Smart integration of food and bioenergy production delivers on multiple ecosystem services

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Abstract
Agriculture is expected to feed an increasing global population while at the same time meeting demands for renewable energy and the supply of ecosystem services such as provision of nutrient cycling and carbon sequestration. However, the current structure of the agricultural system works against meeting these expectations. The spatial separation of crop and livestock farms has created negative environmental consequences, and bioenergy production has created a trade-off between food and energy production. In this paper, we explore the opportunities for ecological intensification at a regional scale made possible by combining food and energy production. We built three scenarios representing farming systems including biogas production using grass biomass and manure. These scenarios included the following: (a) The current system with energy production (CSE) from non-edible agricultural biomasses (CSE). (b) Agroecological symbiosis (AES) identical to CSE except with 20% of the arable cropping area converted to clover-grasses for use in biogas production. (c) Agroecological symbiosis with livestock (AES-LST) where the available grass biomass (20% as in the AES) is fed to livestock and manure then used as a feedstock in biogas production. In each scenario, nutrients were circulated back to crops in the form of digestate. The supply of soil functions (primary production for food and energy, provision of nutrient cycling, and climate mitigation) and impacts on water quality through nutrient losses in these three scenarios were then compared to the current system. Integrating biogas production into food production resulted in an increased supply of nutrient recycling, reduced nutrient losses, and increased carbon inputs to the soils indicating enhanced climate mitigation. Food production was either not affected (CSE), increased (AES-LST), or decreased (AES), and biogas was produced in substantial quantities in each scenario. Our study demonstrated potential synergies in integrating food and energy production without compromising other ecosystem services in each scenario.

Keywords
circularity, food-feed-fuel competition, renewable energy, soil functions, sustainable intensification
1 | INTRODUCTION

Agriculture is facing severe sustainability challenges. These challenges include feeding an increasing global population while also meeting increasing demand for renewable energy to replace fossil fuels without compromising the supply of ecosystem services (Godfray, ; Harvey & Pilgrim, 2011; Sutton et al., 2013). These challenges have been recognized in the Sustainable Development Goals set by the United Nations (2015) and by the European Union, where strengthening of the environmental ambition plays a central role in the current reform of the common agricultural policy (European Commission, 2018). Goals for renewable energy are also ambitious as the target for renewable energy in Europe has been set to 32% for 2030 (European Union, 2018).

In addition, agriculture is responding to an increased demand for food from a growing world population. This has led to intensification in agriculture. Food production has increased, but this intensification has resulted in several negative environmental consequences. These include, for instance, imbalanced nutrient flows, carbon losses from the soil, and reduced biodiversity (Heikkinen et al., 2013; Maillard & Angers, 2014; Steffen et al., 2015; Sutton et al., 2013; Uusitalo et al., 2007).

The intensification and specialization of farms have led to a spatial segregation of livestock and arable farms. In terms of nutrient cycling, the challenge created by the spatial separation of crop and livestock production is that in large parts of the developed world, manure is rarely brought back to the crop farms because of the long distances it would have to be transported. As a result of feed imports, nutrients are concentrated over time on livestock farms and in regions with high livestock densities (Koppelmäki et al., 2021; Parviainen & Helenius, 2020; Schulte et al., 2019; Uusitalo et al., 2007).

At the same time, crop farms relying on mineral fertilizers generally perform well in terms of nutrient use efficiency. However, nutrient use efficiency is often assessed at farm, regional or global scales without taking into account the whole production chain in livestock production (Gerber et al., 2014; Uwizeye et al., 2016). Quantifying inputs and outputs does not take into account an existing “black-box” effect meaning that the environmental impacts emerging in the cattle farms where feed imported from the crop farms is used are often not allocated to those crop farms in the calculations. Also, when the quantification is done at an aggregated level, it fails to differentiate between mined and recycled nutrients (Uwizeye et al., 2016).

The increasing demand for bioenergy has further exacerbated the negative ecological and social consequences of agricultural intensification. The problems related to first-generation biofuels have been widely recognized (FAO, 2008; Searchinger et al., 2008). The main concern has been that these biofuels directly compete for land with the food production and affect food prices. Another concern involves ecological consequences such as the indirect impact on land use change as more agricultural land is needed for food production resulting in increased greenhouse gas emissions and other negative environmental impacts such as land degradation (Houghton et al., 2012).

In addition to this competition between food, feed, and fuel, society wants even more from its agricultural land. This land is also expected to provide other ecosystem services, specifically soil functions such as supply of water purification and regulation, climate mitigation through carbon sequestration, provision and cycling of nutrients, and habitat for biodiversity (Schulte et al., 2019; Staes et al., 2018). Simultaneous maintenance of these other soil functions is essential for sustaining future food production.

There are inherent trade-offs between these soil functions, but we can also search for synergies. One example where such synergies have been found is the concept of Agroecological Symbiosis (AES) (Helenius et al., 2020; Koppelmäki et al., 2019). In the AES-model, biogas production is integrated into nutrient cycling at the farm scale without competing with food production. Clover-grass leys are included in arable crop rotation for production of biomass feedstock to be used in biogas production, for biological nitrogen fixing (BNF), and for soil organic matter maintenance. In the AES system, digestate from the biogasification is recycled as organic fertilizer and soil conditioner to the arable land. Transitioning from the conventional practice of green manuring to practice of growing clover-grass for biogas feedstock brings several positive outcomes. In conventional green manuring, the biomass is ploughed into soil irrespective of the nutrient requirements of the plants, without making use of its energy content. Biogas production allows the farmer to bring all the biomass together, reduce its volume while saving the nutrients in it, and then apply it to the land at rates and in locations where it is most needed. This practice improves nutrient cycling resulting in higher yields, reduced losses, and the conversion of the farm from an energy consumer to an energy producer (Koppelmäki et al., 2019; Stinner et al., 2008; Tuomisto & Helenius, 2008). This concept has produced several positive outcomes, specifically in organic crop production because organic farmers already rely on green manuring. Green manuring is less common on conventional farms, which would mean that changes in land use would be required if the AES-model were to be implemented at a larger scale. Therefore, the examination of the feasibility of the AES model must consider potential food-energy competition for land and other possible trade-offs in the supply of ecosystem services.

In this paper, we aim to find synergies between food and energy production by exploring the opportunities for ecological intensification and by modelling the implementation of the AES model at a regional scale. We hypothesize that the inclusion of context-specific sources of biomass for biogas...
production can negate the oft-observed trade-offs between food and fuel production, and deliver concomitant increases in the production of both commodities. Specifically, we compare the current agricultural production at the municipal level to three farming configurations. In each configuration, biogas is produced from agricultural biomasses not competing with food production with incremental increases of complexity in each configuration. We assess their impact on the following ecosystem services: primary production, provision of nutrient cycling and climate mitigation through carbon sequestration, and safeguarding of water quality through the prevention and mitigation of nutrient losses. Our study is limited to the biophysical perspective and the assessment of economic impact is subject to further studies.

2 | MATERIAL AND METHODS

Using local farming and food production statistics, we conducted a regional modeling study by applying a static annual empirical model developed specifically for this study. In this model, we explored the current system and three in silico scenarios of farming systems that follow a gradient of complexity.

### 2.1 System boundaries

We chose the agricultural area of municipality of Mäntsälä as a case study to represent a typical crop production area in Southern Finland. In the study area, a local energy company is planning to invest in biogas production and the municipality has broader plans to increase the self-sufficiency of their food system (AES Network project, 2019). The agricultural land of close to 15,000 ha covers 20% of the total land area and is dominated by cereal production (Table 1). The main use of crops produced is feed, with c. 80% of the cereal harvest destined for feed use. Dairy production is the main form of livestock production in the area, but the number of dairy farms is low resulting in low livestock density (0.12 animal units per ha) at a municipal scale (Appendix S1). The majority of feed produced in the area is exported to livestock farms located in other parts of the country. Even though the crop production dominates the agricultural

| Field use                  | Cultivation area 2015–2017 | Yield DM t ha⁻¹ | Direct food use % | Mineral N input kg ha⁻¹ | Mineral P input kg ha⁻¹ |
|----------------------------|-----------------------------|------------------|-------------------|-------------------------|-------------------------|
| Cereals                    | 9049                        | 3.0              | 12                | 90                      | 9.1                     |
| Winter heat                | 3381                        | 3.1              | 27                | 103                     | 7.0                     |
| Rye                        | 292                         | 3.0              | 88                | 120                     | 5.0                     |
| Feed barley                | 1406                        | 2.9              | 0                 | 80                      | 9.3                     |
| Malting barley             | 2203                        | 3.3              | –                 | 80                      | 9.3                     |
| Oats                       | 1767                        | 2.8              | 9                 | 80                      | 9.3                     |
| Oilseed and protein crops  |                             |                  |                   |                         |                         |
| Peas                       | 1094                        | 1.5              | 58                | 73                      | 7.7                     |
| Broad bean                 | 301                         | 1.6              | 10                | 36                      | 7.0                     |
| Rape and turnip rape       | 686                         | 1.4              | 90                | 95                      | 9.1                     |
| Grassland under 5 years⁴  |                             |                  |                   |                         |                         |
| Pasture                    | 238                         | 4.4              | 0                 | 140                     | 7.7                     |
| Hay                        | 646                         | 3.1              | 0                 | 100                     | 5                      |
| Silage                     | 1544                        | 4.4              | 0                 | 140                     | 7.7                     |
| Marginal agricultural land |                             |                  |                   |                         |                         |
| Other crops⁵               | 561                         | –                | –                 | –                       | –                       |
| Total                      | 14990                       | 100.0            | –                 | –                       | –                       |

⁴Includes following land uses: fallow, natural management field, green manure leys.
⁵Excluded from the study.
landscape, fallows, which are subsidized by Finland's Agri-Environmental scheme, cover c. 12% of the agricultural land in the study area. Minor crops in the area including rarely cultivated species of arable crops and horticultural plants (“other crops,” Table 1) were excluded from the study. In terms of land use, the study area represents typical arable farming landscapes in Southern Finland.

2.1.1 | Scenarios

To study the supply of soil functions we created three scenarios in addition to the current system (CS) (Table 2). In these scenarios, biogas production was integrated into food production based on the AES-model. The scenarios were built with incremental increase of complexity of the system, from the simplest to the most complex.

The current system with energy production (CSE) scenario demonstrates the potential of agricultural biomass (outside of food or feed production) to be utilized as feedstock for biogas production, with nutrients recycled back to the fields in the form of digestate to replace mineral fertilizers. In this scenario, the feedstock biomasses were harvested from marginal agricultural land under agri-environmental schemes for nature management, and from green manure leys covering 1114 area of ha. Also, undersown cover crops (grown in 20% of the annual arable crop area in the municipality), surplus silage, and manures were used as a feed for biogas production. Fields under the class “fallow” (743 ha) were excluded as these are significant to farmland biodiversity (Toivonen et al., 2015), and their biomass productivity is low.

The agroecological symbiosis scenario (AES) is similar to CSE but with one addition: rotational perennial clover-grass mixture leys are introduced to the arable crop rotations with an allocation of 20% of the area for annual crops. These diversify crop rotations, increase carbon input to soil, increase nitrogen (N) self-sufficiency through biological fixation by the clover component, and produce biomass for biogas production. Nutrients are returned to the fields in the form of digestate replacing mineral fertilizers.

The agroecological symbiosis with livestock scenario (AES-LST) represents a situation where dairy cows are reintegrated into the farming system to meet increased demand for livestock products. To minimize food-feed competition, we introduced bovine cattle (ruminants) because the production is based on the utilization of perennial grasses which meet demand for such soil functions as erosion control and carbon sequestration. Food produced is mostly in the form of milk, but meat is also produced when cows must be replaced.

The scale of the dairy cattle production was determined by the amount of available silage in a situation where 20% of an annual crop’s production area is converted into silage production (same proportion as for the clover-grasses in the AES scenario). In addition to the use of silage, we assumed that cows were fed the feed quality cereals, and some protein crops (broad bean) being produced concurrently within the system. Other feedstuffs, including rapeseed meal, minerals, and vitamins, were assumed to be imported to the system.

This resulted in the addition of 3367 new dairy cows into the system in addition to current number of dairy cows (834) in the area, a four-fold increase. Manure, from both current and new livestock, was assumed to be used in biogas production together with the grass biomass from cover crops and surplus silage. In all scenarios, digestate was assumed to be recycled back to the fields as organic fertilizer, complemented with mineral fertilizers as needed.

2.1.2 | Agricultural data used in the study

Current agricultural land use, N and phosphorus (P) fertilizer inputs, crop yields, and the share of food use of the crops are provided in the Table 1. Land use data, crop yields, and the share of food crops in the harvest were based on Official Statistics of Finland (2019) for the years 2015–2017. For silage yields in the CSE, AES, and AES-LST scenarios, we opted to use our own estimation, 6.4 t DM ha⁻¹, because the yield from the official statistics, 4.4 t DM ha⁻¹ (Official Statistics of Finland, 2019) is most likely lower than the actual achievable silage yield in our study area. This is

| Current system CS | Current system with energy (CSE) | Agroecological symbiosis (AES) | Agroecological symbiosis with livestock (AES-LST) |
|-------------------|----------------------------------|-------------------------------|-----------------------------------------------|
| Mainly crop production system in the case study area of Mäntsälä. Reference years 2015–2017 | Crop production + biogas production from manure, fallows, cover crops, and surplus silage | Crop production + biogas production from manure, fallows, cover crops, surplus silage, and newly introduced clover-grasses for biogas production | Crop production + biogas production from manure, fallows, cover crops, surplus silage, and newly introduced clover-grasses for dairy production + manure for biogas production |

TABLE 2 Description of the current situation and the three scenarios
because, in the statistics, silage yield is calculated for the area of first silage harvest. However, in Finland the silage is usually grown to be harvested 2–3 times a summer, even if the farmers do not necessarily take the following harvests from the entire silage area if the first harvest was sufficient to meet the herd’s need. In these scenarios, the yield estimate we used gave a silage surplus of 2 t DM ha⁻¹, adding to the feedstock for biogas production in all scenarios.

BNF was calculated based on biomass production of each crop by using a formula created by Anglade et al. (2015). We assumed that the silage leys, grasses in the marginal land, and the cover crops had a clover content of 25%, 30%, and 50%, respectively. For N deposition, we used municipal level data, 3 kg ha⁻¹ (Finnish Environment Institute, 2019).

Mineral fertilizer inputs were based on average fertilizer use in the region for cereals and silage (Turtola et al., 2017). For the other crops, we used our own estimation which was 80% of the maximum allowed N input rates set by Finland’s Agri-Environmental Programme (Ministry of Agriculture and Forestry, 2014). N and P contents of the crops were based on National Feed Tables (Natural Resources Institute Finland, 2018). The quantity of N (8.6 kg ha⁻¹) and P (1.8 kg ha⁻¹) in manure produced was calculated by multiplying the number of animals in the study area (Official Statistics of Finland, 2019) by ex-storage nutrient values of the manure (Luostarinen et al., 2017) and further by the agricultural land area (14,429 ha).

The number of animals and the feed use in the CS are provided in the Appendix S1. Data for meat and milk production were based on Official Statistics in Finland (2019) for years 2015–2017. For the current grass-based feed use, we assumed that the produced silage was used in the area by dairy cattle. Feed consumption for dairy production in the AES-LST scenario is provided in the Table 3. Protein feed in the lactating dairy cow diet consisted of rapeseed meal and broad beans (1:1 on N basis). The milk yield of lactating dairy cows was set to 9624 kg cow⁻¹ year⁻¹, which is 1.75% lower than the national average (Nokka, 2019), and higher than current production level at Mäntsälä municipality (8370 kg cow⁻¹ year⁻¹; Official Statistics of Finland, 2019). This was done because milk production was aimed to represent modern intensive milk production. According to Puhakka et al. (2016), 1:1 mixture of

### TABLE 3 Description of dairy production system in the AES-LST scenario

| Feed consumption per cow | Value  |
|--------------------------|-------|
| Grass silage use kg DM year⁻¹ | 5016  |
| Cereals kg DM year⁻¹        | 2275  |
| Broad bean/kg DM year⁻¹     | 579   |
| Straw                     | 237   |
| Imported feed: rape-seed meal | 593  |
| Imported feed: minerals and vitamins | 79   |
| Herd replacement %         | 33.2  |
| Milk yield kg cow⁻¹ year⁻¹ | 9624  |
| Calving interval, day      | 411   |
| Dry period, day            | 60    |
| Number of new milking cows in the system | 3367 |

*Feed consumption of heifers and dry cows included.

![Figure 1](image.png)
rapeseed meal and broad beans (on N basis) results in 1.75% lower milk yield than diets having exclusively rapeseed meal as a protein feed. Dairy cow diets were designed to be in line with the conventional feeding practice in Finnish dairy farms (Huhtamäki, 2019). Thus, the diets of lactating dairy cows were based on grass silage and cereals, had 54:46 forage-to-concentrate ratio, and crude protein concentration of 168 g kg⁻¹ DM. The diets of dry cows had 92:8 forage-to-concentrate ratio in dry matter (DM) and crude protein concentration of 136 g kg⁻¹ DM. Finnish Feed Table values (Natural Resources Institute Finland, 2018) were used to design the dairy cattle diets. The feed consumption of calves and heifers was estimated based on Enroth (2009) using calving age of 25 months. The feed use of livestock other than dairy cattle (Appendix S1) was estimated based on (Risku-Norja et al., 2007).

2.2 Framework for multicriterial sustainability assessment

We applied a multicriterial sustainability framework to assess the multifunctional outcomes of agricultural production (Figure 1). We calculated how different farming systems supply soil functions (primary production for food and energy, provision of nutrient cycling, and climate mitigation) and impact water quality in the different scenarios using the following metrics at annual outputs from the systems:

- For primary production: Food (energy: MJ ha⁻¹, human digestible protein, HDP kg ha⁻¹) in plant and animal products.
- For primary production: Bioenergy (GWh, kWh ha⁻¹).
- For water quality: Nutrient balances (N kg ha⁻¹ and P kg ha⁻¹).
- For the provision of nutrient cycling: Share of recycled nutrients of all nutrients used (%).
- For climate mitigation: Carbon input to the agricultural land (t DM year⁻¹ ha⁻¹).

2.2.1 Food production

To assess food production, we calculated the produced calories and the human digestible protein (HDP) for all crop and livestock products “at farm gate” produced from the Mäntsälä’s agricultural land for export to food industry and directed to human consumption HDP produced from the crops was calculated by multiplying the produced crops by their DM and N content which were obtained from National Feed tables (Natural Resources Institute Finland, 2018). N content for crops was converted into protein content by using a conversion factor 5.6 (Mariotti et al., 2008) and was further converted into human digestible protein by using

the factor 0.9 for cereals and 0.85 for peas and faba beans (Boye et al., 2012). Produced calories were calculated by multiplying average yields by their DM content and by the energy content factor for each crop which was derived from the USDA database (USDA, 2015). The share of direct food use was determined for each cereal crop individually based on statistics for Food use by the industry (Official Statistics Finland, 2019), except for peas and faba beans for which, we estimated the direct food use at 10%. For oilseed crops, we assumed the direct food use to be 90% when considering calories produced but 0% when considering proteins produced because the end food product, edible fat, does not contain proteins.

Food produced in livestock products was calculated by multiplying the meat and milk production (Official Statistics Finland, 2019) by the edible part of the animal and further by energy and protein content based on USDA database (USDA, 2015). Protein content was converted further into HDP by using the factor 0.95 for milk and 0.94 for meat (Gilani et al., 2005). For meat, we assumed that the edible part comprised 45% of the total weight.

For the scale of the environmental externalities through produced agricultural biomass we used a proxy of systems’ feed trade balance: this was calculated by subtracting feed imports (Industrial feedstuff; rape seed; meal and minerals) from feed exports (grain and oilseed crops) in each scenario. Because of substantial by-product flows from oilseed processing and beer brewing, we included the contribution of oilseed meal and mash from beer brewing to the quantity of feed consumed outside of the system. For oilseed meal, we assumed that 70% of the DM is left for use as a feed after oil extraction and, in the case of mash, 48% after beer brewing.

2.2.2 Bioenergy production

In all scenarios, the only bioenergy produced was biogas. Biogas production was calculated by multiplying the produced DM by the biomethane potential (BMP) of different feedstocks. BMP (Table 4) was derived from the literature and is expressed in normal cubic meters (Nm³). We assumed that the whole biomethane potential of the technically available—harvestable—biomasses was realized. The increase in manure production in the AES_LST scenario was calculated by multiplying the number of new animals by the average quantity of manure excreted per animal per year (Luostarinen et al., 2017).

2.2.3 Nutrient flows

To assess the risk for nutrient losses (N and P) in different scenarios, we calculated N and P balances (kg ha⁻¹) as
agricultural field balances by subtracting outputs (harvested crops) from the inputs (fertilizers, manure/digestate, N deposition, and BNF). To assess the provision of nutrient cycling, we calculated the share of recycled N and P from all the N and P used as mineral or organic fertilizer in each scenario. In addition, we calculated the proportion of mineral fertilizers replaced by the use of digestate in each scenario. For N, we used the 80% replacement rate of mineral N (Stinner, 2015). We acknowledge that also bigger N losses than we used are possible when considering all losses during the biogas process, storage, and field application, as reported in a review study by Möller (2015). We decided to use the 80% relative fertilization efficiency for the digestate, because digestion increases the solubility of the N (Möller & Müller, 2012), which improves the fertilization value of manure compared to current manure use in the current system. For P, we assumed a replacement rate of 100% for mineral phosphorus.

2.2.4 | Carbon inputs to the soil

Carbon input to agricultural land included crop residues, roots, root exudates, manure, and digestate. We used values based on the literature (Table 5). To calculate the biomass of crop residues, we first calculated the technical residue potential as:

\[ \text{Crop residue DM} = (1 - \text{HI}) \times \frac{\text{yield DM}}{\text{HI}} \]

in which HI is harvest index as harvestable part of the crop divided by total DM production of the crop (Hakala et al., 2009). Root biomasses including the root exudates were based on a study by Hu et al. (2018).

For digestate, we calculated the quantity of carbon dioxide (CO₂) and methane (CH₄) in the biogas produced from the feedstock and subtracted that from the original carbon content in the biomass. The carbon content of organic matter for all inputs we assumed to be 45%.

2.2.5 | Uncertainties and sensitivity analyses

We carried out a sensitivity analysis in order to explore the implications of our choices in developing this model. We acknowledged that the amount of area allocated for the production of either for livestock feed or feedstock for biogas production had a great impact on the results of our study. Therefore, the impact of the area of green manure leys introduced to the system as well as the shares of fallows and cover crops harvested were tested. In addition to this, we tested how crop affected impacted the results and how much the share of direct food use affected food production.

### Table 4: Biomethane potentials of different feedstock used in the study

| Feedstock                        | Biomethane potential Nm³ CH₄ t⁻¹ | References                          |
|----------------------------------|----------------------------------|-------------------------------------|
| Grass                            | 290                              | (Seppälä et al., 2009; Wahid et al., 2015) |
| Cow manure (slurry and solid)³   | 172                              | (Seppälä et al., 2013)              |

³Included all grasses (silage, green manure leys, nature management fields, and cover crops)

### Table 5: Carbon input of crop residues. Above ground input calculated as by Hakala et al. (2009) and below ground input as by Hu et al. (2018)

| Carbon input | C input above ground, Mg ha⁻¹ | C input below ground (including exudates), Mg ha⁻¹ | C input total, Mg ha⁻¹ |
|--------------|-------------------------------|---------------------------------------------------|------------------------|
| Wheat        | 2.207                         | 1.050                                             | 3.257                  |
| Rye          | 2.024                         | 1.200                                             | 3.224                  |
| Barley       | 1.152                         | 0.960                                             | 2.112                  |
| Oats         | 1.771                         | 1.030                                             | 2.801                  |
| Peas         | 1.281                         | 1.000                                             | 2.289                  |
| Broad beans  | 1.104                         | 1.110                                             | 2.214                  |
| Turnip rape  | 1.699                         | 1.030                                             | 2.729                  |
| Silage       | 0.496                         | 4.430                                             | 4.653                  |
| Fallows      | 1.934                         | 2.658                                             | 4.572                  |
To analyze uncertainties in the model, we carried out a Monte Carlo simulation which produces distributions of possible model outcomes within the uncertainty range of input variables. For this, we determined the uncertainty ranges of each input variable with a specific normal distribution (Appendix S2 for details).

3 | RESULTS

3.1 | Food production

Food production was either at the same level (CSE), decreased (AES), or increased (AES-LST) in these scenarios compared to the CS (Figure 2; Appendix S3). Food production was highest in the AES-LST, where the HDP production was increased by 143% and food energy (MJ ha\(^{-1}\)) production was increased by 77% compared to CS. In the AES, the cropping area was reduced 20%, which resulted in 13% reduction in HDP production and 16% reduction in food energy production compared to CS.

Feed exports to the livestock farms located outside of the studied system, representing the scale of the external environmental impact, were reduced to 20,422 t year\(^{-1}\) (AES) and to 10762 t year\(^{-1}\) (AES-LST) from 26,213 t year\(^{-1}\) in the CS and CSE. At the same time, feed imports to the livestock farms within the system increased from 675 t to 2939 t year\(^{-1}\) in the AES-LST.

3.2 | Bioenergy production

The highest quantity of bioenergy was produced in the AES (Figure 2: Appendix S4). Most of the energy was produced from perennial clover-grasses. In the CSE and AES, manure contributed only 13% and 6% to the total energy produced, respectively. In the AES-LST, the corresponding amount was 51%. When grass biomass produced was used as livestock feed in the AES-LST, 58% less energy was produced compared to the AES and 8% less than in the CSE. This was a result of lower energy production from manure compared to direct energy use of grass biomass.

FIGURE 2  Human digestible protein (HDP kg ha\(^{-1}\)), food energy (MJ ha\(^{-1}\)), and bioenergy (GWh) production in the current system (CS), current system with the energy production scenario (CSE), AES scenario (AES) and AES scenario with livestock (AES-LST). Blue arrows represent the produced food, green arrows represent the produced non-food energy, grey arrows represent the flows related to food production within the system and black arrows represent the flows related to bioenergy production within the system.
3.3 | Nutrient balances and nutrient cycling

The N balance was lowest in the CSE (41.4 kg ha\(^{-1}\)) (Table 6). In the CSE, this was the result of increased N output in the form of feedstock produced for biogas production which also replaced fertilizer inputs (Figure 3). In the AES and AES-LST, N input was higher than in the CS or CSE, because of increased BNF. N and P outputs were higher due to clover-grass being harvested either for feed for livestock or energy. In the CS, there was 0.4 kg ha\(^{-1}\) P deficit which was increased further in all scenarios up to −4.7 kg ha\(^{-1}\) in the AES-LST.

Nutrient recycling was enhanced in each scenario compared to the CS. The proportion of recycled N and P were 9% and 19% respectively, in the CS. Corresponding results for N were 25%, 53% and 45%, and for P were 35%, 74% and 98% for CSE, AES, and AES-LST, respectively.

3.4 | Climate mitigation through carbon sequestration

Crop residues were clearly the largest source of carbon input to the soil (Table 7). Manure or digestate corresponded to only 2–9% of the total carbon input. CSE produced lower carbon inputs in the crop residues because more biomass was harvested for biogas production. Taking into account the digestate applications, higher carbon inputs were projected for the AES and AES-LST at 112% and 109%, respectively, compared to CS. This was the result of larger shares of farmland to clover-grass which contributed substantially to higher carbon input in crop residues.

3.5 | Sensitivity analyses and uncertainty in the model

The share of farmland allocated for clover-grasses had the greatest impact on nutrient flows in the systems (Figure 3 and Appendix S5). When this share was changed, quantities of energy produced in the AES and food produced in the AES-LST were also affected. The digestate produced in the biogas production using cover crops, fallows, green manure leys, and surplus silage as a feedstock replaced the use of mineral N and P which was dependent on the potential area of the land used.

Monte Carlo analyses showed a high level of congruence for most variables in the model (Figure 4). The highest uncertainties in the model were related to carbon input to the soil and produced bioenergy. Furthermore, there was a higher level of uncertainty in the AES-LST scenario compared to the other scenarios.

4 | DISCUSSION

Our study demonstrated potential synergies in integrating food and energy production without compromising other ecosystem services. By applying biogas production in a crop-producing farming system and integrating livestock farming at a regional scale, the supply of ecosystem services was substantially increased (Figure 5) while environmental externalities (indicated by the size of the “black box”) were reduced. However, at the same time, the complexity of the system, as measured by the number of farm components integrated into the system, increased in the sequence CS—CSE—AES—AES-LST, thereby requiring more management and knowledge and making it more challenging to implement. These simultaneous increases in productivity and supply of ecosystem services observed as a result of increased complexity in the system are supported by other studies conducted in different farming systems (Khumairoh et al., 2012).

4.1 | Biomass production for food and energy

Substantially more food was produced in the AES-LST compared to the other scenarios: integrating livestock production into crop production by using cereals produced locally along with the grass forage, increased HDP by 164% and food energy by 89%, even though 20% of the crop

| TABLE 6 Nitrogen and phosphorus balances (kg ha\(^{-1}\)) for arable land in the current system, current system with the energy production scenario, AES scenario, and Alternative scenario |
|---------------------------------|-----------|-----------|-----------|-----------|
| N input                         | CS        | CSE       | AES       | AES-LST   |
| Fertilizers                     | 114.5     | 117.4     | 141.2     | 137.6     |
| Manure/digestate                | 83.7      | 71.9      | 41.1      | 46.6      |
| BNF                             | 8.6       | 23.4      | 46.5      | 37.4      |
| Nitrogen deposition             | 19.1      | 19.1      | 50.7      | 50.7      |
| N output                        | 60.4      | 70.5      | 89.5      | 89.5      |
| Food/feed                       | 60.4      | 55.7      | 47.9      | 86.7      |
| Grass for energy                | 54.1      | 41.4      | 51.7      | 48.2      |
| P input                         | 9.2       | 9.2       | 8.0       | 7.6       |
| Fertilizers                     | 7.5       | 6.0       | 2.1       | 0.1       |
| Manure/digestate                | 1.8       | 3.2       | 5.9       | 7.5       |
| P output                        | 9.6       | 11.1      | 12.3      | 12.3      |
| Food/feed                       | 9.6       | 9.6       | 8.1       | 11.4      |
| Energy                          | −0.4      | −1.9      | −4.3      | −4.7      |
| P balance                       | −0.4      | −1.9      | −4.3      | −4.7      |
production area was converted to grasses. Furthermore, using the manure as a feedstock for biogas production together with crop residues, produced energy at 62% of the average direct energy consumption of 3.14 MWh ha\(^{-1}\) in Finnish agriculture. To convert the system to a net-energy producer, a portion of the fields need to be allocated directly to energy production. In the AES, 20% of the annual crop land was converted to rotational clover-grasses. This almost doubled energy production while HDP and food calories produced were only reduced by 13% and 16%, respectively compared to the CSE.

Allocating part of the cereal area to green manuring in order to produce feed for biogas production resulted in a decreased area for cereal production. Similar results were published by Pugesgaard et al. (2014) and Markussen et al. (2015) who found that allocating part of the land to energy production decreased the total output of food. However, if grasses are cultivated on less productive fields or if yields are increased by improving soil fertility, the impact is not as great as the share of the reduced cereal area would imply. Also, a decrease in food production due to allocation of crop production areas to rotational clover-grasses, can be offset by increasing the portion of crops produced for direct food consumption.

In the study area, 83% of cereals currently produced were used for livestock feed, mostly outside of the system. This is also typical situation in Finnish agriculture (Official Statistics Finland, 2019). In terms of land use, direct consumption of cereals by humans is often more efficient than circulating cereals through livestock production (Godfray et al., 2010). Furthermore, 24% of the cereal area was used for malt barley production, which was not considered as contributory to the human energy supply because the end product is not used for nutritional purposes. Beer production resulted in substantial amounts of mash as by-product, which was used as a cattle feed. Thus, current cereal production has a relatively small direct contribution to food production. However, the direct human use of cereals is difficult to increase because only a relatively small portion of cereals produced meets mill quality standards. In 2015–2017 only 16–23% of wheat produced...
FIGURE 4  Distribution for 1000 model runs in Monte Carlo analyses for different model outcomes. Frequency on y-axis
within the study region was of mill quality (Official Statistics of Finland, 2019). In other words, in the current market situation, there is not sufficient demand for the direct human use of all cereals produced. Furthermore, livestock has an ability to convert non-edible food into edible food for humans. In a study exploring the relationship between land use and human diet in the Netherlands, land was used most efficiently when 12% of dietary protein was derived via animals (Van Kernebeek et al., 2016).

4.2 Enhanced other soil functions

In this study, we demonstrated the beneficial role of perennial clover-grasses used in biogas production. The surplus nutrient balances, both for N and phosphorus were decreased in each scenario compared to current system. At the same time, the proportion of recycled nutrients in the system was increased. This was a result of enhanced nutrient cycling within the system with digestate replacing mineral fertilizers and more biomass being harvested because of the increased clover-grass area. Perennial clover-grasses have also been reported to protect soil from the erosion, fix N from the atmosphere, replace N fertilizers in arable farming (Ten Berge et al., 2016), and increase carbon input above levels seen in annual crops (Conant et al., 2017; Karhu et al., 2012).

In this study, projected changes in annual carbon inputs varied from a 6% annual decrease in the CSE to a 24% increase in the AES. The dynamics of below-ground biomasses and root exudates are poorly understood, which increases the level of uncertainty in the carbon sequestration results. However, the importance of adequate organic matter input to soil is recognized because arable soils tend to lose carbon (Heikkinen et al., 2013). In Finland, where we conducted this study, Heikkinen et al. (2013) observed a yearly 0.4% decrease in carbon content in mineral soils, equating to 220 kg C ha\(^{-1}\) year\(^{-1}\), in a study where the soil carbon concentration was monitored in the upper 15 cm layer from 1974 to 2009. In our study, the biggest driver for the increase in carbon input was the increase in the perennial grass cultivation area. The beneficial impact of grasses on carbon sequestration has been described previously (Conant et al., 2017; Karhu et al., 2012).

In addition to quantity, biogas production also affects the quality of organic matter input. During biogas production, part of the carbon is transformed into methane, and thus, when digestate is applied to the soil, carbon inputs are decreased compared to direct use of manure or green manuring. However, this is not likely to have a long-term impact on soil carbon content. In their review, Möller (2015) concluded that anaerobic digestion would only have a minor impact on long-term soil organic matter content, in comparison to direct green manuring with the same feedstock. However, changes in cropping practices which occur in conjunction with biogas production have a greater influence on soil organic matter content than the changes in organic matter input quality (Möller, 2015).

In this study, we used carbon inputs to soil as an indicator for climate mitigation. However, biogas production and the increases in grass cultivation areas have also other impacts related to climate mitigation. In the AES-LST, increased dairy production would result in increased methane emissions. At the same time, N\(_2\)O emissions are expected to decrease when biogas production is introduced to the system (Möller, 2015). Möller and Stinner (2009) reported a 38% decrease in N\(_2\)O emissions in organic stockless cropping when crop residues and clover-grass leys were digested and the digestate was returned to the fields as a fertilizer. In terms
of climate mitigation, it must also be taken into account that biogas used as fuel replaces the use of fossil fuels, hence offsetting fossil carbon emissions. Finally, replacing mineral compound fertilizer with biogas digestate reduces, depending on transport distance from the biogas plant, greenhouse gas emissions from the fertilization of arable crops by up to half (Kytäa et al., 2020).

Furthermore, in the AES and AES-LST scenarios, the unknown externalized environmental impacts were reduced substantially, along with decreases in feed exports from the system. The environmental impact of the production of imported feed is unknown, but the high risk of emissions to the environment from spatially concentrated and specialized livestock farming, made possible by the imported feeds, has also been quantified in the Finnish context. For example, Uusitalo et al. (2007) and Menzi et al. (2010) have reported excessive nutrient surpluses in areas with high livestock density. Crop production systems which function as net exporters of feed should acknowledge their share of allocation of the environmental costs of intensive livestock farming.

### 4.3 Complexity

As we demonstrated with this study, the supply of ecosystem services increases with the complexity of the system. However, the complexity in livestock management has traditionally been one reason that farmers abandon livestock production (Peyraud et al., 2014), and this logic is also mirrored by the livestock producers’ decisions to specialize and intensify. According to Wilkins (2008), it is unlikely that livestock would be brought back to the farms from which they have been removed. Garrett et al. (2020) suggested that increasing the level of integration of crop and livestock production would require a combination of top-down approaches, for example, new regulations toward a circular economy, with bottom-up efforts, such as dissemination of information that illustrates successful examples or a co-creative design processes between farmers and research.

The implementation of biogas production may be a less challenging alternative on crop farms than would be the re-introduction of livestock to these farms. Biogas production offers a reasonable purpose for grass cultivation in the crop production systems thus enhancing the supply of ecosystem services apart from food production at a regional scale. This ecological intensification has been supported at the farm scale in studies integrating biogas production with organic stockless crop production (Koppelmäki et al., 2019; Serdjuk et al., 2018). However, the environmental externalities are not reduced if a farming system continues producing feed that is exported from the region. Achieving more circular systems requires setting the intensity of livestock production in alignment with regional feed production (Koppelmäki et al., 2021).

### 4.4 Applicability and limitations of the study

This modeling was conducted within a food production system of an area defined by its municipal borders in Southern Finland. The results cannot be assumed to be directly generalizable to other regions of the country or to other countries and other farming contexts. However, the studied area represented an agricultural area dominated by cereal and other arable crops and with an ever diminishing share of livestock production, which are common in many regions around the world.

This study was based on modeling and in it, on many assumptions. Many of the impacts from biogas production would depend on the way in which biogas production is implemented. For example, nutrient losses during storage are determined by the technology applied, and nutrient losses from the fields are most likely related to changes in the cropping system (Möller, 2015).

There are some trade-offs to be considered in planning animal diets and decisions are made based on desired outcomes. In this article, diets were planned giving milk yield and on-farm feed production the highest priority. Lactating dairy cow diets were designed to include mixtures of broad beans and rapeseed meal as protein feeds. This was a compromise between maximizing the on-farm feed production and milk yield. In Finland, rapeseed meal is the most commonly used protein feed in dairy cow diets, and rapeseed meal typically results in higher milk yields than broad bean (Lamminen et al., 2019; Puhakka et al., 2016). In this study, our choice of animal diets considered only those variables affecting productivity, but these choices can also have impacts on environmental loadings. Changes in N and P emissions to the environment and N use efficiency in milk production have been reported by Puhakka et al. (2016) and Lamminen et al. (2018), Lamminen et al. (2019). The highest uncertainties in this study were related to livestock production. This was a result of a higher level of complexity in livestock production compared to other scenarios, which added to the number of model variables and the plurality of scenario outcomes.

In this study, we compared the energy produced in the different scenarios (CSE, AES, AES-LST) to the average energy consumption in Finnish agriculture. This included electricity consumed, heat energy consumed, and fuel oil used in the machinery and for drying of cereals. However, indirect energy use, for example, energy needed to manufacture fertilizers, was not included. Also, energy consumption varies across different farming systems. Results from this study
demonstrated at potential to convert crop production systems from energy consumers to energy producers.

Furthermore, we conservatively assumed that neither biogas production nor introducing clover-grasses into crop rotations had an impact on yields. However, perennial grasses have multiple positive agronomical outcomes on crop farms (Meehan et al., 2013; Weißhuhn et al., 2017; Werling et al., 2014) and biogas production has the potential to enhance productivity on stockless organic crop farms (Blumenstein et al., 2018; Koppelmäki et al., 2019) which may in reality result in increased yields.

4.5 Further research questions

The multifunctional outcomes of different farming systems are often dependent on farm and field-scale management decisions. Thus, further research at the farm level is needed to investigate the supply of soil functions in biogas production based on the AES-mode. Such an assessment should consider the inherent ability of contrasting soils to supply different soil functions. For example, the Functional Land Management framework (Schulte et al., 2014) can be adopted to study Food-Feed-Energy competition and its impact on other soil functions at farm and field levels. This should be complemented by assessments of the demands for commodities and soil functions in different contexts, and their impact on the intensity of cropping systems.

In order to get a more comprehensive picture of different cropping systems’ contribution to food production and their environmental impacts in other regions requires to include external impacts caused by feed exports. This can then be compared to the effects of possible synergies in cases where separate livestock and crop-producing regions are converted into a regionally balanced mixed farming systems. For example, in a study by Van Kernebeek et al. (2016) a small portion of livestock production increases land use efficiency as animals are able to use grasses from land unsuitable for crop production and convert the co-products from crop production into food edible by humans. All such systemic transformations need economic assessments at farm, regional and national levels, for guiding the entrepreneurs and making informed policies. These were outside of the scope of our study but will be the topics for forthcoming papers.

5 CONCLUSIONS

There is much scope for sustainability transformation through smart use and integration of local resources, which negate food-feed-fuel competition in agricultural production. Risks of environmental impacts can be substantially decreased, and much of the impacts can be internalized for improved system design and management. For non-food production, biogas production can be efficiently added to farming systems without food-fuel competition. Integration of clover-grasses to arable farming with dual purpose, namely N-fixing and feedstock to biogas production, is more productive than using (only) surplus biomasses from fallows or cover crops. These practices would also likely be a more realistic option for the crop farms than re-introducing livestock production. In areas currently specializing in arable farming, the introduction of livestock farms increases productivity and reduces environmental externalities. However, while this combination of multiple system components allows productivity and environmental sustainability to be improved simultaneously, it also increases system complexity. This increased complexity necessitates the development of additional skills and knowledge needed within farming system. Depending on the new elements within a particular system, a farmer would need to learn how to manage biogas technology, or how to use digestate as a fertilizer—even further, how to raise livestock. This requires studies on the needs for investments and the economic profitability of these systems.

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**SUPPORTING INFORMATION**

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

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