**(7):2557–2563 (2018).
44. Statistics Sweden, 2020, General Agricultural Statistics, http://www.scb.se/jo1901-en
45. Lantmännen, Slutpriser skörd, 2020, https://www.lantmannenlantbrukmaskin.se/siteassets/om-oss/press-och-nyheter/nyhetsarkiv-2020/prisjamforelse-slutpriser-2020.pdf (2020).
46. Hamelin L, Naroznova I and Wenzel H, Environmental consequences of different carbon alternatives for increased manure-based biogas. *Appl Energy* **114**:774–782 (2014).
47. World Bank, 2021, Commodity prices, https://www.worldbank.org/en/research/commodity-markets
48. Martinsen, L., Andersen, M.S. 2020. Environmental and socio-economic analysis of integrated grass biorefinery scenarios. Aarhus University, DCE – Danish Centre for Environment and Energy, 91 pp. Scientific Report No. 383, p. 91, Scientific Report No. 383.
49. Gunnarsson, C., Ahlström, A., Ljungberg, D., Prade, T., Rosenqvist, H., & Svensson, S. E. (2017). Fresh and siled crops-a new way to organize year-round substrate supply for a biogas plant: Report from a project within the collaborative research program renewable transportation fuels and systems.
50. Swedish Gas Association. (2018). Proposal for National Biogas Strategy 2.0. Swedish Gas Association: Energigas Sverige, Stockholm.
51. Englund O, Mola-Yudego B, Börjesson P, Cederberg C Dimitriou I, Scarlat N and Berndes, G, Large-scale deployment of grass in crop rotations as a multifunctional climate mitigation strategy. *GCB Bioenergy* (2022). https://doi.org/10.1111/gcbb.13015.
52. Marini L, St-Martin A, Vico G, Baldoni G, Berti A, Blecharczyk A *et al*., Crop rotations sustain cereal yields under a changing climate. *Environ Res Lett* **15**(12):124011 (2020).
53. Næss JS, Cavalett O and Cherubini F, The land–energy–water nexus of global bioenergy potentials from abandoned cropland. *Nat Sustain* **4**(6):525–536 (2021).

Sebnem Yilmaz Balaman's

research centers around developing modelling and optimization methodologies to facilitate decision-making in the deployment–sustainability–policy interface of biomass-based production chains. The focus is placed on environmental and economic aspects of strategic and operational planning problems in biomass-based energy and materials production.

Göran Berndes'

research integrates land use, industrial and energy systems at scales ranging from local case studies to the global context. He is particularly interested in the sustainability effects of land use and biomass production for food, energy and materials. Bioenergy's role in climate change mitigation is a special focus.

Christel Cederberg

Chalmers University of Technology, conducts research about sustainable biomass production with a focus on agriculture and food systems. She has long experience of environmental sustainability assessments of agriculture and how assessment methods can be integrated.

Håkan Rosenqvist

is Associate Professor and an independent researcher in collaboration with Chalmers and SLU. Håkan is an economist with a focus on agriculture. He has worked a lot with economics in energy crops and lay. Among other things, he has studied crop rotation effects with lay and studied the economic aspects of biorefineries.