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2019-03-01

Koppelmäki, K V, Parviainen, T O, Virkkunen, E, Winquist, E, Schulte, R & Helenius, J P 2019, 'Ecological intensification by integrating biogas production into nutrient cycling: Modeling the case of Agroecological Symbiosis' Agricultural Systems, vol. 170, pp. 39-48. https://doi.org/10.1016/j.agsy.2018.12.007

http://hdl.handle.net/10138/299518
https://doi.org/10.1016/j.agsy.2018.12.007

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Ecological intensification by integrating biogas production into nutrient cycling: Modeling the case of Agroecological Symbiosis

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ARTICLE INFO

Keywords:
Biological nitrogen fixation
Localized agrifood system
Nutrient losses
Organic farming
Renewable energy
Sustainable intensification

ABSTRACT

There is growing demand to produce both food and renewable energy in a sustainable manner, while avoiding competition between food and energy production. In our study, we investigated the potential of harnessing biogas production into nutrient recycling in an integrated system of organic food production and food processing. We used the case of Agroecological Symbiosis (AES) at Palopuro, which is a combination of three farms, a biogas plant, and a bakery, as a case to explore how biogas production using feedstocks from the farms can be used to improve nutrient cycling, and to calculate how much energy could be produced from the within-system feedstocks. The current system (CS) used in organic farms, and the integrated farm and food processing AES system, were analyzed using Substance Flow analysis. In the AES, annual nitrogen (N) and phosphorus (P) surpluses were projected to be reduced from 95 kg ha⁻¹ to 36 kg ha⁻¹ and from 3.4 kg ha⁻¹ to −0.5 kg ha⁻¹ respectively, compared to the CS. Biogas produced from green manure leys as the major feedstock, produced 2809 MWh a⁻¹. This was 70% more than the energy consumed (1650 MWh a⁻¹) in the system and thus the AES system turned out to be a net energy producer. Results demonstrated the potential of biogas production to enhance the transition to bioenergy, nutrient recycling, and crop productivity in renewable localized farming and food systems.

1. Introduction

There is a growing demand for ecological intensification in food production. Food must be produced in greater quantities and agriculture is concurrently expected to supply other ecosystem services (Schulte et al., 2014; Tittonell, 2014). Furthermore, there is now dual pressure to produce renewable energy and meet European Union targets (European Commission, 2014), and to recycle nutrients (European Commission, 2015). At present, agriculture and the food system as a whole, are de-localized and highly dependent on fossil fuels and mineral fertilizers as net inputs. This has caused many negative environmental impacts (Whatmore, 1995; Kummu et al., 2012; IPES-Food, 2016). Sustainably produced biomasses are proposed to have significant potential to replace fossil fuels and mineral fertilizers as net inputs. This situation works against the objective of recycling plant nutrients (Buckwell and Nadeu, 2016), and has led to a lack of manure for use in crop farms located in areas without livestock. In response, most farms have relied on mineral fertilizers. Contrastingly, organic crop farms have had to rely on green manure or commercial organic fertilizers. A lack of manure in stockless conventional farms and a lack of opportunities to spread manure or other organic fertilizers has resulted in negative environmental impacts, such as diminishing soil carbon contents and substantial nutrient excesses, in the areas with spatial separation of crop and livestock production (Usitalo et al., 2007; Heikkinen et al., 2013; Maillard and Angers, 2014).

The challenge arising from the spatial separation of animal production and crop production is even more apparent on organic farms, because they have to rely on green manure leys instead of using mineral fertilizers. In green manuring, the timing of N mineralization does not spatial separation of crop and livestock production systems has increased. This situation works against the objective of recycling plant nutrients (Buckwell and Nadeu, 2016), and has led to a lack of manure for use in crop farms located in areas without livestock. In response, most farms have relied on mineral fertilizers. Contrastingly, organic crop farms have had to rely on green manure or commercial organic fertilizers. A lack of manure in stockless conventional farms and a lack of opportunities to spread manure or other organic fertilizers has resulted in negative environmental impacts, such as diminishing soil carbon contents and substantial nutrient excesses, in the areas with spatial separation of crop and livestock production (Usitalo et al., 2007; Heikkinen et al., 2013; Maillard and Angers, 2014).

The challenge arising from the spatial separation of animal production and crop production is even more apparent on organic farms, because they have to rely on green manure leys instead of using mineral fertilizers. In green manuring, the timing of N mineralization does not meet with the peak demand of the crop plants (Berry et al., 2002). Also,
the common practise in Nordic conditions of terminating green manure leys by ploughing them in late autumn creates risks for losses of N and other nutrients from the green manure as the nutrients are released from the decomposing biomass too early (Uski-Kämpä and Jauhiainen, 2010). For these reasons there is a need to develop alternative strategies to increase N use efficiency in stockless organic farming (Berry et al., 2002; Möller, 2009; Borgen et al., 2012).

These challenges and opportunities have created a need for finding new ways to integrate food production and renewable energy production in a sustainable manner. One approach is to use green manuring leys, that are not competing with food production, for combined energy and organic fertilizer production.

Stinner et al. (2008), Tuomisto and Helenius (2008), Siegmeier et al. (2015), and Blumenstein et al. (2018) all suggest the use of green manure leys as a feedstock in biogas production in organic farming. As an added benefit, nutrients can be more efficiently reallocated in time and space if these leys are harvested for digestion in biogas plants, instead of tilled in the soil. This increases nutrient use efficiency and returns higher yields, thereby potentially increasing productivity in the farming system (Möller, 2009; Möller and Müller, 2012).

A further innovation was described by Koppelmäki et al. (2016). They proposed Agroecological Symbiosis (AES); as a food system application of the more generic idea of industrial symbiosis (Chertow, 2000), to further enhance nutrient recycling and to make full use of the bioenergy produced within the system. AES is a food production and processing symbiosis of farms and food processors. In addition, as a localized food system model, AES is expected to have cultural and socio-economic benefits (Koppelmäki et al., 2016), which are not dealt with in this article. The first AES is actively forming in the village of Palopuro in southern Finland. In this AES, a dry-digestion biogas unit produces energy from green manure leys together with manure.

However, the knowledge gap regarding potential trade-offs between energy gains and changes in food production, nutrient cycles and among other soil functions remains. There is a need to ensure that the production system is optimized to minimize trade-offs and maximize synergies between food and energy production.

In our study, we explore how agricultural biomasses that are not competing with food production can be utilized in producing renewable energy and enhancing nutrient recycling in food production and processing in an AES context. The aim of our paper is to explore the potential of closing nutrient loops and increasing energy self-sufficiency in food production through AES. We use Palopuro AES as a case and carry out an ex-ante assessment of a biophysical system in terms of (1) agricultural and food products produced and sold, (2) nutrients produced within, imported to, and exported from, (3) energy requirements, energy sources, and salable energy of the AES.

2. Materials and methods

2.1. Case description

In this study, we used Palopuro Agroecological Symbiosis (http://blogs.helsinki.fi/palopuronsymbiosis/) as the pilot case of an energy-positive, circular food production system. Palopuro AES is located in Southern Finland, approximately 50 km north of Helsinki, in the village of Palopuro near the town of Hyvinkää (60°37′50″N, 024°51′35″E).

Palopuro AES consists of the following operations: an organic cereal farm, an organic vegetable farm, an organic hennery, a bakery, and a biogas plant (Fig. 1). An investment decision to build a biogas plant was made at the time of the study. From the beginning, the bakery has participated in planning the AES and formulating a construction plan, but the investment had not yet been realized at the time of our study. Hence, our study comprises of an ex-ante assessment of the AES system, as compared to the current system (CS). A full description of the Palopuro AES can be found in the Supplementary Material (S1).

The biogas plant serves as the heart of energy production and nutrient flows (Fig. 1). By far, silage from green manure leys of the farms will be the most important feedstock for the plant, representing 71% of the total feedstock quantity. The use of grass biomass as a feedstock in biogas production follows the ideas previously presented by Möller et al. (2008), Stinner et al. (2008), and Tuomisto and Helenius (2008). Other feedstocks include chicken manure from the hennery and manure from horse stables. Unlike the other feedstocks, horse manure is not recycled within, but imported to the AES from stables located nearby. Receiving horse manure is a service provided by the AES to small horse stables in the neighbourhood, as these often do not have their own fields for manure spreading.

Through the anaerobic digestion of the biomass, recycled within the AES alone, the AES becomes a net energy producer (Koppelmäki et al., 2016). The biogas can be directly used by the AES in on-farm processes, such as grain drying, and as fuel for the ovens in the bakery. The rest of the biogas will be upgraded to biomethane for use as fuel for the needs of the AES itself, and for sale at a gas station to be built next to the plant.

The nutrient-rich digestate will be used as organic fertilizer on the farm fields. The majority of the fields at Palopuro AES have been managed under organic certification since 2010. Currently, the crop rotations follow commonly used practices of stockless organic farms in southern Finland. A five-year crop rotation consists of two years of perennial green manure leys, followed by autumn- or spring-sown cereals, then a pulse crop and, finally, spring-sown cereal with under-sown grass seeds to establish the subsequent green manure leys. N fertilization relies on the green manure leys and commercial organic fertilizers are used in part of the fields. Horse manure is used as a soil conditioner. In an operating AES, the green manure leys are replaced by dual-purpose leys: this serves as the biological N input into the system, but also converts green manuring leys into mobile organic fertilizers.

2.2. Food production and nutrient flow analyses

In this study, we modeled a current scenario (CS), which represents the typical organic farming system based on current agricultural activities of the farms participating in Palopuro AES. This scenario was compared to the AES Scenario (AES), the functions of which were designed in the completed research and development (R&D) project (Helenius et al., 2017). The farm’s arable land and hennery were system boundaries for the CS. Arable land also included the vegetable farm’s fields, which consisted of one ha of vegetables and two ha of green manure leys. For the AES model, boundaries were the symbioses’ farm fields and operations including the biogas plant, which will begin operating in autumn 2018, and the bakery, which is in the planning stage (Fig. 1).

N and P flows were calculated, and a comparison was made between CS and AES. Nutrient flows were illustrated using STAN 2.5.1302 substance flow analysis software. The data for arable land were compiled from cultivation notes (available arable land and fertilization use) taken at farms of the Palopuro AES and from the literature. Energy use and grain consumption data for the bakery were compiled from Samsara Ltd., which has made plans to move its operations to become part of Palopuro AES. The biogas plant operations were designed based on the results of the R&D project, which was conducted in 2015–2017 (Helenius et al., 2017), and on results reported from biogas literature.

For the CS, the area of green manure leys followed the common practices of organic crop farms in the region, which meant that 40% of the crop rotation was allocated to green manuring. For the AES, the area of green manure leys was set to meet the demand of the biogas plant together with the other fallows, which were not included in the crop rotation. Crop rotation was optimized to the demands of the AES framework, as applied to Palopuro AES. This means that, in addition to supplying enough feed for the hennhouse, the fields should also produce enough baking-quality grain for the bakery and enough feed in the form of silage for the biogas plant.

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The area of other fallows, nature management fields, and buffer zones was set to be the same as in the farm's current crop rotation, comprising approximately 8% of the total farm area. In the AES model, the biomass harvested from buffer zones was used for biogas production. In the CS model, the grass cut from the buffer zones was not used for agricultural purposes. In the AES model, the use of harvest from the buffer zones added 0.5% to the N and 0.6% to the P flows. In addition, a part of the nature management fields was harvested to meet the demand for grass biomass in biogas production. Nature management fields and buffer zones are both common agricultural land uses in Finland covering approximately 9% of the total agricultural land area in the study region during 2017 (Natural Resources Institute Finland, 2018a). This is because they are subsidized by the agri-environmental support system. According to regulations, harvest biomass from these fields is allowed (Ministry of Agriculture and Forestry, 2014).

The total farmland was 385 ha in both scenarios, but allocations to the various crops and land uses varied (Table 1). The crop yields (Table 1) were average organic crop yields in the region (CS) (Natural Resources Institute Finland, 2018a) or adjusted (AES) as follows: in the AES model, biomass from the green manure leys is harvested for anaerobic digestion in the biogas plant. The digestate is recycled to non-leguminous crops. Based on published research (Möller et al., 2008; Stinner et al., 2008; Möller and Müller, 2012), the digestate had 10–28% better fertilizer value in terms of crop response than the same biomass used as green manure. An added benefit is that, while green manure is used in the same field parcel in which it was grown, recycling in the form of digestate allows for re-allocation of nutrients based on optimization between the parcels.

To estimate the achievable yield increases resulting from the advantages described earlier, we calculated how much readily available soluble N (nitrite $NO_2^-$, nitrate $NO_3^-$, and ammonium $NH_4^+$) for plants the digestate from biogas production would include. This was based on the nutrient value of the feeds used. After that, we assumed that the soluble N in the digestate would be used to fertilize non-leguminous crops in the crop rotation, thus increasing yields. Based on these calculations, we estimated that 30 kg of soluble N ha$^{-1}$ (total N 150 kg ha$^{-1}$), available for non-leguminous crops in the AES model, increased cereal yields by 40%, compared to the traditional organic farming practice in CS. The 40% yield increase is factored in the modeling. This is based on N-rate yield response modeling by Valkama et al. (2013). This model was a meta-regression with both Mitscherlich-type exponential and quadratic fit. It was based on various Finnish N fertilizer experiments for low-yielding spring cereals in 1940–2014 at 17 sites in Finland. The nutrient content of the digestate (Table 2) was derived from the nutrient contents of the feedstocks used multiplied by a solubility factor of 1.2 (Möller and Müller, 2012) to obtain the definitive soluble N value for the digestate. Grass biomass value was based on average values for silage obtained from National Feed tables (Natural Resources Institute Finland, 2018b). The value for horse manure was based on results from Luostarinen et al. (2017). The N content of the hen manure was taken from Luostarinen et al. (2017). Because of gaseous N losses from the manure, N content could not be calculated from the input-output balance. P content of the hen manure was calculated from the input-output balance by subtracting the P content of the produced eggs and the disposed hens from all the P inputs to the hennery. Other parameters and explanations for nutrient flow analyses are given in Table 3.

### Table 1
Field use and yields* in the CS and AES models.

| Field use                  | Area (ha) CS | Area (ha) AES | Yield kg ha$^{-1}$ in CS | Yield kg ha$^{-1}$ in AES |
|----------------------------|--------------|--------------|--------------------------|--------------------------|
| Rye                       | 40           | 40           | 1900                     | 2660                     |
| Oat                       | 42           | 32           | 2100                     | 2940                     |
| Barley                    | 25           | 25           | 2300                     | 3220                     |
| Wheat                     | 35           | 70           | 2000                     | 2800                     |
| Pea                       | 20           | 20           | 1800                     | 1800                     |
| Pea-oat intercrop         | 51           | 57           | 2100                     | 2100                     |
| Green manure leys         | 142          | 111          | 20,000                   | 20,000                   |
| Nature management fields  | 20           | 20           | 15,000                   | 15,000                   |
| Buffer zones (not in crop rotation) | 9  | 9           | 10,000                   | 10,000                   |
| Vegetables                | 1            | 1            | 12,000                   | 12,000                   |
| Total area                | 385          | 385          |                          |                          |

* The crop yields in the CS model are based on average organic crop yields in the region (Natural Resources Institute Finland, 2018a) while the higher yield is factored in the AES model.

### 2.3. Energy consumption and production

Data on energy use were collected from the farms and, for the biogas production and the bakery in the AES model, we used data collected in the R&D project, where the functions of symbiosis were planned (Helenius et al., 2017). The energy consumption data included the...
Table 2
Nutrient content, biomethane production, and the quantities of feeds used in biogas production. The nutrient values are based on average values in the National feed tables (Natural Resources Institute Finland, 2018b) and biomethane production ($CH_4$ Nm$^3$ a$^{-1}$) is calculated based on biomethane potential values reported by Seppälä et al. (2009), Wahid et al. (2015), Mönch-Tegeder et al. (2013), and Kafle and Chen (2016).

| Flow | Flow | Explanation | Reference |
|------|------|-------------|-----------|
| 1 | Nitrogen deposition | Nitrogen deposition to the arable land of AES. Derived from the nitrogen deposition to the area of the Hyvinkää municipality in 2016. | SYKE, 2018 |
| 2 | Nitrogen fixation | Biological nitrogen fixation (BNF) according to a formula described by Anglade et al., 2015. The values used for BNF were: Green manure leys 222 kg ha$^{-1}$ (Yield 20,000 tn a$^{-1}$ FM$^*$), Nature management fields 183 kg ha$^{-1}$ (Yield 15,000 tn a$^{-1}$ FM), Pear 71 kg ha$^{-1}$ (yield 1800 kg ha$^{-1}$), and pea-oat intercrop 25 kg ha$^{-1}$ (pea yield 525 kg ha$^{-1}$). | Anglade et al. (2015) |
| 3 | Digestate | Combined nutrient content of feeds (Table 2) subtracted from the estimated nitrogen loss during storage (6%). | Paavola and Rintala (2008) |
| 4 | Crop sales | Cropping area multiplied by average organic crop yields in region multiplied by yield increase 40% for digestate-fertilized crops (explained in the text). Nitrogen and phosphorus content of the crops based on the literature. | Natural Resources Institute Finland (2018a) |
| 5 | Green manure leys | Harvested silage to biogas production. Silage nutrient content was based on the nutrient value of late-harvested red-clover/timothy silage. | Natural Resources Institute Finland (2018b) |
| 6 | Flour | Demand for the bakery (personal communication). Nitrogen and phosphorus content based on the literature. | Personal communication with Zukale, P. (2016) and Antikainen et al. (2005) |
| 7 | Feed | Demand for the henry (personal communication). Nitrogen and phosphorus content based on the literature. | Personal communication with Latostenmaa V. (2017) and Natural Resources Institute Finland (2018b) |
| 8 | Bread | Same as flow 6. | Luostarinen et al. (2017) |
| 9 | Horse manure | Feedstock to the biogas plant as an input to the system. Nutrient content based on the literature. | Luostarinen et al. (2017) |
| 10 | Organice fertilizer | Organic fertilizers utilized on the farms in the CS model. | Cultivation notes |
| 11 | Chicken manure | Organic fertilizers utilized on the farms in the CS model. | Cultivation notes |
| 12 | Chicken feed | The quantity of concentrate used in the henry. Nutrient values were obtained from the concentrate manufacturer. | Personal communication with Latostenmaa V. (2017) and Hemmila T. (2017) |
| 13 | Ready-to-lay poultry | Ready-to-lay hens into the henhouse. | Anal. Methods (2014) |
| 14 | Eggs | Average egg production per chicken per year multiplied by the number of hens in the henhouse (5600). | Arö (1998) |
| 15 | Hens | Hens out. | Anal. Methods (2014) |
| 16 | Losses | Nitrogen leaching and gaseous losses from the arable land were calculated by subtracting the phosphorus content of the produced eggs and the disposed hens from all the phosphorus inputs to the henry. | Tattari et al. (2017) |
| 17 | Losses | Nitrogen losses from the biogas production to be 6% during storage. | Paavola and Rintala (2008) |
| 18 | Losses | Nitrogen losses from the henhouse = Inputs – Outputs. | — |

Table 3
Explanations: dry matter (DM), fresh matter (FM), Total nitrogen (TN), Soluble nitrogen (SN), Total phosphorous (TP). *To determine the digestate's soluble nitrogen content, we used a solubility factor of 1.2 based on the review study by Möller and Müller (2012). Electricity and heating needed for agricultural operations, the energy needed for bread baking in the bakery, fuels for the machinery, and the biogas plant’s own energy consumption. All the energy consumption needed for bread baking in the bakery, fuels for the machinery, and the electricity and heating needed for agricultural operations, the energy consumption due to erosion and leaching were based on the literature and is expressed as normal cubic meters (Nm$^3$). The BMP for silage, 298 Nm$^3$ CH$_4$ tn$^{-1}$ total solids, was based on values (229–353 Nm$^3$ CH$_4$ tn$^{-1}$ for various herbaceous grasses) reported by Seppälä et al. (2009) and the values (292–320 Nm$^3$ CH$_4$ tn$^{-1}$) reported by Wahid et al. (2015) for grass-clover mixtures. We determined the BMP for horse manure as 120 Nm$^3$ CH$_4$ tn$^{-1}$ total solids based on values (88–196 Nm$^3$ CH$_4$ VS$^{-1}$) reported by Mönch-Tegeder et al. (2013) and we used the value 324 Nm$^3$ CH$_4$ tn$^{-1}$ total solids for chicken manure, based on results by Kafle and Chen (2016). We assumed that the whole biomethane potential was realized over a digestion time of three months.

4. Uncertainties and sensitivity analysis

The uncertainty of various factors was determined by classifying them into three different uncertainty levels (10, 20, and 30%) (Supplementary Table 1). The classification was based on ranges used by Antikainen et al. (2005). To account for the variability in flows depending on management decisions and the availability of, for example, horse manure imported from neighboring farms, we relied on personal communication with the operators of Palopuro AES. After assigning uncertainty levels to each factor, data reconciliation was performed using the STAN data calculation tool for uncertainty reconciliation (Cencic and Rechberger, 2008). The sensitivity of results of the models’ outputs to variation to input parameters was tested by changing the parameter values one-by-one.
while keeping other variables equal. After this we reran the calculation. To observe the sensitivity of the calculated nutrient surpluses from arable land, we changed the original values within the uncertainty ranges. To observe the sensitivity of energy production, we changed the feed dry matter (DM) content ± 10%, and to observe BMP sensitivity, we used the minimum and maximum value ranges from the literature, as explained earlier.

3. Results

3.1. Nutrient flows

Compared to CS, circulating the grass biomass and manure through the biogas plant in the AES increased the mobile N input to the arable land, which resulted in increased crop production and reduced nutrient losses from the system (Table 4). Nitrogen and P surpluses were reduced by 36 kg ha\(^{-1}\) (1–70 kg ha\(^{-1}\)) and 3.9 kg ha\(^{-1}\) (2.8–5.1 kg ha\(^{-1}\)), respectively, compared to CS. Also, the smaller area for green manure leys reduced the biological nitrogen fixation (BNF) resulting in smaller N surpluses.

By far, the most substantial N input to both systems was BNF from the atmosphere (Fig. 2). In the AES model, BNF was 30% smaller than in the CS model. The BNF quantity resulted in the greatest uncertainty in N surplus (Table 5). The most substantial P input was derived from the hen manure (Fig. 3). This was due to net imports of chicken feed concentrate, as the exported eggs only contained 21% of the P imported in the feeds. Also, horse manure contributed a substantial quantity of P to the system, resulting in 43% of the total P imports. In the CS model, the majority of P was imported in the form of organic fertilizers (Table 4), which were no longer used in the AES model. In both models, crop sales formed the largest N and P exports.

3.2. Energy production

The AES produced 2809 MWh gross energy from the green manure leys, fallows, and manures (Table 6). Silage harvest from the bioenergy-green manure leys was the most important feedstock to biogas production. This produced approximately 83% of the total energy while contributing only 71% to the total quantity of feedstock materials used in biogas production. The share of horse manure in the feedstock was 23%, but its contribution to produced energy was only 10%. The operations of the AES consumed ca. 59% of the quantity of produced energy.

Energy production from the biogas plant was very sensitive to feedstock quality (Table 7). Energy production was increased when the horse manure was replaced by silage with a higher biomethane potential.

4. Discussion

Our study showed that biogas production based on utilizing biomass available within the farming system has the potential to increase primary production in farming, reduce nutrient losses, and produce renewable energy in excess while enhancing nutrient recycling.

4.1. Increased nutrient use efficiency

Reduced N and P surpluses and increased nutrient use efficiency were consequences of increased crop production from arable land, which led to greater outputs from the system. In the AES model, the biogas plant plays a key role in nutrient recycling and in increased system-level plant nutrient use efficiency by allowing for spatial and temporal nutrient re-allocation in the crop rotation without importing new nutrient inputs from outside of the system.

The projected cereal yield increase was 40% for the AES model compared to average yields on organic farms without livestock in Southern Finland. The digestate from biogas production enabled an increased quantity of soluble N to be available for crops in spring, thus enhancing crop growth. The positive effect on cereal yields attained by using digestate as a fertilizer is supported by findings from other studies, though the reported effects have been smaller; 10% by Stinner et al. (2008) and 14% by Brozyňa et al. (2013). Farmers have reported a 20–25% yield increase and increased protein content for cereals in a survey conducted in Germany (Blumenstein et al., 2015). In the AES model, the assumption of a yield increase was based on modeling results from metadata by Valkama et al. (2013): these indicated substantial yield responses when original yields were low, as is the case in stockless organic farming in Finland. Similar yield responses (37–38%) were achieved in a study by Blumenstein et al. (2018), where the impact of integrated biogas production was modeled on yields in stockless organic farming. However, the 40% yield increase presents the potential achievable yield increase in situations when no other factors, such as unfavourable weather conditions or weed competition, limit the yield response. We used the ± 20% sensitivity range for the yield response to the digestate to account for situations where agricultural yields vary depending on many factors not included in the modeling.

In both the AES and CS, nutrient imports into the system were equivalent with the exception of BNF, which was substantially influenced by the reduced field area needed for green manuring due to enhanced nutrient use efficiency. As a result, the nitrogen surplus was reduced by 38% in the AES model compared to CS. This reduction was further augmented by increased crop yields per hectare and per system. Nitrogen losses were reduced, but further specification of these N losses to air or water was not included in this study. Dahlin et al. (2011) compared how harvesting the green manure vs. mulching affects N recycling in field experiments. They suggested that harvesting the green manure leys’ biomass is likely to reduce both gaseous losses to the atmosphere and nutrient leaching compared to conventional mulching where grass mulch is left on the ground.

In our study, we assumed that BNFs from green manure leys were equal in both models. However, biomass harvesting can result in increased BNF. Hatch et al. (2007) found that clover leys increased BNF...
by 9–61 kg ha$^{-1}$ compared to treatments where clover was mulched and left on the ground. Stinner et al. (2008) reported that reduced soil N availability was compensated for by enhanced BNF, resulting in equal pea yields. However, biomass harvest has not always enhanced BNF, as Dahlin and Stenberg (2010) have reported. According to Dahlin et al. (2011), only 14% of the N from the aboveground biomass is recycled back into grass growth when used as green manure.

In the AES model, the P balance was slightly negative ($-0.5$ kg P ha$^{-1}$), whereas a surplus of 3.4 kg P ha$^{-1}$ in the CS was near the average balance of 4 kg P ha$^{-1}$ in Finland (OECD, 2018). As with N, this caused by larger yields in the AES model, which resulted in increased P exports from the system. Phosphorus exported out of the system, including erosion, was replaced by imports in the form of horse manure and concentrate feed for hens (Fig. 3).

In our study, the henery contributed 34% (CS) and 57% (AES) of total P imports to the system, in the form of feed concentrate, but only 14% (CS) and 10% (AES) of the total P exports, in the form of eggs. Most of the P in the chicken feed is excreted in the manure. This results

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**Fig. 2.** Nitrogen flows (tn a$^{-1}$) in the AES and CS models. The width of the arrow is proportional to the flow rate. Blue arrows illustrate imports into and exports out of the system, red arrows illustrate the losses from the system, and black arrows are flows within the system. Explanations of the flows are provided in Table 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
in a potential risk for P accumulation in soils where manure is used continuously. Such an outcome was reported in Finland by Uusitalo et al. (2007), who observed greater P balances resulting in increased P contents in the soils of livestock farms compared to arable crop farms.

In light of the slightly negative P balance in the AES model, imports are needed to compensate for the exports to maintain soil fertility. As an

| Sensitivity scenario | Nitrogen surplus CS kg ha$^{-1}$ | Nitrogen surplus AES kg ha$^{-1}$ | Phosphorus surplus CS kg ha$^{-1}$ | Phosphorus surplus AES kg ha$^{-1}$ |
|----------------------|---------------------------------|---------------------------------|---------------------------------|-----------------------------------|
| Green manure ley biomass +20% | 16.0 | 12.5 |
| Green manure ley biomass −20% | −16.0 | −12.5 |
| Crop yields (cereals) +20% | 2.7 | 2.0 |
| Crop yields (cereals) −20% | 2.0 | 0.5 |

Table 5
Sensitivity to change in model parameters to the model outcomes of nitrogen and phosphorous surpluses.

Fig. 3. Phosphorus flows (tn a$^{-1}$) in the AES and CS models. The width of the arrow is proportional to the flow rate. Green arrows illustrate imports into and exports out of the system, red arrows illustrate the losses from the system, and black arrows are flows within the system. Explanations of the flows are given in Table 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Table 6
Gross energy production and consumption in the AES model.

| Energy produced, and current energy use (MWh a⁻¹) |
|--------------------------------------------------|
| Produced energy:                                |
| Silage                                           | 2809 |
| Horse manure                                    | 288  |
| Chicken manure                                  | 185  |
| Consumed gross energy*:                         | 1650 |
| Biogas plant                                     | 390  |
| Cereal farm                                      | 625  |
| Machinery                                        | 250  |
| Grain drying                                    | 250  |
| Electricity                                      | 125  |
| Hennerly                                         | 275  |
| Vegetable farm                                  | 10   |
| Bakery                                          | 350  |
| Energy surplus                                  | 1159 |

* Consumed electricity was converted to needed primary energy using a factor of 0.4 (Boyce, 2001)

Table 7
The effect of increasing and decreasing various parameters in the energy production. Silage biomethane potential min. and max. Values described earlier.

| MWh a⁻¹ |
|---------|
| Silage DM content +10% | 234 |
| Silage DM content -10% | −234 |
| Silage biomethane potential max. value | 432 |
| Silage biomethane potential min. value | −541 |
| Replacing 500 t of horse manure by silage | 179 |

outcome of decades of mineral fertilization at rates exceeding plant uptake, current P levels in Finnish farmland soils are high and yield losses are not expected in short term, even if negative P balances are maintained (Ylivainio et al., 2014).

The AES is not a fully closed system, because certain nutrients are imported into and certain nutrients are exported out of the system in the form of crop sales. Nitrogen required in crop production can be supplied by BNF, but with P the interpretation of a desirable level of self-sufficiency depends on the intrinsic or historic soil P level.

4.2. From energy consumer to energy producer

The AES model converted the studied production system from an energy consumer to a net energy producer by taking advantage of available biomasses within the system that were not used in food production. Seventy percent more biogas was produced than was consumed in total by the farm operations, bakery, and biogas plant (plant’s own energy needs).

In the AES model, biomasses from within the system boundaries, which included the green manure leys and chicken manure, produced energy equal to 7.29 MWh ha⁻¹ in the AES field area. The biomethane potential of horse manure is substantially lower than that of silage and chicken manure (Seppälä et al., 2009; Möhlin-Tegeder et al., 2013; Wahid et al., 2015; Kafle and Chen, 2016). In terms of energy production, horse manure was not an important feedstock and could be replaced by crop residues such as a straw. However, horse farms often lack fields for manure spreading, which means they may be willing to pay biogas companies for manure management.

4.3. Sensitivity analyses

Results were sensitive to certain input factors in both models. Changes in grass biomass produced ha⁻¹ substantially affected N balances as the formula for calculating BNF was based on the quantity of biomass produced. Biogas production was most sensitive to the quality of green manure leys, which were used as feedstock in biogas production.

4.4. Applicability and limitations of the study

Our study explored how integrating biogas production into a cereal production system affected nutrient flows and energy self-sufficiency in an integrated system of organic farming and food processing. Our study focused on one AES case located in southern Finland. The results confirm previous findings that nutrient recycling from green manuring through a biogas plant is productive in stockless organic farming. The introduction of dry biogas production into a stockless organic crop rotation therefore allows for the arable area allocated to green manuring crops to be reduced, which further negates undue competition between fuel and food competition.

The case study further demonstrates that food production and processing can be made energy-positive through its own bioenergy, with a dramatic climate change mitigation benefit through the replacement of fossil energy. This requires re-localizing to the scale required for AES. The results cannot be directly applied to other AES, as the concept requires situated system designs.

The green manure leys in the AES model have an important function: their purpose is even more multi-functional than typical in organic crop farming. On organic farms, green manure leys are traditionally used for BNF, soil conditioning, and weed suppression. In the AES model, the leys maintain these functions while also serving as feedstock for biogas production and for the production of recyclable digestate, allowing for more efficient use of BN and nutrient reallocation within the system to better meet crop nutrient demand.

Based on the results of our study, net energy production is significant in areas not used in food production. If the fallows available in all of Finland were farmed for biogas feedstock with the same productivity as in this study, they would produce over 4 TWh a⁻¹ of energy. As a comparison, the motor fuel oil consumption in Finland's agriculture and horticulture sector was 2.45 TWh a⁻¹ in 2016 (Official Statistics of Finland, 2016).

In Finland, the proportion of perennial green manure leys is larger than in organic crop farms in other Northern European countries or in Central Europe. In terms of energy production, this makes the implementation of the AES system described in this study specifically relevant to Finland, and more challenging in these other areas.

The results are applicable in stockless organic crop farms. However, both organic and conventional farms typically have fallow land in addition to cash crops or rotational green manure leys. This is a typical situation in Finland, where 11% of agricultural land was fallows in 2017 (Natural Resources Institute Finland, 2018a), creating a substantial potential resource for biogas production. However, yield increases as described in our study would not apply to conventional systems, as there, the digestate would be replacing mineral fertilizers. This would require re-parameterization of our model for non-organic conditions.

4.5. Further research questions

The feasibility of the AES mode-of-action needs to be studied for a range of food products in variable production conditions at various spatial and organizational scales. In addition to food and energy production and nutrient recycling, impacts on soil functions, such soil carbon content, on greenhouse gas emissions, and on biodiversity should also be studied at the farm level and at a regional scale.

In our case study, the integration of food processing and primary production at the farm did not influence nutrient flows, because there were no losses from the bread-baking process. Other types of food processing, such as dairy processing, meat processing, or vegetable
cleaning and peeling processes, could potentially provide additional waste biomasses that could be utilized in energy production and subsequently recycled back into food production. However, it is notable that with a redesign for AES, a bread system can be converted from an energy consumer to an energy producer, from primary production to deliveries.

In more intensive farming systems, the risk for trade-offs in various farmland functions increases. For example, there might not be as much available grass biomass that could be utilized in biogas production without competing with the conventional food production. However, especially in warmer climates, a longer growing season means a greater potential for cover crops to produce substantial biomasses, which can function as an alternative feedstock in biogas production without competing with other farmland functions.

In this study, results were based on modeling. The Palapuro AES case needs to be evaluated by direct measurements and competing with other farmland functions. Potential for cover crops to produce substantial biomasses, which can especially in warmer climates, a longer growing season means a greater without competing with the conventional food production. However, available grass biomass that could be utilized in biogas production deliveries.

In this study, we also explored the potential of biogas digestates as a new source for energy production. Our results demonstrated the impacts of biogas production on nutrient flows and energy production. However, other environmental impacts, including soil organic matter changes and greenhouse gas emissions, should be studied in the future. Also, the N value of digestates should be studied with plot experiments. Further studies concerning variable production conditions, including other types of food production systems, are needed to gain full understanding of the potential of an AES for sustainable food production.

Acknowledgements

We would like to thank the Ministry of the Environment in Finland for funding the Palapuro AES project. The authors also wish to thank all the participants in the Palapuro AES project: especially Markus Eerola from Knehtilä Farm, Virva Latoestmanna from Mäntytmie luomu Ltd, Peter Zuzale from Samsara Ltd, and Jukka Kivelä from the University of Helsinki. We are also grateful for two anonymous reviewers who gave their comments.

This work received funding from the Finnish Ministry of the Environment's Programme (RAK12) to promote the recycling of nutrients and improve the ecological status of the Archipelago Sea [grant number YM52/481/2015].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agee.2017.10.016.

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