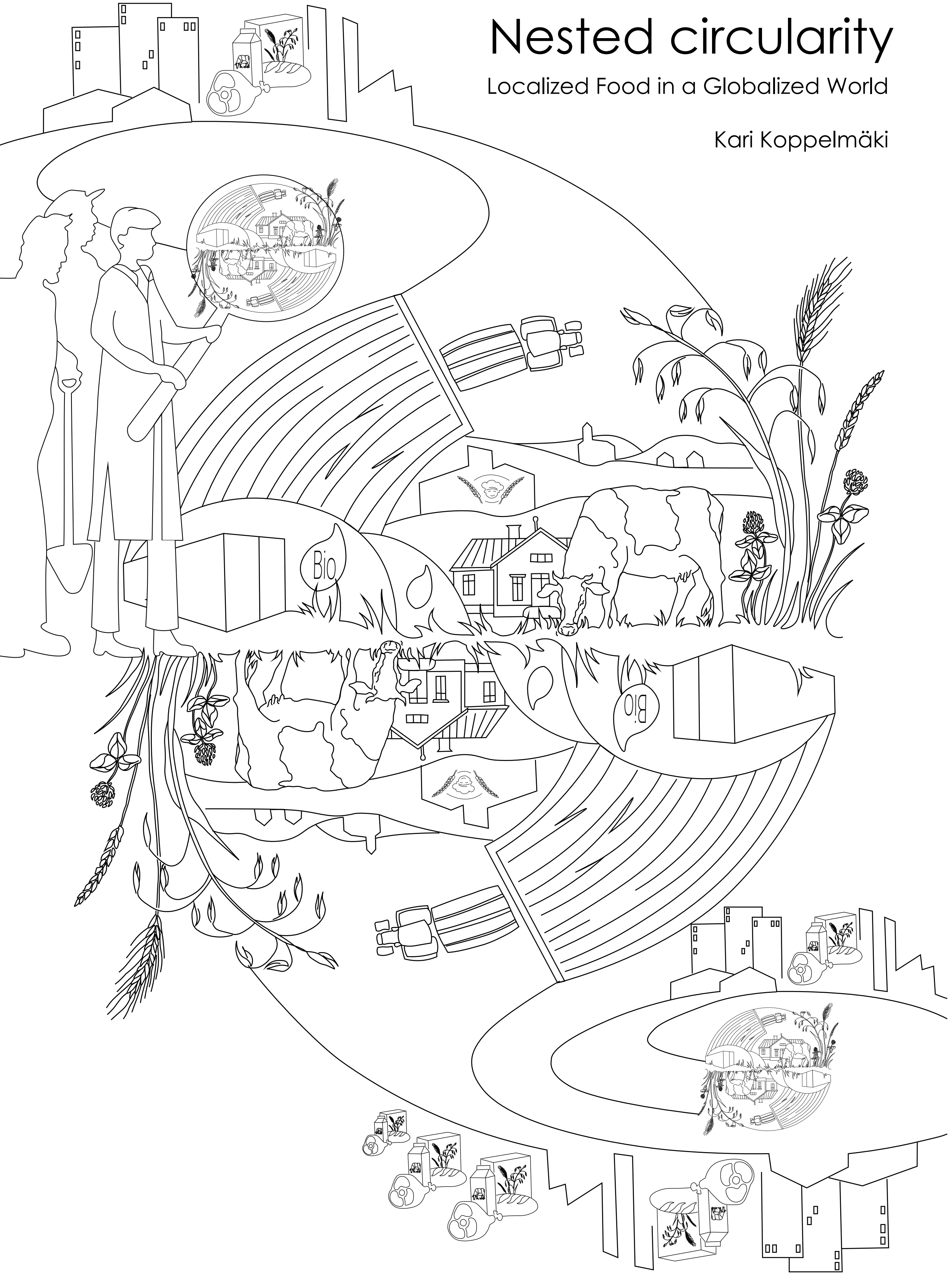
Nested circularity

Localized Food in a Globalized World

Kari Koppelmäki



Propositions

1. Synergies in the multifunctional use of biomass outweigh food-fuel competition. (this thesis)

2. Biomass-nutrient-energy integration is key to localized circular food production. (this thesis)

3. The use of robots in agriculture can only be sustainable when farmers have greater sovereignty in the food system.

4. The challenge of understanding complexity by stakeholders, including scientists, should not be overlooked in the dissemination of science.

5. The line between realism and idealism is thinner in real life than in our minds.

6. Combining a PhD project with farming provides exceptional synergies if the trade-offs in time management are resolved.

Propositions belonging to the thesis entitled

Nested Circularity – Localized Food in a Globalized World

Kari Koppelmäki

Wageningen, 30 August 2022

Nested Circularity – Localized Food in a Globalized World

Kari Koppelmäki

Thesis Committee

Promotors

Prof. Dr R.P.O. Schulte
Professor of Farming Systems Ecology
Wageningen University & Research

Prof. Dr J. Helenius
Professor of Agroecology
University of Helsinki, Finland

Other members

Dr P. Reidsma, Wageningen University & Research
Prof. Dr L. Alakukku, University of Helsinki, Finland
Dr H. Känkänen, Natural Resources Institute Finland (Luke), Jokioinen, Finland
Dr A. Müller, Research Institute of Organic Agriculture (Fibl), Frick, Switzerland

This research was conducted under the auspices of the Doctoral Programme in Sustainable Use of Renewable Natural Resources of the University of Helsinki, Finland, and the Graduate School of C.T. de Wit Graduate School for Production Ecology & Resource Conservation of Wageningen University & Research, The Netherlands.

Nested Circularity – Localized Food in a Globalized World

Kari Koppelmäki

Thesis
submitted in fulfilment of the requirements for a jointly supervised bi-national doctorate
between
The University of Helsinki
by the authority of the Faculty of Agriculture and Forestry
and
Wageningen University
by the authority of the Rector Magnificus,
Prof. Dr A.P.J. Mol
in the presence of the
Thesis Committee appointed by the Academic Boards of both universities
to be defended in public
on Tuesday 30 August 2022
at 1.30 p.m. in the Omnia Auditorium.

Kari Koppelmäki
Nested Circularity – Localized Food in a Globalized World

A jointly supervised bi-national doctorate (PhD) thesis, University of Helsinki, Finland, and Wageningen University, the Netherlands (2022)
With references, with summary in English

ISBN: 978-94-6447-333-9
DOI: https://doi.org/10.18174/574488

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Chapter 1

General Introduction

Kari Koppelmäki

1.1 A brief history of linear food systems

Humans began cultivating land to grow biomass for food about 10,000 years before the common era (BCE). Throughout the Holocene, land use intensified gradually along with population growth, transforming ecosystems across the globe (Ellis et al., 2015). However, this cultivation did not reach global significance until the recent centuries. A reason for lower impact of land use in the past was that food was only produced using locally available resources. For example, cattle grazed in pastures and nutrients in the manure were circulated in the fields, which were adjacent to the cattle house. The energy needed to produce food was also locally generated. Humans and farm animals provided the labour for food production. Food production relied on solar energy, which was transformed into biomass in the vicinity of the land where food was produced. Consequently, the environmental impacts of food production were also local.

Intensification of agriculture

The early intensification of agriculture involved the shift from human labour to animal power, the use of organic fertilizers including manure, human excreta and the crop residues, and the greater variety of crops and animal breeds (Smil, 2017). In Western Europe agriculture began to intensify significantly during the 18th century due to innovations that slowly spread across the European continent. One early innovation was replacing plowed fallows with crop rotations that included legumes and root crops. This shift in production resulted in an increase in domestic cattle (Vasey, 1992). The use of farm animals to power field work increased productivity and required fewer people to be directly involved in food producton (Smil, 2017). Until the advent of fossil fuels, agriculture relied solely on animate power which limited the intensification of food production because part of the farmland had to be allocated for feed production to support the work animals.

The mechanization of agriculture through technological innovation, including the motorization and the use of mineral fertilizers was the biggest driver for the intensification of agriculture (Jepsen et al., 2015; Smil, 2017). The large-scale adaptation of these innovations was enabled through the use of fossil fuels. The greatest change brought by the implementation of fossil energy was a population expansion coupled with a higher per capita supply of food. The use of mineral fertilizers was central in these shifts (Smil, 2017).

The use of external nutrient resources in food production began initially in the 19th century. However, the industrial scale production of nitrogen-based fertilizers in the early 20th century heralded a new phase in agricultural innovation. This was due to the discovery of the Haber-Bosch process, which enabled converting atmospheric gaseous, non-reactive nitrogen (N_2) to ammonia (NH_3) (Bouwman et al., 2011). This new era had unprecedented impacts to the food production and life all over the globe (Bouwman et al., 2011; Vasey, 1992; Vitousek et al., 1997). During this era humans began to transform the planet at anccelerating speed (Erisman et al., 2008; Vitousek et al., 1997).

The Western European industrialization of agriculture accelerated again after World War II (Jepsen et al., 2015). Mineral fertilizers eliminated the requirement for integrated crop and livestock production since manure could be replaced with these industrially produced fertilizers. Livestock that were traditionally utilized for field work were replaced by more efficient machines which enabled managing larger areas in less time compared to the time required when using the labor of oxen or horses to pull farm equipment. In Finland in the 1950s, just before agricultural intensification began, there were about 400,000 horses (Lith, 2006) whose purpose was physical labor in primary production. Mechanization allowed land that was previously needed for growing feed for horses to be used to grow food for humans. With the advent of industrialization in agriculture, thousands of years of integrated food and energy production, came to an end in most parts of the Western world.

The increased spatial scale of food systems

The second effect of fossil fuel powered mechanization and use of mineral fertilizers was an enlargement of the spatial scale in food production. This transitioned food production, once relying on immediate resources, to the current globalized system where inputs are less dependent on the context where the food is produced. This has allowed for an increase in farm size as inputs could be imported and mechanization has allowed larger areas of land to come under cultivation. This expansion in spatial scale has impacted the food system from the field to food consumption. As food consumption has become increasingly global, the geographical gap between food production and consumption has increased (Kastner et al., 2014; Naylor et al., 2005).

International trade has enabled globalizing food systems. This trade is currently essential for global food security (Kummu et al., 2020). However, agricultural trade is not a new phenomenon. It has existed for thousands of years in different forms. Initially, trade mostly spread new food crops and domesticated animals (Anderson, 2014). The use of domesticated animals and technological innovations related to mechanization increased the size of food systems as the food and biomass produced could be transported further away from the point of origin (Vasey, 1992). Though relatively remote, even Finland was connected to distant countries through the food trade already in the 14^{th}-16^{th} century. For example, fish was exported from Finland and wine and spices were imported through the networks of the Hanseatic League (Kylli, 2021).

Between its production and consumption, a large proportion of food produce is processed. As such, the role of food processing is an important factor to assess when examining the changes in food production. Processing is needed to convert most of the primary produce to food products thus influencing the type of food we eat, and how and where it is produced (Hendrickson, 2015; Knorr and Watzke, 2019). The continued concentration of actors and geographies in the food business has resulted in in a loss of regional processing and has contributed to regional specializations of primary productions, and to homogenization trends in agricultural landscapes. (Hendrickson, 2015; Rotz and Fraser, 2015).

Trade-offs between increased food production and the environment

The changes in food production in the past 100-150 years have altered the structure and functioning of ecosystems, with many trade-offs between food production and environmental protection (Campbell et al., 2017; Ellis et al., 2013; Foley et al., 2005; Steffen et al., 2015; Vitousek et al., 1997). The industrialization of agriculture has resulted in imbalances in nutrient flows as inert soil and atmospheric nutrients are converted into reactive fertilizers across multiple specialities from the farm to the global scale (Kahiluoto et al., 2021; Potter et al., 2010). Other impacts of industrialization include, for example, increased reliance on fossil energy, carbon losses from the soil, and homogenous landscapes and reduced biodiversity (Foley et al., 2005; Steffen et al., 2015).

The sustainability of food production is further challenged by projected future increases in demand for food. Globally, the main drivers for the growing demand for agricultural products are population growth and dietary change towards increased consumption of livestock products (Alexandratos and Bruinsma, 2012; Delgado et al., 2001). The world population is projected to reach almost 10 billion people by 2050 (UN, 2019). While agricultural intensification has enabled this rapid population growth, it has also prompted further challenges to agricultural systems' ability to continue providing enough food for this increasing population. However, in many countries, dietary change towards an increasing consumption of livestock products is expected to supersede population growth as the dominant driver of agricultural land use (Fukase and Martin, 2020; Kastner et al., 2014).

In recent decades, livestock production in particular has resulted in an increase in production systems which are detached from local feed production (Bai et al., 2018; Naylor et al., 2005). This change has been driven not just by increased demand, but also by subsidies and agri-environmental policies that have favored the concentrated livestock production (Bai et al., 2018; European Court of Auditors, 2021). Specialized livestock systems often compete for land with food crops as feed for animals is grown, at least in part, on land that is also suitable for production of food for direct human use (Zanten et al., 2018).

The demand for agricultural land is further accelerated by increased global energy consumption. This is because polices and subsides aimed at reducing dependence on fossil fuels and reducing greenhouse gas (GHS) emissions in order to meet sustainability goals has made bioenergy production from agricultural biomasses an attracitve option (European Commission, 2018; United Nations, 2015). These dynamics have raised concerns about food-fuel competition (Muscat et al., 2020; Tokgoz, 2019).

Circular food systems in the context of food systems

The great challenge to sustainable food is that the structure of food systems works against many of the sustainability goals. The concepts of circular (bio)economy has gained interest as a model for redesigning systems to meet environmental challenges without having economic trade-offs within these systems (e.g. D'Amato et al., 2017). In the context of food systems, a circular bio-based economy has been proposed as a new way to organize food systems to support sustainable food production in the future (Muscat et al., 2021). The central principles of circular food systems include the recycling of nutrients, reusing by-products, avoiding losses, and using renewable energy (Cowie, 2020; Jurgilevich et al., 2016; Muscat et al., 2021).

The aforementioned reasons have created a demand for a circular system design that considers multiple facets simultaneously and aims for synergies between different components of food systems. In this thesis, I explore biomass-energy-nutrient nexus (Figure 1) and how a circular design for localized food production in a globalized world could look in the context of the Finnish food system.

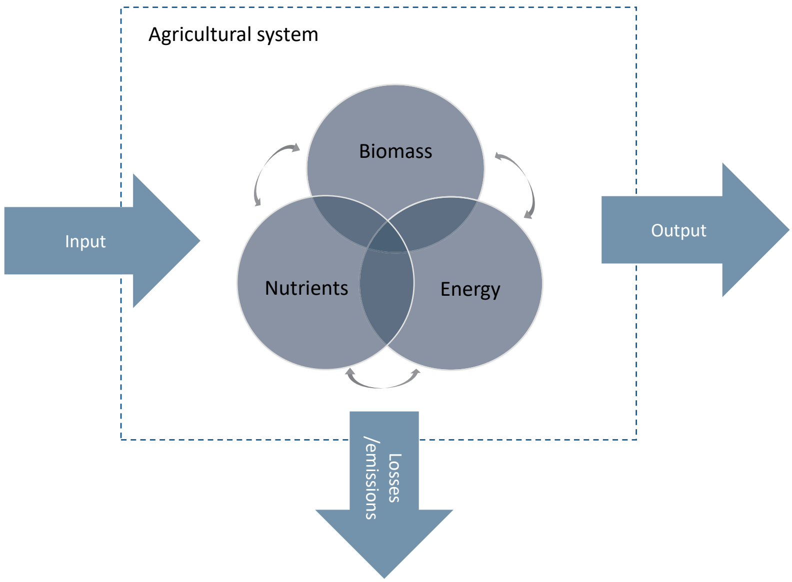

Figure 1. The nexus of biomass, nutrients and energy. In an agricultural system biomass production requires both nutrients and energy while biomass can also be used as a recycled nutrient source for plants and to produce energy. In most systems biomass (feed), nutrients (fertilizers), and energy (fossil fuel) is used to produce food which is the main output of most agricultural systems.

1.2 Circular food production in the nexus of biomass-energy-nutrients

1.2.1 Increased demand for biomass for food and feed

As stated earlier, there is an increasing demand for food systems that produce more biomass for food. In order to secure basic human needs without the depletion of natural resources and in the context of circularity, Muscat et al. (2021, 2020) have proposed that directly producing food for humans should be prioritized over the biomass production for feed or energy. When following the cascading principles of biomass use with the idea of maximizing resource use efficiency, the role of livestock in food systems should be to make use of biomasses that are not edible for humans (Muscat et al., 2021; Van Zanten et al., 2019; Zanten et al., 2018).

These principles have been defined in a global context. However, demand for food and feed is not distributed evenly across the globe. Livestock production has a key role in creating demand for agricultural land and in how this demand is distributed. Globally livestock production uses nearly 80% of agricultural land and 40% of crop land (Mottet et al., 2017). In many parts of the world, livestock production has been detached from the land where feed is produced (Naylor et al., 2005; Renner et al., 2020). Furthermore, in Europe and China, increased imports of soybean and corn are reported to correspond with increased livestock production (Wang et al., 2018). This trajectory has been enabled by cheap transportation costs and trade liberalization, which has led to a shift toward the production of monogastric animals instead of the ruminants that have traditionally been used for grazing (Bai et al., 2018; Naylor et al., 2005). Consequently, animal feed production corresponds to 44% of global phosphorus flows while food commodities correspond to just 28% (Nesme et al., 2016).

In addition to unevenly distributed livestock production, human population has also become more concentrated. Currently, more than half of world population lives in urban areas (United Nations, 2018). Subsequently, the concentration of food consumption has accelerated. Therefore, regions with low population often function as net producers of food, which enables cropland to be used for exports, while regions with high population are net consumers of food, relying on externalized cropland for imports (Erb et al., 2009; MacDonald et al., 2015). Globally, approximately 20-25% of the harvested cropland area is devoted to producing food that is subsequently exported (Kastner et al., 2014; MacDonald et al., 2015).

Furthermore, 81% of the world population currently live in the regions where reliance on food imports is projected to increase (Alexandratos and Bruinsma, 2012; Fader et al., 2013; Porkka et al., 2013). Although the food trade is essential to achieving food security in the global food system, there are also direct and indirect adverse consequences of international agricultural commodity trade. Food and feed trade has been linked to land-use change because cropland expansion is largely driven by export-oriented crop production (Huber et al., 2014; Kastner et al., 2014; MacDonald et al., 2015). The use of mineral fertilizers and fossil energy has enabled agriculture to produce enough food for growing population (Bouwman et al., 2011; Smil, 2017). Yet, the international trade of agricultural products means that the emissions, created in the place of production are embedded in the products and are emitted far away from the place of consumption (Oita et al., 2016; Uwizeye et al., 2016).

1.2.2 (Bio)energy from agricultural biomasses– solution or burden?

In addition to food production, interest in using agricultural biomass for energy has grown in recent decades. This increase in interest is propelled by the desire to reduce society's dependence on fossil fuels. Bioenergy production can play an important role in circular systems by recovering energy from waste, nutrient recycling in primary production, and reducing GHS emissions (Cowie, 2020).

A food system's own energy demand is already substantial as the path that food takes from the field to consumers requires energy at each step of production. Energy is needed to manufacture inputs such as fertilizers, to run machinery on the fields, for food processing, transportation and storage, and finally in food preparation. Modern food systems are heavily dependent on non-renewable energy resources, including both direct and indirect inputs used throughout the food chain (Pelletier et al., 2011). Food systems consume about 30% of global energy (FAO, 2021). Primary production (crop and livestock production) accounts for around 20% of total energy consumption in food systems globally while food processing and distribution, retail, and cooking make up the rest. In high-income countries, food processing and distribution corresponds to almost half of energy consumption in food systems (FAO, 2021). Furthermore, since processed food consumption has grown in recent decades, the significance of food processing in energy consumption has increased (Crippa et al., 2021).

Bioenergy production from agricultural biomasses

As a result of rising demand for bioenergy, approximately 2% to 3% of arable land worldwide is used to cultivate feedstock for bioenergy production (Rulli et al., 2016). Currently, bioethanol production is the largest contributor to the global biofuel market, with the United States and Brazil as the largest users (Rulli et al., 2016). Globally, the most important potential sources of biomass for energy production are energy crops and agricultural residues (Slade et al., 2014).

In addition to liquid biofuel production (bioethanol or biodiesel) bioenergy can also be produced in the form of biogas from anaerobic digestion. It is estimated that full utilization of the global sustainable biogas potential would cover approximately 20% of the current natural gas demand. Current biogas production covers only 6% of this biogas potential (IEA, 2020). In Europe, the biggest potential is found in agricultural residues and intermediate crops. However, the estimates of global biomass potential vary greatly depending on if the estimate considers what is physically possible and whether the estimate includes the environmental and social constraints (Slade et al., 2014). For example, in Europe the actual biogas potential from manure was estimated to be around 70% of the theoretical potential (Scarlat et al., 2018b). Biogas production in Europe has increased in recent years, yet there are significant differences between countries (Scarlat et al., 2018b).

Negative environmental impacts of bioenergy production

Despite this substantial energy potential and increasing interest in bioenergy production, it has become clear that bioenergy production can have some negative trade-offs. Bioenergy production has been criticized for direct competition with food production for land, and for its increased use of resources due to feedstock production resulting in negative environmental impacts (e.g. Houghton et al., 2012; Rosegrant & Msangi, 2014; Searchinger et al., 2008). This criticism is often focused on so-called first-generation biofuels that are produced on arable land, using simple conversion technology (Wright and Wimberly, 2013). High corn and soybean prices resulting from high demand for biofuel feedstocks have been a driving force behind land use change. For example, in the United States of American and Germany, there are reports of conversion of grassland to soy and corn production for bioenergy feedstock (Lüker-Jans et al., 2017; Wright and Wimberly, 2013). Also, biogas production has resulted in food-fuel competition when produced from non-waste feedstock. In Germany, a subsidized biogas production have has resulted in higher food prices and in significant land use changes (Britz and Delzeit, 2013).

Changes in land use resulting from bioenergy production on farmland have contributed to increased GHG emissions from agriculture. Searchinger et al. (2008) calculated that bioethanol produced from corn almost doubled GHG emissions due to land use change. Food security is also affected. In their review, Ahmed et al. (2021) found that over half of related studies reported a negative impact from bioenergy production on food security. This negative impact was caused by increasing food prices, and direct competition for land that could be otherwise used for food production. Considering these factors, it is proposed that moving from first generation biofuel production towards biofuels that are produced from crop residues or non-food energy crops grown on marginal lands not suitable for food production is essential (Hammond and Seth, 2013).

Bioenergy production without food-fuel competition

Recently, more emphasis is put on bioenergy production from biomasses that do not compete with food production. Biogas production is an effective technology for producing bioenergy from the by-products of food systems, such as food waste and agricultural biomasses including manure and crop residues (Winquist et al., 2021; Zhu et al., 2019). Souza et a. (2017) emphasized the importance of approaches that aim for synergies between food and energy prouction. When considering the overall demand for different types of biomasses (food, feed, and energy) in a specific context (e.g., a farm or region) together with the societal demand for other functions the agricultural land could provide (e.g., nutrient recycling and climate mitigation (Schulte et al., 2014), the question of food-fuel competition becomes more complex.

The impact of energy production in an agricultural system is much bigger than simply providing renewable energy. Depending on how bioenergy production is integrated into an agricultural system, it can have both direct and indirect effects on the performance of the farming systems. In a review study, Möller (2015) concluded that indirect impacts on land use and nutrient cycles were greater than the direct effects of using digestates instead of manure. This creates demand for appropriate design approaches that help to avoid the potential trade-offs between food and energy production, and the supply other ecosystem services. In addition to having an impact on biophysical flows, bioenergy production provides a new source of income in the system in the form of energy sales (Scarlat et al., 2018a).

1.2.3 The need to shift from linear nutrient use to nutrient recycling

A transition toward more circular nutrient flows is suggested as it would reduce the negative environmental impacts of a linear system while increasing resource use efficiency in material and energy use (Valve et al., 2020). The increase in nitrogen and phosphorus use in agriculture has been remarkable. Erisman et al. (2008) estimated that the use of mineral nitrogen has more than doubled the number of people that one hectare of arable land can feed. However, the increased efficiency in food production has been paid by the envriroment. From the beginning of the 20^{th} century, global nitrogen surplus has increased 7-fold. During the same time period the phosphorus surplus increased from 0.25 Tg y-1 to 11 TG-y (Bouwman et al., 2011). As a result, food production is a major cause in the exceeding of the planetary boundaries of the nitrogen and phosphorus cycles (Campbell et al., 2017; Steffen et al., 2015). Currently, the flows of nitrogen and phosphorus are greater in manure than in mineral fertilizers, which emphasizes the great significance of livestock production in nutrient cycling (Bouwman et al., 2011).

A substantial portion of the nitrogen and phosphorus applied in food production is lost to the environment. Junguo et al. (2010) estimated that approximately 40% of nitrogen inputs are lost to the environment. Nutrient leaching to the water systems causes eutrophication and decreases the quality of groundwater. In addition to negative impacts in water systems, nitrogen contributes to GHG-emissions in the form of nitrous oxide (N_2O), and worsened air quality in the form of nitrogen oxides ($NO_{x)}$ and ammonia (NH_3). Whereas lost nitrogen can be replaced either industrially or by biologically fixing, phosphorus is a non-renewable resource and about 55% of phosphorus applied to food production is lost between production and consumption highligtning the importance of more efficient nutrient recycling (Cordell et al., 2009).

The use of nitrogen and phosphorus is distributed unevenly across the globe. This results from excess fertilizer use and nutrients from intensive livestock production accumulating in some regions such as in Western Europe while in many other regions, especially in Africa, soils are depleted of nutrients (Potter et al., 2010). Hence, as in the case of food production, countries and regions are either net exporters or importers of nutrients (Harder et al., 2021; Parviainen and Helenius, 2020). International trade has had an important role in global nitrogen and phosphorus cycles (Schipanski & Bennett, 2012). For example, European food production is a substantial driver of global phosphorus use and pollution as its food production relies on the nutrient imports within the imported biomass, which is further linked to causing nutrient surpluses in Europe (Nesme et al., 2018; Wang et al., 2018). Feed imports, and thus livestock, also play and important role in global nutrient flows as 44% of phosphorus flows are related to livestock feed trade (Nesme et al., 2018).

Different solutions and approaches for more circular nutrient economy and mitigation impacts from current nutrient uses have been proposed. In order to reduce negative impacts from excess nutrient use and to improve food security, a global redistribution and re-balancing of nutrient flows is suggested (e.g. Kahiluoto et al., 2021; Nesme and Withers, 2016). A more regional approach was suggested by Granstedt et al. (2008), who proposed a spatially integrated livestock and crop production system to reduced nutrient loading in the Baltic Sea. Also logistical strategies are suggested to unburden regional nutrient surplusses through nutrient recovery from manure and processing which would enable longer transport distances for nutrients from manure (Valve et al., 2020). However, mixed farming systems (integrated livestock and crop production) have been seen as a potential and more comprehensive strategy for improving nutrient cycling on a farm scale (Kronberg et al., 2021). By in the 1950s Finnish Nobelist A.I.Virtanen suggested a nitrogen self-sufficient farming system (Virtanen, 1943). In this system, crop rotation based on perennial clover leys was used to fix nitrogen from the atmosphere and provide feed for cattle in a crop rotation which also included cereals and potatoes.

1.2.4 The need for a system perspective to design synergist food systems

There is a demand for food productions systems which integrate food production, energy production, and nutrient cycling. The modern food system involves several interconnected activities and processes related to primary production, food processing, distribution, retail and consumption that take place at multiple spatial scales (HLPE, 2014; Van Berkum et al., 2018). Achieving sustainability at the food system level necessitates a systems perspective that acknowledges the interconnections between the social and ecological systems related to these processes (Kirchherr et al., 2017; Pla-Julián and Guevara, 2019). This would also involve recognizing connections to systems outside of the studied systems and targeting multiple goals simultaneously. As such, there is a great demand for a synergic and integrated solution that could produce sufficient food and energy and be consistent with other ecosystem services (Kline et al., 2016; Knorr and Augustin, 2021; Liu et al., 2015; Schulte et al., 2021).

1.3 Research objectives

The aim of this thesis was to provide a design for circular food production which utilizes the synergies of the interconnected nexus of biomass-nutrients-energy. To do that, we studied the biophysical and economic impacts of such an integrated food and energy production design at different spatial scales in the context of the Finnish food system.

Research questions are:

1. What is the potential for integrating food and energy production to close nutrient cycles on a farm scale? (Chapter 2)
2. What are the theoretical foundation and principles of a circular food production design? (Chapter 3)
3. What is the potential for integrating food and energy production through the multifunctional use of agricultural biomasses on a regional scale. (Chapter 4)
4. How could circularity in the context of food systems be assessed and how circular is the current food system? (Chapter 5)
5. What is the potential of integrated food production, food processing and bioenergy production creating economic value and how would it be distributed at food system level? (Chapter 6)

1.4 Research context

Food systems are global and operate across scales. To make the research manageable and tangible, I conducted my research at national level. I chose Finland as the case country as the importance of sustainability goals and circularity has been emphasized in different national reports and strategies related to Finnish food systems. The Finnish government report on food policy outlines several key challenges for the Finnish food system (Ministry of Agriculture and Forestry, 2017). These challenges include improving profitability and productivity both in primary production and food processing while simultaneously increasing environmental sustainability and developing the circular economy. In Finland, national polices are ambitious as Finland is committed to becoming a model country for nutrient recycling (Ministry of Agriculture and Forestry, 2011), aims for carbon neutrality by 2035, and wants to become the world's first fossil free welfare society by 2040 (Ministry of Economic Affairs and Employment, 2019).

It is obvious that the need for a transition from a fossil-based economy to a circular bioeconomy is recognized at the societal level. However, transforming food systems is challenging because of the lock-in in the current food system. Through three trajectories, Kuokkanen et al.

(2017) demonstrated in their study how the current Finnish food system is locked-in. They showed how these trajectories, namely food production, agri-environmental polices, and the supply chain, are interlinked in multiple ways that serve to strengthen the current food system configuration. A transition to sustainability, therefore, would require changing the whole architecture of the system design rather than just technological changes in production.

The current structure of food supply in Finland goes against the goals of circularity. The rate of self-sufficiency in the food supply is high, but food production is heavily dependent on imported fossil fuels, fertilizers, and protein feed (Antikainen et al., 2005; Huan-Niemi et al., 2021; Parviainen and Helenius, 2020). Food production has been developed to favour specialized crop and livestock production systems both at the farm and regional levels. For example, around 70–80% of agricultural land is used for feed production, but only one third receives manure. (OSF, 2020). Furthermore, this structural concentration is projected to continue because of increasing farm sizes (Niskanen et al., 2020). In addition to food production, food processing and the retail sector are highly concentrated in Finland (European Commission, 2016; Kuokkanen et al., 2017).

However, Finland has the advantage of having relatively extensive agricultural land use. The area of set-aside agricultural land under various schemes of non-harvested leys is over 200,000 hectares, which corresponds to about 10% of total agricultural land area (OSF, 2021). Furthermore, due to the long indoor housing period for livestock in Finland, manure can be efficiently collected and stored for most of the year, thus providing a substantial energy resource. These resources, together with other food system biomasses, provides a substantial energy production potential without creating of food-energy competition. However, the potential of biogas production is not fully understood in Finland and the sector remains undeveloped (Winquist et al., 2019).

1.5 Methodological approach

In my thesis, I used the real-life example of the pilot project of Palopuro Agroecological Symbiosis (AES) as an inspirational model for a circular food system. Elements from this model were upscaled from farm scale to municipal and regional scale (Figure 2). The AES pilot is currently been carried out in Palopuro (a small village in Southern Finland approximately an hour outside the capital city) where the biogas production model is being implemented. I have a personal connection to Palopuro as I live with my family in the village and our own farm has been part of the AES pilot. The AES concept is a result of co-creative process between local farmers, and research institutes. The co-creative efforts used a bottom-up approach, which is supported by Loos et al. (2014) who argued that regionally grounded approaches acknowledging regional differences and the importance of spatial scale are needed in order to achieve sustainability in food production

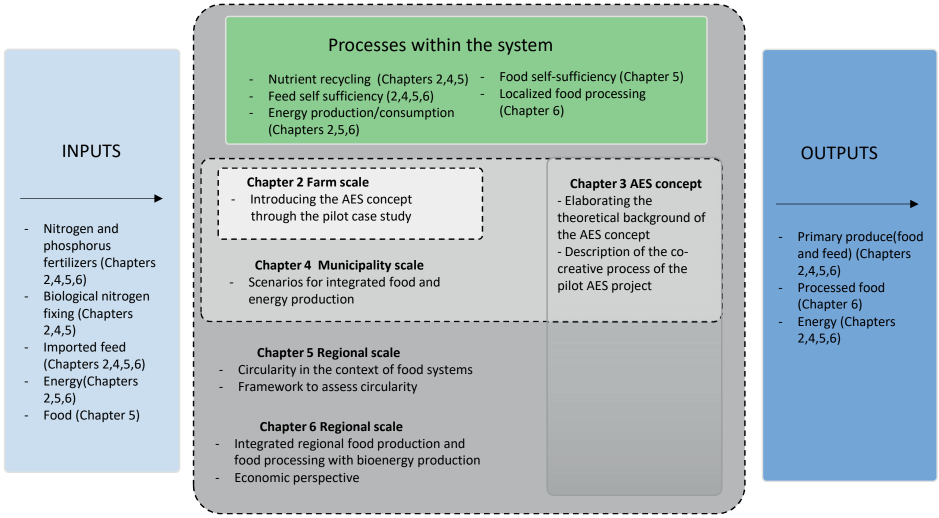

Figure 2. Outline of my thesis structure including the system boundaries for each chapter, and the focus of each chapter.

In this thesis I used systems thinking as the conceptual approach. A system is a limited part of reality that contains different interrelated elements (Jones et al., 2017; Vries et al., 1993). Compared to studies which focus only on individual system components, a systems approach allows for acknowledging the effects caused in and by other systems and enables an understanding of the complexity and interconnectivity of food systems (Liu et al., 2015).

My thesis focused mostly on agricultural systems while acknowledging that food production is part of broader food systems which includes several interacting elements and processes. A food system is defined as system that includes all the elements, activities, and outputs related to food production, processing, distribution, and consumption (HLPE, 2014). In addition to the primary production aspect of the system, I included the role of food processing. Current food consumption was included as an external driver for food production.

The varying system boundaries in my case-studies, included the farm, municipality, and regional food system scales (Figure 2). By regional food system, I am referring to regions that includes primary production, food processing, food consumption and regional governance. I studied these systems from a circular perspective by focusing on the supply of biomass production that was produced for food, feed, and energy. In addition, I examined the provisions for nutrient recycling. From the processes that transcended the system boundary but have an impact on the studied system, I included nitrogen and phosphorus inputs to fertilizers, feed imports, and energy input (Figure 2). By examining how self-sufficient these systems are in biomass production, and how much these systems produced biomass (feed) to other agricultural systems allowed me to acknowledge the role of the studied system as a part of a larger food system. I used scenario analyses to explore the solution space for the future form of integrated food and energy production systems. I used multiple indicators from the farm scale to the regional food scale.

1.6 Thesis outline

The structure of this thesis is represented in Figure 2. In Chapter 1, I have described the challenge of the current linear food systems in relation to sustainability in the context of biomass-nutrient-energy. In Chapter 2, together with the co-authors, we show how food and energy production can be integrated to enhance productivity and nutrient recycling at the farm scale. We use the pilot project of Palopuro Agroecological Symbiosis as a case study which also serves as an inspiration for localized food system integrating primary production and food processing. In Chapter 3, we propose the concept of AES as a generic arrangement for re-configuring primary production and food processing and forming a network of localized food systems. We discuss the sustainability of the concept in the context of industrial ecology and include the role of consumers in the localized food system.

In Chapter 4, we show how increasing complexity through the multifunctional use of biomass based on the AES model provides synergies in food and energy production without compromising other ecosystem services

In Chapter 5, we provide a framework which acknowledges the spatial connections of biomass flows and can be used for assessing the circularity of food systems. This framework is applied to a regional case study in the context of Finnish food systems. In Chapter 6, we apply the framework which is introduced in Chapter 5 from an economic perspective and expand it to include the role of food processing by using the same case study regions outlined in Chapter 5. In Chapter 7, the general discussion, I discuss the results and implications of this body of research.

1.7 Acknowledgements

I thank Rogier Schulte and Juha Helenius for their constructive comments on earlier versions of this chapter.

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2

Chapter 2

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

Kari Koppelmäki, Tuure Parviainen, Elina Virkkunen, Erika Winquist.
Rogier P.O. Schulte and Juha Helenius

Published as Koppelmäki, K., Parviainen, T., Virkkunen, E., Winquist, E., Schulte, R.P.O., Helenius, J., 2019. Ecological intensification by integrating biogas production into nutrient cycling: Modeling the case of Agroecological Symbiosis. Agricultural Systems. 170, 39–48. https://doi.org/10.1016/j.agsy.2018.12.007

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 systemand 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

2.1. 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 facilitate the transition to the pro duction of renewable energy in a circular economy (Haas et al., 2015).

One challenge across the Global North is that farms have specialized into either livestock or crop farms, fertilizer use has intensified, and 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 leys 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 (Uusitalo 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 (Uusi-Kämppä 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 saleable energy of the AES.

2.2. Materials and methods

2.2.1 Case description

In this study, we used Palopuro Agroecological Symbiosis (http://blogs.helsinki.fi/palopuron-symbioosi/) 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 (Figure 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 (Figure 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 biomasses, 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 undersown 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.

2.2.2 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 systems 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 symbiosis' farm fields and operations including the biogas plant, which will begin operating in autumn 2018, and the bakery, which is in the planning stage (Figure 1).

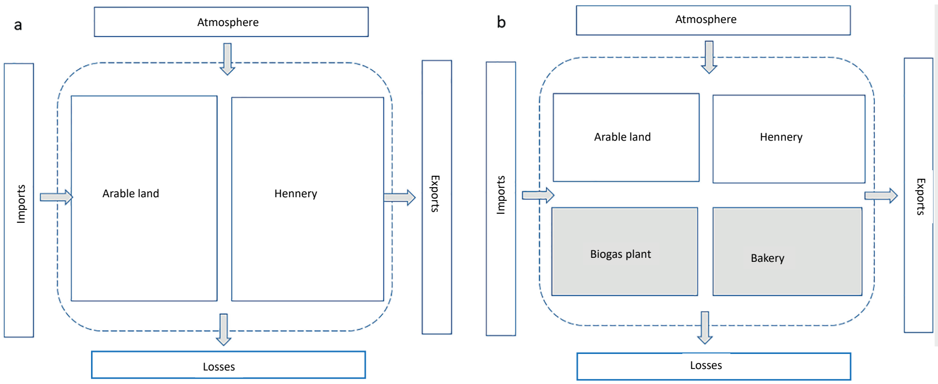

Figure 1. System boundaries of the modeled case as (a) the current system and (b) as a system converted to agro-ecological symbiosis (AES). The AES adds not just a biogas plant, but also a food processing unit to the system.

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 henhouse, the fields should also produce enough baking-quality grain for the bakery and enough feed in the form of silage for the biogas plant.

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.

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	1 900	2 660
Oat	42	32	2 100	2 940
Barley	25	25	2 300	3 220
Wheat	35	70	2 000	2 800
Pea	20	20	1 800	1 800
Pea-oat intercrop	51	57	2 100	2 100
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.

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 based on Luostarinen et al. (2017), but the P value was calculated 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 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) 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).

	Silage	Horse manure	Chicken manure	Feed together	Digestate
Feed FM tn a	2 450	800	185	3 435	2 804
DM %	0.32	0.30	0.31	0.31	0.29
Feed DM t a^{-1}	823	270	57	1150	813
TN kg t^{-1} FM	7.0	3.4	14.02	6.8	8.4
TN tn a^{-1}	18.1	2.7	2.59	23.5	23.5
SN kg t^{-1} FM	1.1	0.5	3.47	1.1	1.6
SN tn a^{-1}	2.7	0.4	0.6	3.7	4.5*
TP kg tn^{-1} FM	0.7	0.8	6.3	1.0	1.0
TP tn a^{-1}	1.8	0.6	1.2	3.6	3.6
CH_4 production Nm^3 a^{-1}	233 632	28 800	18 508	280 940	

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).

Table 3. Explanation of nutrient flows

Flow number	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 (Yield 20 000 tn/a FM*), Nature management fields 183 kg/ha (Yield 15 000 tn/a FM), Peas 71 kg /ha (yield 1 800 kg/ha), and pea-oat intercrop 25 kg/ha (pea yield 525 kg/ha).	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[1]. Nitrogen and phosphorus content of the crops was derived from the literature[2].	[1]Personal communication with Zukale, P. (2016) and [2] Antikainen et al. (2005)
7	Feed	Demand for the hennery[1]. Nitrogen and phosphorus content based on the literature[2].	[1]Personal communication with Latostenmaa V. (2017) and [2]Natural Resources Institute Finland (2018b)
8	Bread	Same as flow 6.	
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	Manure produced by the hennery. Nutrient content based on the literature.	Luostarinen et al. (2017)
12	Chicken feed	The quantity of concentrate used in the hennery. Nutrient values were obtained from the concentrate manufacturer.	Personal communication with Latostenmaa V. (2017) and Hemmilä 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 hennery (5600)	Aro (1998)

Table 3. Explanation of nutrient flows (*continued*)

Flow number	Flow	Explanation	Reference
15	Hens	Hens out	Anal. Methods (2014)
16	Losses	Nitrogen leaching and gaseous losses from the arable land were calculated by subtracting exports (flows 4 and 7) from imports (flows 1,2,9,10). Phosphorus losses due to erosion and leaching were based on the literature	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 hennery = Imports – exports	

* FM = Fresh matter

2.2.3 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 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 data are expressed in Megawatt hours (MWh). The energy production data consisted of the biogas production described earlier. The biomethane potential (BMP) of the various biomasses was derived from the literature and is expressed as normal cubic meters (Nm3). The BMP value for silage, 298 Nm3 CH4 tn−1 total solids, was based on values (229–353 Nm3 CH4 tn−1 for various herbaceous grasses) reported by Seppälä et al. (2009) and the values (292–320 Nm3 CH4 tn−1) reported by Wahid et al. (2015) for grass-clover mixtures. We determined the BMP for horse manure as 120 Nm3 CH4 tn−1 total solids based on values (88–196 Nm3 CH4 VS−1) reported by Mönch-Tegeder et al. (2013) and we used the value 324 Nm3 CH4 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.

2.2.4 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.

2.3. RESULTS

2.3.1 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.

Table 4. Nitrogen and phosphorous balances and nutrient use efficiency (Beatty et al., 2016) for arable land in the CS and AES models. Uncertainty range in parentheses. Units are in elemental nutrients $kg^{-1}y^{-1}$

	N		P	
	CS	AES	CS	AES
Input	**118 (±24.3)**	**136 (±23.9)**	**7.1 (±1.0)**	**8.9 (±0.8)**
BNF	*96 (±20.2)*	*77 (±14.3)*		
Manure/organic fertilizers/	*18 (±3.0)*	-	*7.1 (±1.0)*	-
Digestate		*55 (±8.6)*		*8.9 (±0.8)*
Nitrogen deposition	*3 (±1.0)*	*3 (±1.0)*		
Output	**23 (±2.9)**	**76 (±10.2)**	**3.7 (±0.7)**	**9.4 (±1.3)**
Harvested crops	*23 (±2.9)*	*76 (±10.2)*	*3.7 (±0.7)*	*9.4 (±1.3)*
Surplus	**95 (±20.2)**	**59 (±14.2)**	**3.4 (±1.4)**	**-0.5 (±0.2)**
Nutrient use efficiency	**0.2**	**0.24**	**0.52**	**0.58**
Surplus kg tn^{-1} harvest	**89**	**44**	**3.20**	**-0.40**

By far, the most substantial N input to both systems was BNF from the atmosphere (Figure 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 hennery (Figure 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.

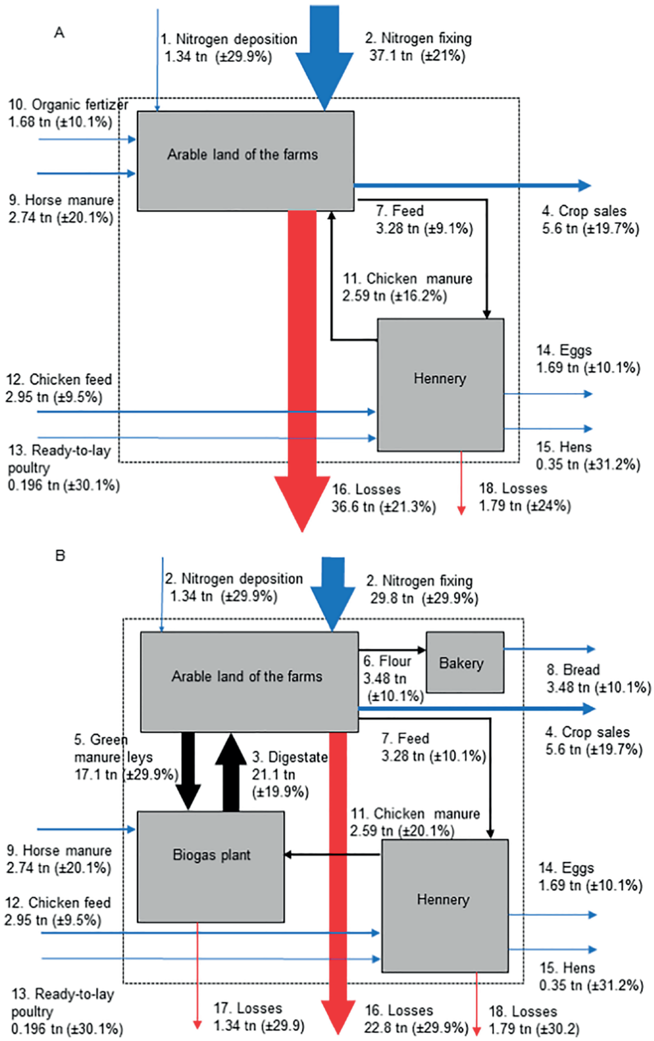

Figure 2. Nitrogen flows (tn a^{-1}) in the AES and CS models. The width of the arrow is proportional to the flow rate. Blue arrows illustrate imports into and exports out of the system, red arrows illustrate the losses from the system, and black arrows are flows within the system. Explanations of the flows are provided in Table 3.

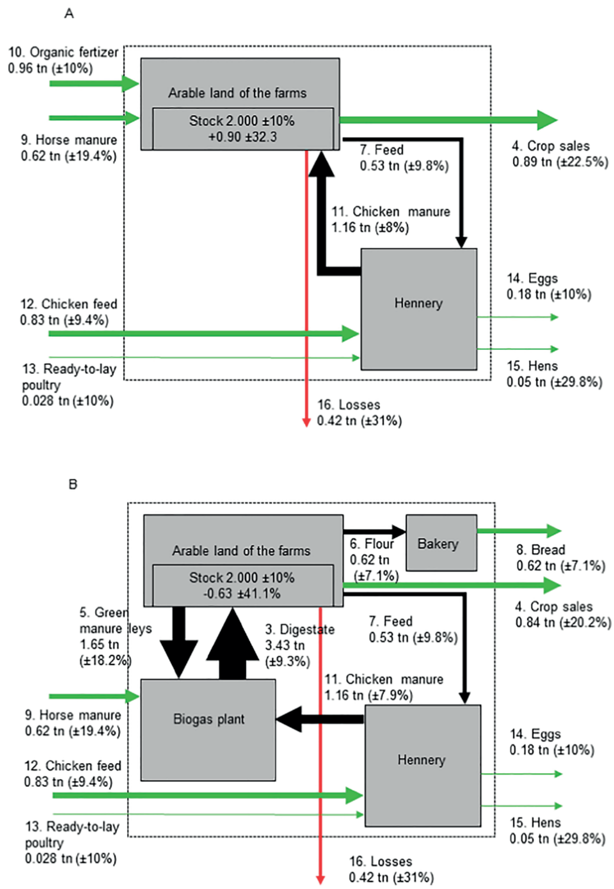

Figure 3. Phosphorus flows (tn a^{-1}) in the AES and CS models. The width of the arrow is proportional to the flow rate. Green arrows illustrate imports into and exports out of the system, red arrows illustrate the losses from the system, and black arrows are flows within the system. Explanations of the flows are given in Table 3.

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

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	-0.5	-0.4
Crop yields (cereals) -20%	2.7	2.0	0.5	0.4

2.3.2. Energy production

The AES produced 2 809 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 produced was increased when the horse manure was replaced by silage with a higher biomethane potential.

Table 6. Gross energy production and consumption in the AES model

	Energy produced, and current energy used MWh/a
Produced energy	**2809**
Silage	*2336*
Horse manure	*288*
Chicken manure	*185*
Consumed gross energy*	**1 650**
Biogas plant	390
Cereal farm	625
Machinery	*250*
Grain drying	*250*
Electricity	*125*
Hennery	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 300 tn of horse manure by silage	179

2.4. Discussion

Our study showed that biogas production based on utilizing biomasses 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.

2.4.1 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 Brozyna 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 (Figure 3).

In our study, the hennery 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 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 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.

2.4.2 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; Mönch-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 a straw. However, horse farms often lack fields for manure spreading, which means they may be willing to pay biogas companies for manure management.

2.4.3 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.

2.4.4 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 BNF 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.

2.4.5 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 Palopuro AES case needs to be evaluated by direct measurements and ex-post assessments once fully functional. Field experiments examining the fertilizing effect of digestate have been conducted with digested slurries or other slurries combined with energy crops or crop residues (Stinner et al., 2008; Möller, 2009; Benke et al., 2017). To our knowledge, no other available studies have explored the fertilizing effect of digestates with as high of a dry matter content as the digestate from the dry-fermentation type of biogas plant modeled in our case study.

2.5. Conclusions

Agroecological Symbiosis serves as an adaptive model in meeting the challenge of nutrient recycling and the transition to renewable energy for ecologically intensified localized food systems. Such utilization of the multiple beneficial functions of leys helps diversify rotations in, especially, specialized arable farms. AES systems may turn food production and processing to an energy-positive sector, while reducing environmental loading. Our study 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.

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Appendix. Supplementary material

S1 Description of the Palopuro Agroecological Symbiosis

Knehtilä, an organic arable cereal farm of 382 ha, is at central part of Palopuro AES. It has traditionally served as a venue for local food markets and catered other events, and has invested in a farm café and restaurant with a meeting facility. Mäntymäen Luomu is an organic hennery of 5600 egg-laying hens, and is located approximately two km from Knehtilä. The vegetable farm, Lehtokumpu, is also located close by. The energy company, Nivos Energia Ltd, is a regional enterprise prospecting on biogas business. Nivos Energia together with the two farms and with the Finnish technology provider Metener Ltd joined in the AES to establish Palopuron Biokaasu Ltd for owning and running the biogas operation. When writing this report in 2018, the plant is being built in the geographical center of the AES. It is planned to be fully operational for processing the ley harvest of 2018. The biogas plant comprises of two leach bed silos (800 m3) and a percolation liquid tank. Biogas is produced in a batch process, where the silos are filled with dry feed material and percolation liquid is circulated continuously through the bed during anaerobic digestion.

S2. Suppelmentary Table 1

Supplementary Table 1. Uncertainty levels for various factors. Uncertainty levels were determined based on ranges used in the study by Antikainen et al. (2005)". To account for the variability in flows depending on management decisions and availabilities, such as horse manure imported from the neighboring farms, we relied on personal communication with the operators of Palopuro AES. The flow numbers refer to the numbering in Figures 2 and 3.

Uncertainty level (%)	Flows	Flow number
10	Flour	6
	Feed	7
	Bread	8
	Chicken feed	12
	Eggs	14
20	Digestate	3
	Crop sales	4
	Horse manure	9
	Chicken manure	11
	Losses	18
30	Nitrogen deposition	1
	Nitrogen fixation	2
	Green manure leys	5
	Ready-to-lay poultry	13
	Hens	15
	Losses	16
	Losses	17

3

Chapter 3

Co-creating Agroecological Symbioses (AES) for Sustainable Food System Networks

Juha Helenius, Sophia E. Hagolani-Albov and Kari Koppelmäki

Published as Helenius, J., Hagolani-Albov, S.E., Koppelmäki, K., 2020. Co-creating Agroecological Symbioses (AES) for Sustainable Food System Networks. Frontiers in Sustainable Food Systems. 4, 229. https://doi.org/10.3389/FSUFS.2020.588715/BIBTEX

Abstract

Critics of modern food systems argue for the need to shift from a consolidated and concentrated, often monoculture based agro-industrial model toward diversified, post-fossil, and nutrient recycling food systems. The abundance of acute and obvious environmental problems in the agricultural sub-systems of the broader food system(s) have resulted in a focus on technological and natural scientific research into "solving" these point of production problems. Yet, there are many facets of food systems that are vital to sustainability which are not addressed even if the environmental problems were solved. In this article, we argue for agroecological symbiosis (AES) as a generic arrangement for re-configuring the primary production of food in agriculture, the processing of food, and development of a food community to work toward system-level sustainability. The guiding principle of this concept was the desire to base farming and food processing on renewable bioenergy, to close nutrient cycles, to break away from the consolidated food chain, to be more transparent and connected with consumers, and to revitalize the rural spaces where farms generally operate. Through a consistent and robust collaboration and co-creative process with transdisciplinary actors, ranging from food producers, and processers to policy actors, we designed a food system model based on networks of AES (NAES). The NAES would form place-based food networks, replacing the consolidated commodity chains. The NAES supports sustainable interactions from a biophysical and socio-cultural perspective. In this paper, we explain the AES concept, give an overview of the process of co-creating the pilot AES, and a proposal for the extension of the AES, as NAES, to create sustainable food systems. Overall, we conclude that the AES model holds potential for creating place-based food systems that further the sustainability agenda.

3.1. Introduction

Critics of the current dominant food system argue for the need to shift from a centralized, agro-industrial model toward diversified, post-fossil, and circular food systems (Pimbert, 2009; Monteleone, 2015). This type of shift would mean a reversal of the trend of globalization and consolidation in food systems in favor of (re)localization (IPES-Food, 2016, 2017). There are well-justified arguments for abandoning the productionist agricultural model (Lang and Heasman, 2004), which include environmental, public health, socio-cultural, and economic reasoning (Marsden and Sonnino, 2012; Willett et al., 2019).

Along with the loss of important structural characteristics, such as local adaptations and diversity, the agro-industrialization of food systems has resulted in loss of the essential functional properties of stability and resilience. The excessive environmental impacts of these agro-industrial systems include the wasteful use of, and associated pollution and emissions from, the extracted natural resources, such as plant nutrients. In addition, the agro-industrial system contributes to loss of biodiversity, and loss of services from the ecosystems, such as pollination and carbon capture to soils. In addition, it contributes to the pollution and ecosystem impacts of plant protection chemicals. Globally, the current modes of food production are a major cause of exceeding the known planetary boundaries, particularly the ones of biological diversity, and nitrogen and phosphorus cycling (Steffen et al., 2015). The misconception of industrializing food and agriculture has resulted in extreme environmental degradation and destruction (Campbell et al., 2017; Willett et al., 2019). Failure to recycle the nutrients used in agriculture production is striking (Buckwell and Nadeu, 2016; Sherwood, 2020). The present system is highly dependent on external and excessive energy inputs, especially in the form of fossil fuels (Sherwood, 2020).

From a socio-culture perspective, the agro-industrial model (Figure 1) contributes to the homogenization of food supplies and diets (Khoury et al., 2014), and the fragmentation and homogenization of rural landscapes (Jongman, 2002). The fundamental set up of the industrial agricultural model renders the products of primary production placeless, as they move through middlepersons and into vast storage facilities. Food produced through the processes of the industrial agricultural chain has been likened to being from "nowhere" as the links between producer, processer, and consumer are complicated and difficult to trace (Schermer, 2015). There are also externalized costs of agro-industrial food systems, as they do not serve public health and create imbalance and inequity in entitlement to food. On one hand these agro-industrial food systems are contributing to diet-linked, non-transmittable diseases, and on the other hand they contribute to hunger and malnutrition (Tilman and Clark, 2014; Willett et al., 2019). One is justified to ask if agribusiness and the consolidated food industry on their own can make the transformations needed to transition to more sustainability oriented systems.

Global and national food policies seem to be needed, and at the same time, transformative initiatives formed at the grassroots level need to be enabled.

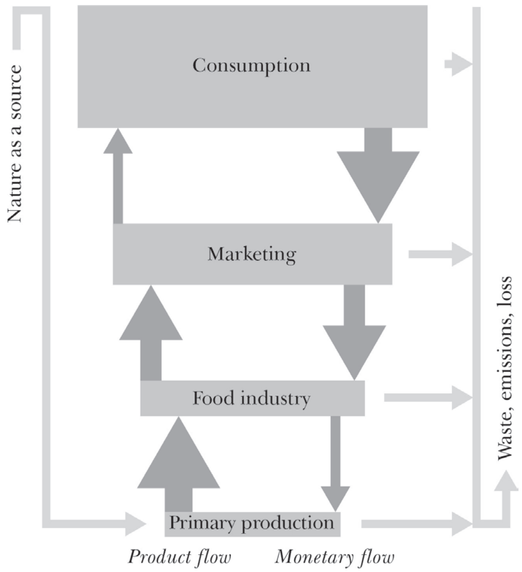

FIGURE 1. Schematic model of the conventional food system wherein the production, processing, and consumption functions primarily as a "food chain," in which the product flows and economic exchange are the focus with little regard to externalities or contextual factors whether biophysical or socio-cultural. The size of the boxes symbolically illustrates the number of participants in that level of the system and the size of the arrows represents the volume of the flows.

These challenges appear to be as equally pressing as the need to reverse the food systems disproportionate contribution to and impact from global climate change (Wheeler and von Braun, 2013; IPCC, 2019). The globally shared commitment to every persons' entitlement to food and adequate nutrition is derived from Article 25 of the Universal Declaration of Human Rights (UN, 1948), which provides a clear goal for improving food systems. The stark failure of the conventional food chain in addressing human rights is well-documented, but largely ignored even in (food)policies, not to mention the commodity-based agribusiness (De Shutter, 2010). The dominance of consolidated food chains threatens food security and leaves the food system vulnerable, with little resilience to external disturbance. In the context of the Covid-19 pandemic, this concern was publicly brought up by news media, as the centralized meat chains in several countries stumbled (see for e.g., van der et al., 2020).

The socio-cultural impacts of the globalized food system revolve around the homogenization of food cultures, the physical and cultural distancing of an increasing majority of "consumers" from the producers, and associated loss of sense of food. By the concept of sense of food, we mean a loss of understanding about the food one consumes in its full place-based context (Wilkins, 2005; Kneafsey et al., 2008; Spiller, 2012). These developments have had the alarming consequence of resulting in lack of public interest in food policy, or in insufficient policies. Calls for increased food sovereignty—food systems that are designed to accommodate the context and needs of the participants in the system (Rosset, 2008; Patel, 2009; Clapp, 2016)—and agroecology as a movement (Wezel et al., 2009) have emerged as a response, but often represent resistance and alternatives rather than full systemic transformation. From an economic perspective, the industrial food system and the "cheap food" it produces, creates imbalance and dysfunction (Patel and Moore, 2017). It has contributed to the decline of rural livelihoods, farmer incomes, and to a vicious cycle of an ever-increasing need for intensification to maintain yields from agricultural land (Tilman et al., 2002; IPES-Food, 2016).

In the context of addressing the need for transformative change of the food system, many if not most of the scientifically well-founded analyses focus only on parts of the food system, which appears as only a partial optimization, or even redundant. This is especially true in attempts to improve sustainability of agriculture by tinkering around with the details of the agricultural system while taking the rest of the system for granted. In other words, agriculture cannot achieve sustainability separately from the wider food system, where it is a foundational building block. This understanding is emerging, even if it is still only partially addressed, in the ongoing debate about "sustainable intensification" of agriculture (Rockström et al., 2017). The abundance of acute and obvious environmental problems in the agricultural sub-systems of the broader food system(s) have resulted in a focus on technological and natural scientific research directed at "solving" these point of production problems. Within agricultural sciences, agroecology with its sustainability science orientation and multiple facets—that is as a science, practice, and socio-cultural movement—serves to address sustainability at the food system level (Francis et al., 2003; Helenius et al., 2019).

Developing food system(s) to support sustainability is a typical "wicked problem." The problems of the food system cannot be directly "solved" by science alone (Rittel and Webber, 1973). The systematic integration of other types of knowledge is needed to begin to approach the sustainable transformation of food systems. There is also need for citizen led initiatives and scientific processes supported and augmented by food system participants at multiple levels. Involving persons living and working within the agricultural system carry knowledge about the system that cannot always be gleaned from top-down science and policy (Schillo and Robinson, 2017). Yet, the introduction of new actors and modes of collaboration has potential for creating tension and must be administered thoughtfully and in a way which respects the context of the transformation (Keune et al., 2015). Even with the introduction of co-creative processes and engagement of transdisciplinary actors and citizen scientists there are no simple solutions when it comes to food system redesign. Each facet of the food system has many sub-facets that must be taken into consideration when seeking transformational change. For example, this becomes obvious when looking at how the challenge of transforming almost any aspect of the food system links (FAO, 2018a) to the 17 sustainable development goals of the United Nations (SDGs: UN, 2015). Yet, there are some emergent and promising food systems models which speak to food system redesign and supporting a sustainable, holistic food system. Transformative change requires supportive policy mixes and governance (Geels and Schot, 2007; Diercks et al., 2019), which are outside of scope of this article. However, we witnessed this through a co-creative process with the involved non-science actors, for example the farmers, entrepreneurs, and consumers in place. All these parties came together and participated in the development of a food system model that, as we argue, deserves full attention for supportive and enabling policies and governance. In this article, we argue for agroecological symbiosis (AES: see Figure 2) (Koppelmäki et al., 2016, 2019; Helenius et al., 2017) as a generic model for re-arranging the primary production of food, from the agricultural and processing perspective, toward sustainability. Furthermore, we propose that using AES as the organizing principle to form networks of agroecological symbioses (NAES: Figure 3) would serve sustainable transformation at food system level. In this paper, we will: (1) explain the concept of AES; (2) propose a network of AES (NAES) as a foundation for a sustainable food system; (3) discuss the sustainability of NAES-concept based on analysis on Huber's (2000) generic framework of transformational strategies toward sustainability in context of industrial ecology; and ultimately, (4) we will describe the co-creation process from the first AES pilot case to the further implementation of the concept.

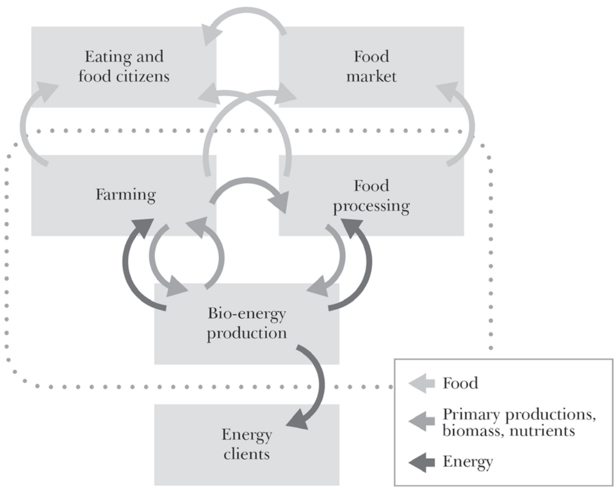

FIGURE 2. Schematic model of an agroecological symbiosis (the AES itself is represented within the dotted box). It is a recycling, bio-energy self-sufficient industrial symbiosis of farm(s), an energy producer, and food processor(s). It produces contextual food identifiable to consumers, either directly or via the market, with an emphasis on localized production, processing, and consumption. The AES brings the people who eat to the community it creates, bolstering the creation of a food community. The arrows within the AES represent primary product flows, recycling of plant nutrients, and bioenergy. The arrows from the AES represent flows of products: food and any excess bioenergy to the market.

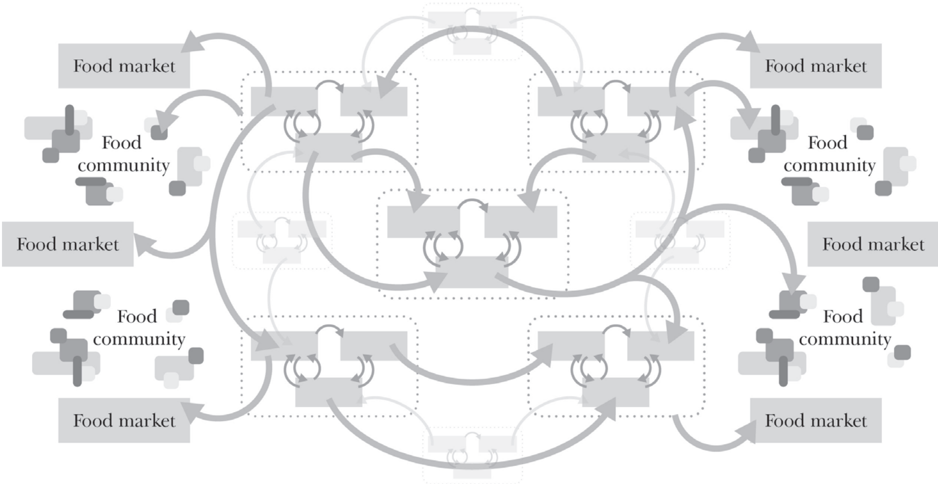

FIGURE 3. Schematic model of the agroecological symbioses (see this figure for a detail of an individual AES) forming a localized food production and processing system, an AES network (NAES). The NAES is an open system. The AESs can serve in neighboring NAESs, and together, the NAESs form a regional grid that connects to a national, and even a global meta-system. It represents a circular economy, runs largely on its own bioenergy with high climate-efficiency, and forms a foundation for a cyclical, adaptive, and resilient food system. In this system, the consumers become sovereign members of a food community created through the shared NAES. They gain an increased sense of food, and sense of place in the agroecological context of the NAES.

3.2. Agroecological Symbiosis (AES)

By our definition, an AES is a food production and processing industrial symbiosis that runs on renewable energy derived from its own feedstocks (Figure 2).

Definition for Agroecological Symbiosis (AES)

Agroecological symbiosis–AES–is a form of food production and processing in which the farms, the food processors, and the energy producers function in an integrated manner. The operations are running in spatial proximity to each other allowing efficient material and energy integration. In an AES, nitrogen as plant nutrient for the primary production is biologically fixed. The main source of energy is renewable, generated from the biomasses produced within the AES in a biorefinery, such as a biogas plant, belonging to the AES. In case of a biogas plant, the biorefinery has the dual purpose of providing the energy, and in the form of the digestate, producing the organic fertilizer and soil-conditioner for recycling plant nutrients back to the farmland. An AES sells agricultural or horticultural products, food products, and if produced in excess, bioenergy. The volume of the production, and the reach to the surrounding farmland within the AES are limited by the biophysical potential of the specific agroecosystems without compromising the other ecosystem services. The spatial extent of the biophysical operations is limited to sustainable logistic efficiency for the transport of the *feedstock and the recycling fertilizers. The AES strengthens the local socio-economic connections and diversifies the regional food culture.*

The term agroecological symbiosis (Koppelmäki et al., 2016) stems from the concept of industrial symbiosis, which—with extensions—we applied to the food chain. Chertow (2000) describes how mutually beneficial inter-firm cooperation, as an application of industrial ecology (Frosch and Gallopoulos, 1989; Graedel and Allenby, 2010), can be organized to form "industrial symbiosis," such as eco-industrial parks. Chertow (2000) argues for the benefits of the spatial proximity of the industrial partners who seek to maximize resource efficiency from minimizing the waste of materials and energy through forming a symbiosis. In the pilot AES, described in section Co-creation in the Palopuro pilot project below, the biophysical range was within a radius of approximately 15 km, but this may vary widely from one agroecological region to another. As we describe in the following sections, agroecology as a prefix refers not only to ecological outcomes of the redesigned food system model, but also to socio-economic and to cultural outcomes.

3.2.1 Organizing Principles and Functions

Food production inseparably relies on ecological primary production through photosynthesis of plants, and (not obligatorily) on secondary production of livestock fed with plants. Diverse food products are produced through the industrial processing of agricultural plant or animal "raw-materials," but the energy, the proteins, and the nutrients (some mineral or synthetic vitamin additives as exceptions) of food originate from farmed crop plants grown in farmland soil. From the ecosystem origin of food, it follows that all that is required for ecological sustainability of the use of ecosystems in general, applies to food production and agricultural ecosystems specifically.

An essential condition to ecosystem functioning is ecological integrity, which depends on biological diversity within the ecosystem (Hooper et al., 2005). This integrity is, in principle, similar to what is required for the functioning of mechanical machines as systems with many subsystems and parts, for example engines or computers. The difference is that ecosystems—and life—are orders of magnitude more complex than anything humans have ever manufactured. The lack of understanding of the structural details, the role of species diversity, the feedbacks, and the fine-tuning that exist in life-supporting systems, i.e., the ecosystems, must at least partly explain their neglect in decision making. The social psychology of continuous ecological destruction (Oskamp, 1995) is outside of scope of this article, but it must be closely linked to growing loss in increasingly urbanized societies of the sense of food and the understanding of the ecosystem as the origin of food.

Awareness of place and the embeddedness of agriculture goes hand in hand with the concept of sense of food, and is a necessary component in developing a (re)localized production and consumption system (Murdoch et al., 2000; Feagan, 2007). Place is a concept that is essential to both the producer and consumer sides of food systems, as it transcends both the physical and the socio-cultural valuation of any specific food product (Feagan, 2007; Cresswell, 2013). Every single agricultural product that is grown in the world has a physical location, a discrete space where it came into being. In addition, every food item that is consumed in the world is also rooted in the physical action of biological primary production (that is growth), which takes place in a real physical space. Even as the ease of transportation has created a smaller seeming world; technology still has not created a provision to provide "wireless" calories, or "land-less food." The social disconnection from food production continues to happen at multiple levels, including biophysical and social (Dorninger et al., 2017). This disconnection has been articulated as the metabolic rift (Foster, 1999; Wittman, 2009; Schneider and McMichael, 2010), which extends across both the biophysical and social metabolisms of food production, process, and consumption.

The number one consideration for an AES is that while the agroecosystems are managed to serve the production needs, at the same time the needs of the system also must be served. In anthropocentric terms, serving ecosystems aims at maintenance of their ecological integrity, as an essential condition for continuous productivity. In AES thinking, ecosystem services are reciprocal rather than a one-directional concept (Comberti et al., 2015). The ecosystem has multiple functions in the mosaic that comprises the biosphere; while it is still used by humans to extract products and value, humans are obliged to return these services.

The number two consideration is recognition of agroecosystems as subsystems in the wider food systems. City dwellers living solely in metropolitan areas may well-hold escapist illusions of being decoupled from agroecosystems, yet with every mouthful of food they most concretely, physically link upstream to the material and energy flow of the food from the farmland field ecosystems that comprise their foodsheds (in an analogy to watershed, Kloppenburg et al., 1996). Spiritually, if this aspect can be acknowledged, eating is an everyday sacrament, devoted to the food's ecosystems of origin. This sacrament includes acknowledging the work fellow-citizens do in the food chain, but essentially, it represents a personal and essential biophysical linkage to the ecosystems, and to the life-supporting integrity of the biosphere at large.

Food systems need to be adaptive and resilient. It follows from their place-bound ecosystem foundation that adaptiveness and resilience must emerge at each place of production, down to the most local farm scale. From the local scale, these properties can then be expanded to wider system scales.

From the above considerations we propose an AES maintains and as needed, increases and improves:

1. biological diversity, the ecological community essential for ecosystem function;
2. abiotic soil, water and atmospheric condition required by the ecological community;
3. recycling of elements, called plant nutrients that the process of primary production of crop plants take up, but need again for the next harvest;
4. energy-self-sufficiency of the system through its primary production by photosynthesis of solar energy;
5. psychological, socio-cultural (mental, spiritual) connection to the food ecosystem of the people who eat through fostering a sense of food and food citizenship.

3.3. Networks of AES (NAES) as A Foundation for A Sustainable Food System

As complementary modules in an interacting network of AESs, the AESs form a foundation for a transformative food system. Conceptually, a network of agroecological symbioses (NAES), represents a distributed model for the food processing industry. It redefines the vertical integration between the processor and the primary producer: the farmers in the AES sell primary products directly to their processing AES partners, which increases the transparency in the production system as one can track the journey of particular primary products into production. The communication is direct. In the conventional system, the farmer usually sells the commodity to an anonymous commodity market, often to middlepersons running centralized storage facilities. Farm products are not often sold directly to a specific processor and often are mixed into a bulk of "commodity," which results in losing knowledge about the origin of specific primary products during the journey through consolidated industrial processing. NAES also adds horizontal integration that is lacking in the conventional system. This integration is between the AES-units of production and processing. This can be visualized as working within the context of the rural landscape as the specific configure of the integrated entities is malleable within each AES. The key is spatial proximity and a scale consistent with requirements of the ecosystems' economy—not just the bio-economy—and circular economy. In practice, spatial proximity is determined by the extent to which it is economical to transport biomasses such as manures, (other) recycling fertilizers, or feedstock for bioenergy. Within a NAES, each AES contributes, with its own food and energy production, to the total production of the NAES. The individual AESs specialize in seeking optimal roles within the reality of their individual production capacities. These capacities converge at the NAES level.

By definition, a NAES is a network of many AESs. A NAES forms a foundation for a local food system, when it produces food products from its agroecological context to the market and to the people who eat those products (Figure 3). When forming a national and global grid, at the meta-NAES level, the NAESs are building blocks for a sustainable food system.

Wezel et al. (2016) proposed “agroecology territories” as territorial sustainable food systems. We find the NAES would be a food system model for such a transformation. Wezel et al. (2016) criticize the narrow emphasis on sustainability of a single agricultural commodity production, or on a single food product chain. With its emphasis on adaptation of agricultural practices to local and regional agroecological conditions, and on embedded food systems, the agroecology territories concept is consistent with the NAES concept. Wezel et al. (2016) list within-territory conservation of biodiversity and natural resources as conditions for the biophysical adaptation. NAES adds reliance on renewable energy produced within-territory, and recycling of plant nutrients. Owen et al. (2020, p. 2) propose that “geographical indications” (GIs) as a rural development mechanism that can serve in delivering transitions to agroecology territories, to “quality-led, place-based food systems.” In the GI scheme, a value-adding geographical indication can be administratively granted to a product (EU, 2020). Owen et al. (2020) cite Bowen’s (2011, p. 326) definition of a territory as “a space that is socially constructed, culturally marked, and institutionally regulated.” They call upon stakeholders adopting a territorial governance approach consistent with the Food and Agricultural Organization’s “10 elements of agroecology” (FAO, 2018b). GIs are consistent with, and would serve in supporting, the transition to NAES.

As an organizing principle for the food system, NAES contrasts with current industrial consolidation and the type of vertical integration, the monocultural concentration, characteristic to globalizing food chains. These treat food as a manufactured product, and the farmed products as commodities without recognition of food systems’ unique biosphere-base in agricultural ecosystems, and their socio-cultural foundation in the rural landscape.

Industrialization of the food system goes hand in hand with discourses of “feeding the world.” The principle of adapting the food system to a safe operating space set by the (agro)ecosystem directly challenges the idea of feeding the world at any cost. This position is echoed in other strands of the discourse, for example, in the polarized debate concerning whether food security is only possible through further intensified industrial agri-business, or only through the widespread uptake of organic farming (Connor, 2013; Eyhorn et al., 2019). It is obvious that planetary boundaries exist, which sets a ceiling to how big a population can “be fed” (Rockström et al., 2017). Food policies need to be explicit about their positioning regarding the underlying balance between population size and quality of life, including the quality of food and nutrition. Population increase enforces drivers that may push toward tipping-points of the system, result in loss resilience, and generate reactive rather than proactive regime shifts (Pereira et al., 2020). In advocating the principles of circularity, reciprocity of ecosystem services, reliance on self-produced non-fossil energy, and engagement of the people who form the food community, NAES suggest discourse of ensuring entitlement to food and nutrition, more a "right to eat," rather than "right to become fed."

With any combination of farming practices, diets, food cultures, and population size, there is a ceiling set by the carrying capacity of the biosphere. How the key questions are answered of who produces what, where, how, and to whom, there still looms a planetary boundary for increasing the production. This speaks to the far to future reaching vision of NAES for dynamic, but harmonic equilibrium between population and use of the biosphere for food production. It reinforces the idea of food sovereignty—but not individuality—as the NAES food communities define their own food, but are also entitled to their food production systems.

In contrast to the conventional, increasingly delocalized or globalized, and centralized food production chain of the industrialized countries (IPES-Food, 2016, 2018; Ellen MacArthur Foundation, 2019), NAES as a generic model would result in a "glocalized" (e.g., Quaye et al., 2010) and distributed system of food production. In terms of food cultures, it would result in diversification as opposed to the current trend of homogenization (Ritzer, 2013; Clapp, 2016). Such a reorganization would boost rural livelihoods, and would have implications to structural developments in the society, including the current unsustainable and fossil-fueled trend of urbanization toward metropoles. Without trying to explore the issue of urbanization further, we express our deep concern about the possibility to "feed the big cities" within any sustainable realm at the same time when people are abandoning the regions where food is produced. Without prior planning nor control, the cities simply mushroomed as products of the fossil fuel era. The metropoles are comparable to feedlots in animal farming, highly unsustainable, highly dependent on continuous feeding from the global rural. Food communities around NAES are best when local; the NAES-based food system offers a possibility to sustainably de-structure the big cities. To achieve this goal in addition to other supports for sustainable food systems, policies for "ruralization" need to link with food policies.

NAES gives the promise for increased food sovereignty and resilience in terms of food security. It gives promise for transformative change from extractive food capitalism toward sustainable ecology-based food systems. This is a functional model of human-scale agriculture that is flexible to be adapted for the local contexts it inhabits (Condon et al., 2010).

3.4. Efficiency, Sufficiency, and Consistency of NAES

In the following sections, we use Huber's (2000) framing of efficiency, sufficiency, and consistency to explore the promises for sustainable transformation in the NAES food system model.

We took the liberty to interpret what Huber presented as complementary strategies, as criteria for sustainable transformation. All three criteria need to be met to achieve a sustainable transformation in a production and consumption system. By consistency, Huber (2000) refers to coherence with the wider goals of environmental sustainability. We found this framing useful because it speaks to the viewpoints and driving motivations of multiple actor groups within sustainable transformations.

In discussing industrial symbiosis, Chertow and Ehrenfeld (2012) point out the need for explicit recognition and institutional support as enabling factors, if such symbiosis is adopted as an organizing principle for sustainability transformation. There is the pitfall of eco-efficiency being a winning strategy for the business through financial savings, while ignoring the rebound effect and hence, not resulting in ecological savings (Hukkinen, 2001; Heikkurinen et al., 2019). In any case, technologies and policies enabling eco-efficiency are surely welcomed by industry. At the same time, there is a public interest in policies that control the rebound effects, ensure sufficiency as a ceiling to material growth, and govern for consistency—in both meeting societal goals and the grand planetary challenges.

3.4.1 Efficiency of NAES

In generic terms, ecological efficiency simultaneously allows further economic growth and ecological adaptation of industrial production (Huber, 2000). In the context of food production systems, increasing efficiency means producing more food per unit of resource used. In crop production, efficiency is commonly measured by a ratio of quantity of product (harvest) to area of agricultural land harvested. Emphasis on land productivity tends to leave other natural resource efficiencies unnoticed, even though water, nutrients, and energy efficiencies are equally important. For example, nutrient use efficiency (NUE) measures how well-crop plants use the available nutrients for the harvestable product (Reich et al., 2014). Similarly, in livestock production, the feed conversion ratio measures the ratio of feed inputs to food outputs (Garnett et al., 2015). Nevertheless, these all are efficiencies measured at process level, or at sub-system level within a system, rather than indicators of system level efficiencies.

For understanding system-level efficiencies, it is essential to understand through what kinds of feedback the processes within sub-systems operate, and how the sub-systems are connected to other parts of the food system at different spatial and temporal scales. Field scale efficiency is not equal to farm scale efficiency. Similarly, farm scale efficiency does not guarantee efficient use of resources at regional or wider geographical scales. This disconnect is demonstrated by the following example. A crop farm using mineral fertilizers may produce high yields of cereals utilizing a relatively small fertilization. In other words, the ratio of outputs to inputs is high. A livestock farm, located next to the crop farm, produces moderate yields by applying high quantities of manure as a fertilizer, which results in a much lower ratio of outputs to inputs when compared to the crop farm. A simple conclusion is that the crop farm has a better NUE. However, when considering efficiency, it is essential to take also into account what happens after harvest. If the cereals harvested on the crop farm are used as feed on the livestock farm, the NUE looks different when considering both farms as a single continuous feed/animal production system. Furthermore, the origin of inputs and the quality of output varies on these farms. This implies that conclusions about efficiency cannot be derived by observing efficiencies at the sub-systems' level only, or only at a small spatial scale when the feedbacks reach larger scales.

In the current conventional agricultural sub-system of the food chain, two trajectories have had a substantial impact on efficiency. First, a low-cost feed transport has enabled livestock farms to concentrate and to spatially disconnect the animal husbandry from local feed production and secondly, mineral fertilizers have enabled farms to increase crop per-unit-area productivity while simultaneously releasing farms from the need—or possibility—to recycle the plant nutrients in crop production. As a result of this specialization at the farm and regional levels, nutrients are concentrating spatially; nutrients are dislocated and recycling is disrupted (Buckwell and Nadeu, 2016; Schulte et al., 2019; Parviainen and Helenius, 2020; Koppelmäki et al., 2021). What has looked like increasing efficiency in crop and in animal production has in fact been a dramatic decline in efficiency of the use of plant nutrients at the food system level, and an inefficiency in producing food.

Instead of increasing efficiency at the sub-system level, while sacrificing it at the whole-system level, the aim should be in system's efficiency. This is what NAES provides, it allows for explicit system level efficiency indicators and improvement (Koppelmäki et al., 2021, submitted manuscript). The requirement of circularity alone is a strong incentive for example, to the farms of the NAES to match the number of animals with the local feed production, in case NAES produces foods of animal origin. Feed imports from outside the agroecological region where the AES functions do not match with the concept, and if done, need costly arrangements for recycling the plant nutrients back to the feed producing farms. By-products from the food system, such as plant nutrients recovered from food waste and from municipal sewage, represent recycled resources within an NAES-based food system.

The requirement of reliance on internally sourced bioenergy, linked with the system's property of biological nitrogen fixation makes NAES by far more climate efficient than systems that rely on fossil fuels and on industrial nitrogen fixation, such as present industrial farming. In addition, requirements for increased rotational diversity, increased share of leys in the rotation, and use of organic recycling fertilizer, such as the digestate, serve stocking carbon to soil and reversing the current loss of carbon from farmland.

In the context of sustainability, efficiency as a system's output per unit of negative environmental impact generated also needs to be quantified, or at least qualitatively assessed. For example, at what rate per unit product does the food system cause biodiversity loss? Expressed this way, the expectation of increased biodiversity would return a negative value for a positive trend.

We argue that redesigning the system of primary production and processing of food along the lines of the NAES concept increases efficiency at food system level. As a food web rather than a food chain, NAES can produce more food energy and protein per unit farmland area, with less nutrient loading and less atmospheric emissions per unit farmland, and per unit of food produced, than would be the case if the production continued conventionally. Compared to current conventional practice, agroecological benefits include increased organic matter input to farmland soil, diversification of crop rotations, maintenance of soil organic matter and soil fertility, increased or even full self-sufficiency on biologically produced nitrogen, practically full recycling of phosphorus and other mineral plant nutrients (Koppelmäki et al., 2021, submitted manuscript), and radically improved climate-efficiency per hectare of farmland and per unit product. NAES makes it possible not only to enhance ecosystem services to production, but also to serve the ecosystems in maintaining their biological diversity, integrity, and function.

3.4.2 Sufficiency of NAES

Huber (2000) argues that efficiency can only be an intermediate for sufficiency. The concept of sufficiency encompasses a strategy involving consumption patterns and lifestyle, explicitly asking the question, how much is enough? (Huber, 2000). The need to ask this question follows from the limited planetary operation space. In food systems, the most critical factors to what becomes "too much" are population and diet.

Increasing efficiency in agricultural land use seems to give temporary relief, while simultaneously, global analysis already emphasizes the need for controlling diets (Foley et al., 2011), and even population (Crist et al., 2017). During the last decades, the area of agricultural land necessary to feed one person has deceased, but population growth and dietary change have offset the potential land savings from this increased productivity (Kastner et al., 2012). In NAES, the volume of primary production is limited by the agroecosystem's biophysical potential to produce biomass without substantially relying on external nutrient and biomass inputs.

In the "feeding the world" discourse there is a lively and persistent side-stream, the land sparing vs. land sharing debate (Loos and von Wehrden, 2018). The proponents of land sparing argue for increasing productivity of the existing farmland as a means to save nature (which in this thinking, is found outside of farmland). The productivity would be increased by increasing input intensity. As a rule, this camp ignores the fact that the path of intensification has come to an end (Tilman et al., 2002), hitting the wall of ecological sustainability. The proponents of land sharing argue for farming that would allow wildlife to share the farming environments with crops and cattle. This sharing would aim to wider biodiversity goals than simply maintenance of the "ecosystem services" of farming (Zhang et al., 2018).

Obviously, "sustainable intensification" (Rockström et al., 2017) would be sustainable, and wherever ecological space there is for it, it may push the population-times-diet limit further. In our theory of NAES, while we find that it provides means for sustainable intensification, we rely on the idea of sharing. As the human impact reaches all ecosystems in the biosphere, it is best to learn to live decently with our fellow species. With this thinking, the focus is on adjusting the intensity to ecological sustainability. For industrial, input intensive farming, this would mean lowering the intensity and even lowering productivity per unit land area for increasing productivity per unit other inputs, including biological diversity. In subsistence farming, in which the insufficiency of sustainable inputs, e.g., recycling fertilizers, coupled with a high rate of population growth often results in land degradation, there is space for agroecological intensification (Pretty et al., 2006). In terms of sufficiency, what is enough must not exceed what is too much for the ecosystems that the human species shares with other species, both presently and in the future.

In the NAES thinking, agroecological contextualization brings a geographical dimension to sufficiency. What is sufficient in what place? NAES food systems would favor adapting diets to local ecological provisioning and limits (knowing that such an adaptive arrangement might not be politically achievable). This would ease the burden of the (still missing) global food governance in holding back the pressures that created the present commodified, agro-industrial system, which lacks inherent control other than destruction of land as a result of over-exploitation. The idea of a food community in NAES implies participation by those who eat. Even though food production is localized (i.e., relying on local integrated nutrient recycling and energy production, local feeds in livestock production, and local food processing), food is exported from NAESs to other regions and also globally. Participatory governance by the food community should reach the production systems of origin of the exotic foods alike. Philosophically, these exotic foods may be geographically imported, but still not imported from outside of the NAES food community.

Another diet related aspect of sufficiency is the share of exotic, imported foods. In many cases, local food production could provide foods with the same function. For example, in the Nordic countries several berries, as horticultural or non-wood forest products, are available to anyone willing to pick them. Reengaging with locally available foods would reduce the need of importing exotic fruits and berries. In the NAES thinking, local products rather than imported ones would add value, as the production system and its possible externalities would be internalized. Rather than merely seeing added value in local production, the efficient utilization of locally available resources should be seen as a value choice. The composition of diet is a sensitive cultural issue, but prone to value-driven changes.

Some of the material flows in the industrial systems are incompatible with sustainability (Huber, 2000). This also applies to current food systems. This incompatibility is related to land use, food consumption, and inputs used in food production. From the land use perspective, food production must be compatible with the supply of other ecosystems services. For example, in peat lands the cultivation of annual crops produces greenhouse gas emissions in quantities substantially higher than use of these lands for perennial leys (Maljanen et al., 2007). In the NAES model, these peatlands would be used, for example, to produce grass to feed cattle or as a feedstock for biogas production instead of cereal production. In the NAES thinking, land use should not be incompatible with sustainability, but rather adapted to growing biomass that is suitable to that specific agroecosystem.

Material flows are currently largely based on non-renewable resources (Haas et al., 2015). In the conventional food chains, agriculture relies heavily on external inputs such as mineral fertilizers and fossil energy. Many of these flows are related to intensive livestock production. This has created a need for massive biomass imports to feed cattle resulting in nutrient concentrations in livestock farms (Buckwell and Nadeu, 2016; Uwizeye et al., 2016; Spiegal et al., 2020). Food production that is so heavily relying on inputs from non-renewable resources is not compatible with sustainability. As such, this leads to the fundamental principle that sustainable food systems must be based on use and maintenance of renewable resources.

3.4.3 Consistency of NAES

In Huber's (2000) framing, consistency relates to the production processes in a system and their ecological functioning in support of the development of balance and compatibility between the natural and industrial metabolisms of the system in question. It should be noted that while Huber (2000) does not make a direct reference to Marx's concept of metabolic rift, the balance between the industrial and ecological metabolisms is in line with the academic work which revolves around healing the metabolic rift (Schneider and McMichael, 2010). The NAES model speaks to Huber's conceptualization of consistency through its development and implementation of new systems level materials flows, which serve to change the underlying qualities of the industrial ecology of the agricultural system, and the food system based on NAES. The innovative material flows in the NAES model are fundamentally aimed at the sustainable transformation of the overarching system, rather than simply minimizing the impacts of the traditional material flows within industrial farming. Within the NAES model the focus remains on integrated environmental solutions, rather than piecemeal solutions or a focus on solely downstream remediation measures. We argue that NAES is consistent with the goal of circularity, as each AES in it is designed to recycle, and within the network, the AESs can co-operate in recycling.

The aim of NAES is not to mimic a natural ecosystem, as it remains a food production and processing system that does require inputs and produces outputs. However, it does bring the industrial and natural ecology into a more harmonious metabolism by respecting and working with the biophysical and socio-cultural realities of each individual place. In addition, the NAES model is not a top down or rigid interpretation of what constitutes a sustainable agricultural system. Rather, it is a co-creative model focused on utilizing the creativity and motivation of the people participating in the discrete system. Too often system models are designed in the academic or policy sphere with not enough deference to the challenges faced on the ground. The NAES model overcomes this problem through its flexible approach to the goal of creating local and regional food systems. An important aspect of the consistency strategy is to foster an innovation process that utilizes the productive capacity and creativity of modern society (Huber, 2000). We interpret the role of co-creation as an expression of citizen science, which fills this facet of consistency. In the next sections we will discuss the role of non-academic participants in the design and implementation of the pilot AES and the subsequent expansion to the NAES concept.

While Huber (2000) refers to consistency within environmental sustainability, any suggested transformative food system needs to meet with wider sustainability goals. A framework through which integrated solutions are accessible and widely understood are the Sustainable Development Goals (SDGs) of the United Nations (UN, 2015). Each of the goals represents an approach to sustainability that transcends siloed approaches and seeks for holistic solutions to the wicked problems which are a barrier to transition (Rittel and Webber, 1973). We agree with the caution raised by Randers et al. (2018), and with their concern that the socio-economic goals in the SDGs are not compatible with the aim of not exceeding planetary boundaries. We find that the NAES approach to food systems is consistent with the idea underlying the SDGs, given that the socio-economic goals need to be consistent with the environmental goals, and that the systems operate within the planetary boundaries.

3.5. Co-Creation in Developing the AES And NAES Concepts

Bringing industrial symbiosis to the food production arena creates some additional challenges and opportunities. The AES model asks not only for a transformation in spatially detached production systems, but a redevelopment of the physical spaces where the involved entrepreneurs live and produce food. This is because one feature of involving farms is that they often serve a dual purpose of being production spaces, but also human spaces where people live within the landscapes. All the farms in the pilot project were homes as well as being productive spaces. This dual use of the land requires a fundamental buy-in from the people that live within the symbiosis, this is one of the reasons why the co-creative model and the involvement of the farm-based entrepreneurs was so fundamental to our development of the AES and NAES concepts. For the food processing partners in an AES, the mental step is different, but equally big. In the present system, the agricultural products which they use to make food products are commodities from the general market, and location of their processing plants is not dependent on where these commodities are produced. In an AES, the food processor with their processing plant comes physically to the location of the agroecosystem.

3.5.1 Co-creation in the Palopuro Pilot Project

The term agroecological symbiosis (AES) was first used in the development of a redesigned production system in Palopuro village, Finland (Koppelmäki et al., 2016; Helenius et al., 2017). The co-creation process was integral to the Palopuro case and the expansion of AES into the NAES concept. The entrepreneurs in Palopuro came together naturally to figure out a model for integrating their operations for mutual benefit. This was a result of their everyday interaction and shared goals for the development of their respective businesses. At the start of the co-creative endeavor there were three farmers based in Palopuro village and a bakery owner from the Helsinki capital region. An energy company, represented by its CEO, joined at a later date. It was these entrepreneurs who developed the first proposal for what this cooperation might look like in practice and the entrepreneurs contacted the scientists at the University of Helsinki to assist with moving from idea to practice. The entrepreneurs and other transdisciplinary actors such as, civil servants from the relevant municipality and the ministries served as transformative agents in this project and were active in asking the scientific participants to investigate issues that were pertinent to their community (Shirk et al., 2012).

In practice this project would not exist without the cooperation from both the academic and non-academic actors. Both types of knowledge were needed to identify the problems and solutions that went into designing the pilot project AES. It should be noted that the farmers and the other entrepreneur actors at the heart of the pilot had a base motivation of improving the livelihood of their lived environment. They were the initiators of the transformative process. The farms and the bakery were already practicing organic production when the pilot project was planned. Alternative production methods when implemented in isolation, like organic production, do not change the entrepreneurs' position in the food systems. In that sense the substantial change from the actors' perspective is re-designing the roles of the actors and their respective agency within the food systems.

The entrepreneurs played a key role as food system innovators. A grain farmer living in Palopuro led the charge to develop a redesigned food and farming system as he was not happy in being an anonymous supplier to the industrialized grain supply chain, serving equally anonymous consumers. The development of the AES model could be characterized as taking back agency over the functioning of the local food system. This collaboration was also born in the idea of being able to add value to the grain produced, when sharing with other farmers the problem of increasing price margin between farm price of the grain agricultural products and price of food in the market for the consumers. This general phenomena in the commodity chain means decreasing share to farmers, and is the main cause of loss of farm income (Peltoniemi and Niemi, 2016). For example, the grain farmer saw that a shift from solely supplying a raw commodity to the grain food chain, to producing an added value local product with the bakery serves as insurance against the ups and downs of the global grain market. While there also was an economic aspect to the development of this idea, focusing solely on the economic component does not capture the scope of the motivation. There were considerations that extended beyond the financial, including quality of life and the development and maintenance of a vibrant local community.

Additionally, in the co-creation of the AES model the producers sought for an avenue to step back from the fossil-based industrialized food system. After listening to the goals of the entrepreneurs in Palopuro, it was relatively straightforward for us as scientists to match their vision to the concept of a circular, localized bioeconomy. For example, our previous theoretical work on producing biogas from nitrogen fixing leys and using the digestate as recycling fertilizer (Tuomisto and Helenius, 2008) matched perfectly to the case. Neither farm scale biogas production or localized small scale food processing were novel ideas [for farm-scale biogas in the Nordic context see Berglund and Börjesson (2006); Raven and Gregersen (2007); Ahlberg-Eliasson et al. (2017)]; rather, what is unique in AES, it is the combination of existing ideas to develop a symbiosis that explicitly addresses several facets of sustainability.

Existing spatial and social connections significantly lowered some potential barriers to this co-creative collaboration. The academic aspect of the co-creative endeavor served to support the actualization of the initial ideas of the entrepreneurs, rather than directing the project. Thus, the initial motivation and design ideas came from the bottom-up and were led by the persons in place. This helped in developing ideas that were appropriate for the place and people that would be implementing these ideas in practices. There was a mutual decision to apply for public funding to further explore the validity and feasibility of the proposed system, which led to the development of the Palopuro AES pilot project. It should be noted that the name agroecological symbiosis itself was coined by a policy actor who was invited into the grant writing process as an advisor. The inclusion of policy actors, for example from the municipal and ministerial level, was an important step in actualizing the pilot project as they were integral to accessing the funding mechanisms that made the implementation possible.

In discussions of food system change there is a focus on consumer behavior, usually centered around on what consumers do and do not buy (for e.g., Kneafsey et al., 2008). Understanding this dynamic is important; however, the role of consumer behavior alone is not enough for systems level change, as the farmer and the food processor must be willing to participate in a system that steps back from the conventional system long before the food reaches the consumer. The role of farmer-level and food processor level buy-in is vitally important for designing contextually appropriate and actionable food systems. It is very difficult for policy players and other non-farm-based actors to design a place-based model to support food system redesign as if place-based, the food systems are intimately tied to the context of the individual place where they operate (Murdoch et al., 2000; Feagan, 2007; Woods, 2012). In addition, the dual role as farmers and residents of the physical space of the food system gave the farming partners in the symbiosis a unique insight into what would work for their iteration of the AES.

There were parallel goals in the AES pilot of designing a sustainability-based production and processing model and revitalizing the surrounding rural area. In the face of other socio-spatial changes in the area, opening a social space on the farm through the farm market and other activities filled a void in the fabric of the Palopuro community, as many of the publicly accessible social spaces in the area were defunct. The opening of social spaces within the production landscape of the farm served the function of bringing the "people who eat" quite literally to the farm. Please note that the widely used term "consumers" does not fully capture the range of roles that play out in a food system based on the principles of agroecology, however, for the sake of clarity we will continue to use this term in this paper as needed.

Bringing non-farming actors into the food system in the AES pilot project served to lessen the distance between producers and consumers, both physically and mentally. It served in building the consumer side of the food community within the AES. The farmers of Palopuro AES specifically wanted their farms to be more than remote places, they wanted their farms to be more accessible, shared space where citizens can get in touch with their local food system. One of the goals in bringing the consumer participants to the farm was exposing functions of the food system that are not in the realm of the consumer experience in an industrialized food chain. For example, the baker was excited about the possibility of making concretely visible to the consumers how the grain flows from the farm to the bakery and is turned to bread through the use of transparent piping in a production area that was visible to visitors.

This acquaintance takes place on multiple levels, both through a growing familiarity with the process of turning raw materials into retail food products and developing one-on-one social ties with their local farmers and food processors. The farmers and food processors are a central feature in the farm markets held in the farmyard of the grain farm in Palopuro. In addition to the strictly food system-based participants, these markets also support the participation of other types of food retailers and local craftspeople. Creating a consistent space where these various types of local makers could come together allowed the farm to serve as a point of connection where social relationships were formed, and information was shared. In addition to the farm markets, the social space has also served as an education space for information exchange hosting numerous visits of other farmers, academics, and policy players to learn about the AES model and share their own experiences in redesigning local food systems. Creating platforms for this level of knowledge exchange supports the ethos of continuing opportunities to engage in citizen science (Ryan et al., 2018).

The way in which the scientific and non-scientific participants came together was both co-creative and contractual, as the members of the community in question were the drivers in identifying the key themes pertinent for their community (Shirk et al., 2012). For example, the food producers and processors decided that they wanted to change their positioning within the food system, rather than an entity outside the community indicating that there should be a change to serve a broader purpose. The level of buy-in in the pilot project was high, this most likely a result of the core ideas emanating from the participants themselves. “Science” in isolation can design a tight and interesting model, but if it is not functional for the people who aim to live with it, then ultimately it will not work in practice (Poulsen et al., 2014). The Palopuro AES has been a grassroots effort, rather than an innovation that came from the top down. While there were scientists involved in the process from very early on, they came to the table on an equal footing as the entrepreneurs. There were multiple forms of knowledge explored and respected in the formation of the AES model. Both the AES idea, the pilot AES, and to a lesser degree the subsequent networks extension for a food system model, are manifestations of citizen science in action. Regular people in place working with scientists to design a food production and processes system that served to improve the local foodscape, while fostering sustainability and livelihoods. Citizen science and knowledge co-production are the vital links between designing a sustainable food system in theory and practice (Poulsen et al., 2014).

3.5.2 Co-creation in the NAES Concept

The successful collaboration over the AES pilot project laid the ground for the continued co-creation of knowledge that has led to the expanded concept of NAES. It should be noted that both these concepts support the development of placed-based food systems that are bio-physically, socially, and culturally appropriate for the area where they operate (Feagan, 2007; Woods, 2012). Having the entrepreneurs as the initial drivers of this relocalization driven transformation of the food system was vital to creating a robust buy-in to the project. In addition, by bringing many different types of actors to the table, each actor was able to lean into their strengths and expertise. This aided in bringing the system from initial concept to functioning pilot in a relatively short period of time.

The NAES concept builds on the AES concept by proposing networks of AES forming the production-processing foundation for transformative change from food chain to sustainability. The continued development of the more generalized food system model moved beyond the direct work with the on the ground actors. The extension from AES to NAES, which addresses a higher system level, made it obvious that new stakeholder groups must be included in the co-creating process. We are working on this in our current project, "Eco-Industrial Symbioses for Food Production Chain–Feasibility for South-Savo" (2020–2021, Regional Council of South-Savo, Finland). We aim to engage key people representing regional administration, policymakers, marketing channels, food processing companies, and action groups among farmers committed to the creation process. Redesigning a food system beyond the local level is an endeavor that requires a range of actors, including those close or within the existing system to be able to accurately reflect the reality on the ground. It is necessary to have a sufficiently deep level of co-creation between the stakeholders to achieve systemic transformation. Transformative change is more than simply societal intervention, requires co-creation beyond citizen science, and involves contributions from, to, and between the micro, meso, and macro levels (Schäfer and Kieslinger, 2016). Our experience encourages such an endeavor even if enabling policies are not (yet) there. This is because scientists as public servants may rather underestimate than fully appreciate and tap to the skills, enthusiasm, and ability of, especially, the entrepreneurs to creatively solve any emerging challenges as they appear. The scientists' role becomes one of process facilitators, especially in regard to analytically cross-checking the system model proposal against sustainability criteria (Horlings et al., 2020).

A system can be co-creative, yet still very linear and conventional in its manifestation. The motivation of the producers and processors revolves most directly around the economic sphere; an AES must ultimately allow the entrepreneurs to maintain, with a prospect of improving, a livelihood while making commitments to participate. For co-creating a NAES, it is important to find further support for maintenance and improvement of the livelihoods through the network. The scientific actors are more directly able to keep the detailed environmental and wider sustainability goals in mind and at play within the development of the system, while the non-academic actors are able to keep track of what is functional within their community. The co-creation is not about just different groups reporting what they want. Rather it is activation, enthusiasm, and personal involvement of the parties at each level—producers, policy players, science practitioners, and the citizenry—all working together in the interest of sustainability and local food.

3.6. Concluding Remarks

In this paper, we argued how rearranging farming, food processing, and energy systems to follow the concept of AES would result in a shift to sustainable food production at systems level. Such a transformative change would require networks of AES, NAES, which would serve as the foundation of an emerging agroecology-based, geographically, and culturally contextualized food systems. We propose NAES as a generic principle for a transformative change in food systems toward sustainability. The NAES concept offers a systems-level alternative to the industrial and globalized food chains. NAES are distributed rather than consolidated, and entrepreneurial rather than centralized agribusiness. NAES based food systems are adaptive and resilient, ecologically more efficient, inherently more sufficient, and more consistent with sustainability goals than the present conventional agribusiness-based food chains. We argue that food systems based on NAES grids are able to produce enough food for a healthy diet at the local level. This may require deintensification of farming systems in some regions, while intensifying food production in other regions. The NAES food system(s), like any other system, is explicitly not proposed for "feeding" any population at any cost; rather, we propose NAES for a transformative change in which the population times diet times sustainability equation is explicit.

The AES model supports agency for the participating farmers, food processors, and energy producers engaged in developing place-based food production systems. At the wider system level, the NAES invites the food market and the people who eat the food from the NAES to participate in forming a food community, and in regaining an agroecosystem-based sense of food.

There are benefits to the system from a biophysical and sociocultural perspective. As the AES and NAES, represent a circular bioeconomy, that runs on—and even in some cases can produce in excess—renewable bioenergy, the obvious environmental benefits include plant nutrient recycling and balanced nutrient flows, as well as unforeseen climate efficiency. We have not yet quantified the carbon sinks or offsets of emissions from our pilot AES to give an example. This needs to be done. Diversification of agricultural land use gives some benefits to biodiversity, but further guidelines need to be developed, following the principle of land sharing. An obvious danger is biofuel production supplanting food production; in the AES concept, the biofuel production is integrated to, and primarily serves the primary production, processing, and delivery of the food that the AES produces.

From a social perspective there are benefits for the entrepreneurs through their direct involvement in the co-creation of the NAES. These include creating sustainable and viable livelihoods in place, while creating a food and energy infrastructure that supports a robust local food system. Under the NAES model both farming, and food processing can move away from the fossil-fuel based, industrial model. In addition, the producers are more able to develop food systems that speak to their own needs, rather than being solely at the mercy of the globalized market. In addition, the NAES concept allows for the potential of community development in the rural spaces as evidenced by the use of the social space in the AES pilot project.

We based our concept development on co-creation of the first pilot AES, the Palopuro symbiosis (in Hyvinkää, Finland). It cannot serve as a universal model, rather we used it to propose design principles and a system vision.

We have not studied the issues of the food market. For example, how to best organize the purchasing procedures for the distributed food production. We have no direct evidence of the higher (environmental and social) value of the products mirrored in the relative prices, compared to products from the conventional chains. How to meet the challenge of the food processing tending to industrialize and consolidate, rather than stay entrepreneurial at small and medium scales? We are aware that the bulk of food presently originates in only a small number of food industry giants. For the NAES model to be realized, it might be essential to get the present consolidated industries to get involved, and their production distributed to emerging NAESs. This requires a new business model for the industry. However, the Palopuro symbiosis grew from a grassroots effort, thus it appears that there is space for entrepreneurial food producers to initiate AESs and facilitate formation of NAESs. NAES based food systems seem to be able to grow parallel to, although competing with, complementary to the conventional consolidated chains.

Finally, based on our experiences in developing the Palopuro AES pilot project, we conclude that co-creation is a productive and rewarding, if not essential mode of research for systemic transformations in the food sector. The farmers, the food processors, and the associated energy producers, as entrepreneurs, have the knowledge, the motivation and the vision for improving not only their own businesses, but especially, their lives and the livelihoods of their clientele, and their social communities. Our experience reflects the importance of reciprocity between non-science actors and scientists in the development of the AES model. There is an added value from an increase in buy-in from non-scientific actors that are invited and welcomed to the innovation process works in favor of sustainability transformation. However, it should be emphasized that the non-science actors welcoming the scientists into the space was highly important to the success of the project. The bottom-up design of the AES pilot served to build a foundation and is an important facet in developing place-based food systems redesign. The AES and by extension the NAES model are dependent on the local and context-based knowledge that the food systems entrepreneurs brought to the discussion. A robust localized food system cannot be designed by scientists and policy actors alone, it must be inclusive of the non-science actors living and working within that system. Based on the experiences we had in the co-creation of the Palopuro symbiosis, we find that there is a huge potential in tapping into co-creation as a method for transforming the food system.

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4

Chapter 4

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

Kari Koppelmäki, Marjukka Lamminen, Juha Helenius, and Rogier P.O. Schulte

Published as Koppelmäki, K., Lamminen, M., Helenius, J., Schulte, R.P.O., 2021. Smart integration of food and bioenergy production delivers on multiple ecosystem services. Food and Energy Security. 10, 351–367. https://doi.org/10.1002/fes3.279

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.

4.1. 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.

4.2. 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.

4.2.1 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 (Appen+dix 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 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.

Table 1. Agricultural data in the study area in years 2015-2017

Field use	Cultivation area 2015-2017		Yield DM	Direct food use	Mineral N input	Mineral P input
	ha	%	t ha^{-1}	%	kg ha^{-1}	kg ha^{-1}
Cereals	**9049**	**60,4**	3.0	**12**	**90**	9.1
Winter heat	3381	22,6	3.1	27	103	7.0
Rye	292	1,9	3.0	88	120	5.0
Feed barley	1406	9,4	2.9	0	80	9.3
Malting barley	2203	14,7	3.3	-	80	9.3
Oats	1767	11,8	2.8	9	80	9.3
Oilseed and protein crops	**1094**	**7,3**	**1.5**	**58**	**73**	**7.7**
Peas	107	0,7	1.7	10	36	7.0
Broad bean	301	2,0	1.6	10	36	7.0
Rape and turnip rape	686	4,6	1.4	90	95	9.1
Grassland under 5 years*	**2429**	**16,2**	**3.9**	**0**	**129**	**7.0**
Pasture	238	1.6	4.4	0	140	7.7
Hay	646	4.3	3.1	0	100	5
Silage	1544	10.3	4.4	0	140	7.7
Marginal agricultural land	**1857**	**12.4**	-	**0**	-	-
Other crops**	**561**	**3.7**	-	-	-	-
Total	**14990**	**100.0**	-		-	

* Includes following land uses: fallow, natural management field, green manure leys

** Excluded from the study

4.2.1.1 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.

Table 2. Description of the current situation and the three scenarios

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

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 "fallows" (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.

4.2.1.2 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 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 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).

Table 3. Description of dairy production system in the AES-LST scenario

Feed consumption per cow*	Value
Grass silage use kg DM yr-1	5016
Cereals kg DM yr^{-1}	2275
Broad bean/ kg DM yr-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} yr^{-1}	9624
Calving interval, d	411
Dry period, d	60
Number of new milking cows in the system	3367

*Feed consumption of heifers and dry cows included

4.2.2 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}).

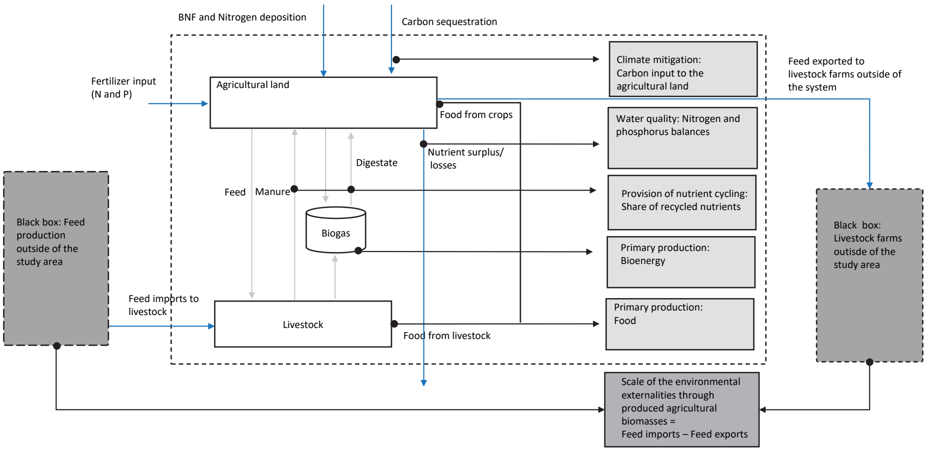

Figure 1. Schematic model of the system. Boundary of the system is the dashed line. Dark grey boxes represent feed production and livestock farms located outside of the system boundary. Grey arrows represent flows within the system and blue arrows represent inputs and outputs to and from the system. Black arrows represent the model outcomes explained as system's functions (boxes with gray shading)

4.2.2.1 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.

4.2.2.2 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).

Table 4. Biomethane potentials of different feedstock used in the study

Feedstock	Biomethane potential Nm^3 CH_4 t^{-1}	References
Grass*	290	(Seppälä et al., 2009; Wahid et al., 2015)
Cow manure (slurry and solid)**	172	(Seppälä et al., 2013)

*Included all grasses (silage, green manure leys, nature management fields, cover crops)
** Included dairy and beef cattle manure

4.2.2.3 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.

4.2.2.4 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:

$$\text{Crop residue DM} = (1\text{-HI}) \times \text{yield DM/HI}$$

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).

Table 5. Carbon input of crop residues. Above ground input calculated as by Hakala et al. (2009) and below ground (0-25 cm) 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 and rape	1.699	1.030	2.729
Silage	0.496	4.430	4.653
Fallows	1.934	2.658	4.572

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%.

4.2.2.5 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.

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).

4.3. Results

4.3.1 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.

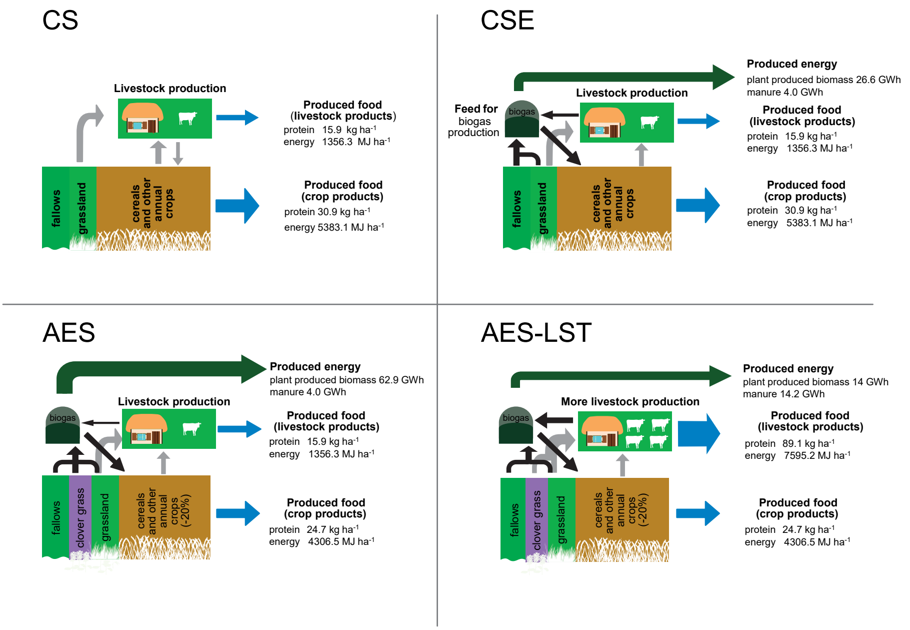

Figure 2. Human digestible protein (HDP kg ha-1), food energy (MJ ha-1), and bioenergy (GWh) production in the current system (CS), current system with the energy production scenario (CSE), AES scenario (AES) and AES scenario with livestock (AES-LST). Blue arrows represent the produced food, green arrows 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.

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.

4.3.2 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.

4.3.3 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.

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

	CS	CSE	AES	AES-LST
N input	**114.5**	**117.4**	**141.2**	**137.6**
fertilizers	*83.7*	*71.9*	*41.1*	*46.6*
manure/digestate	*8.6*	*23.4*	*46.5*	*37.4*
BNF	*19.1*	*19.1*	*50.7*	*50.7*
Nitrogen deposition	*3.0*	*3.0*	*3.0*	*3.0*
N output	**60.4**	**70.5**	**89.5**	**89.5**
Food/feed	*60.4*	*55.7*	*47.9*	*86.7*
Grass for Energy	-	*14.8*	*37.8*	*3.2*
N balance	**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	-	*1.4*	*4.1*	*0.9*
P balance	**-0.4**	**-1.9**	**-4.3**	**-4.7**

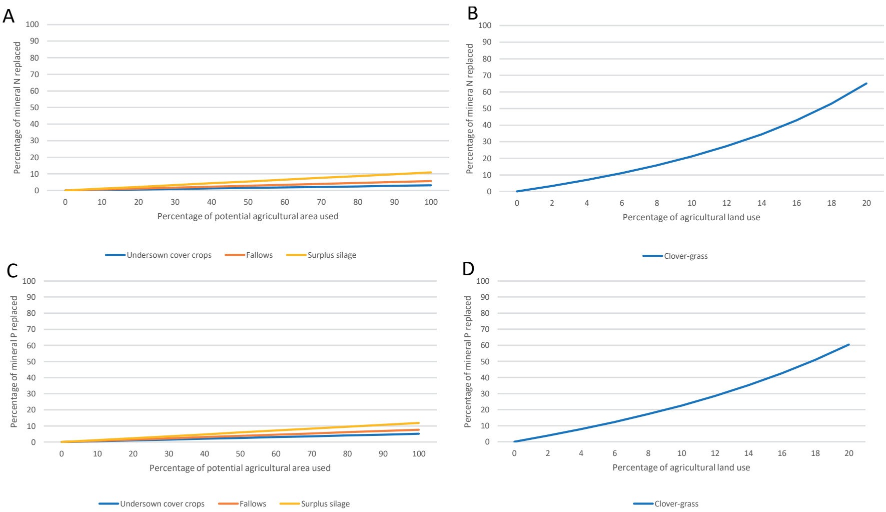

Figure 3. Percentage of the mineral N (A-B) and P (C-D) fertilizers replaced when the undersown cover crops, fallows, surplus silage and green manure leys are used as a feedstock in biogas production and the nutrients are recycled back to the fields. The x-axes show the percentage of the potential implementation area for the practice in the sensitivity analyses, in the form of agricultural land use (%) and the share of land under clover-grass green manuring.

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.

4.3.4 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.

Table 7. Carbon input to the soil (t DM yr^{-1})

	CS	CSE	AES	AES-LST
Crop residues	45676.7	40745.8	47271.2	47271.2
Manure/digestate	788.7	2896.0	4859.5	3591.74
Total t	46465.4	43606.5	52130.7	50862.9
Total t ha^{-1}	3.2	3.0	3.6	3.5

4.3.5 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.

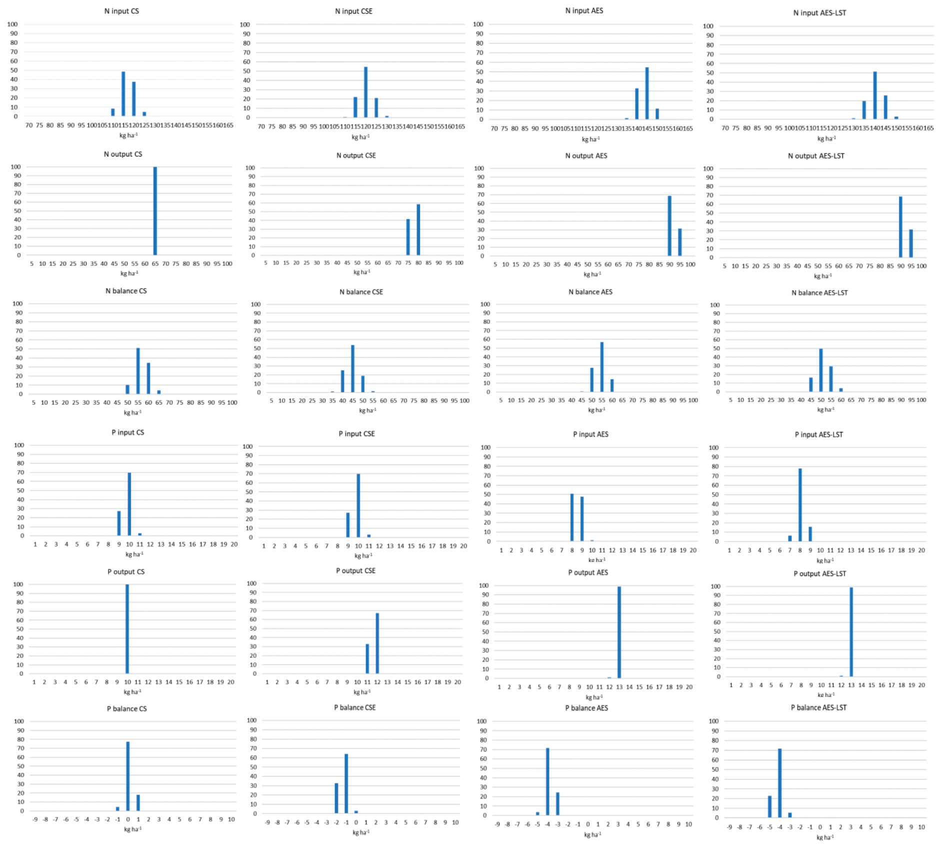

Figure 4. Distribution for 1000 model runs in Monte Carlo analyses for different model outcomes. Frequency on y-axis.

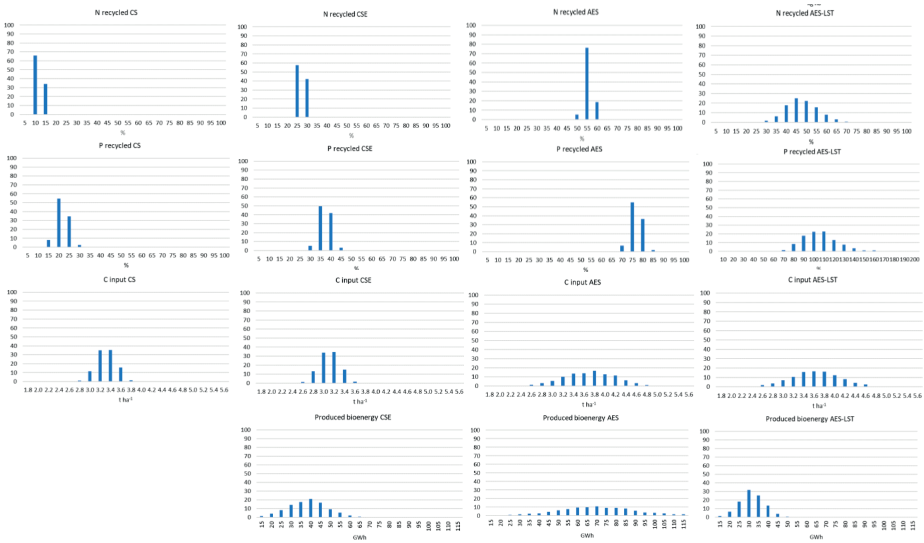

Figure 4. *(continued)* Distribution for 1000 model runs in Monte Carlo analyses for different model outcomes. Frequency on y-axis.

4.4. 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).

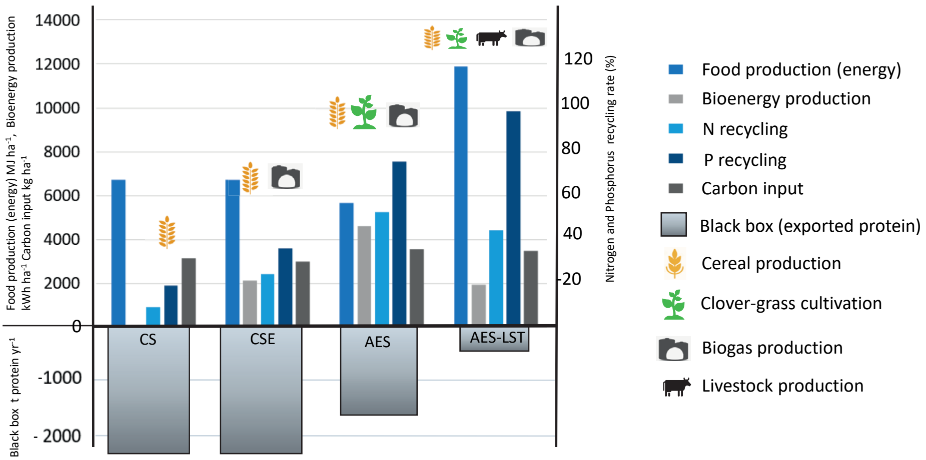

Figure 5. Supply of different soil functions in the current system of farming in Mäntsälä municipality (CS), scenario in which energy production from fallows in introduced (CSE), scenario in which in addition, rotational clover-grass leys are introduced (AES), and scenario in which, in addition, dairy cattle livestock production is introduced (AES-LST). Black boxes represent the scale of environmental externalities in the form of exported protein to the livestock farms located outside of the studied system. Symbols for cereal production, clove-grass cultivation, biogas production and livestock production illustrate the number of the elements in the system.

4.4.1 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 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 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).

4.4.2 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_2O 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_2O 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 (Kyttä 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.

4.4.3 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).

4.4.4 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.

4.4.5 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.

4.5. 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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Supplementary material

Appendix Table S1. Number of livestock and feed use in the current systems*

	Dairy cows	Suckler cows	Heifers	Bulls	Calves under 1 year	Sheep
Number of animals	834	15	408	83	591	727
Grass (silage, pasture, hay) **	-	-	-	-	-	-
Grains kg DM yr^{-1}	2376	434	434	1337	217	72
Broad beans/ peas	648	0	0	236	0	7
Imported feed (concentrates, minerals, vitamins) kg DM yr^{-1}	574	0	131.6	131.6	65.8	65.8

* Pigs
** Used grass feed was based on the land use and the yields in the statistics (Official Statistics Finland 2019a) and thus not separated to each animals group.

Appendix Table S2. Uncertainty levels for various model input factors.

	Uncertainty level %
N and P input fertilizers	10
N and P input manure	20
Manure quantity	20
Cover crop aboveground biomass	30
Cover crop´s belowground biomass	30
Crop´s belowground biomass	30
Biomethane potential (grass and manure)	30
Food/feed use	30

Appendix Table S3. Human digestible protein (HDP kg ha^{-1}), energy (MJ/ha), 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).

	CS		CSE		AES		AES-LST	
	HDP kg ha-1	Energy MJ/ha	HDP kg ha-1	Energy MJ/ha	HDP kg ha-1	Energy MJ/ha	HDP kg ha-1	Energy MJ/ha
Crop products	30.9	5383.1	30.9	5383.1	24.7	4306.5	24.7	4306.5
Livestock products	15.9	1356.3	15.9	1356.3	15.9	1356.3	89.1	7595.2
Milk	*15.1*	*1295.0*	*15.1*	*1295.0*	*15.1*	*1295.0*	*85.0*	*7308.6*
Meat	*0.9*	*61.4*	*0.9*	*61.4*	*0.9*	*61.4*	*4.0*	*286.7*
Total	**46.8**	**6739.4**	**46.8**	**6739.4**	**40.6**	**5662.8**	**113.8**	**11901.7**

Appendix Table S4. Energy produced (GWh) in current system with the energy production scenario (CSE) , AES scenario (AES) and AES scenario with livestock (AES-LST).

Feedstock	CSE	AES	AES-LST
Manure	**4.0**	**4.0**	**14.32**
Plant biomass total	**26.6**	**62.9**	**14.0**
Fallows	11.3	9.3	
Clover-grasses		39.6	
Surplus silage	8.7	8.7	8.7
Cover crops	6.6	5.3	5.3
Total	**30.6**	**66.9**	**28.2**
Energy production MWh/ha	2.1	4.6	2.0

Appendix Table S5. Sensitivity to change in clover grass area in the AES and AES-LST scenario

	Scenario	Clover grass area for feed/ biogas from 20% to 10%	Clove grass area for feed/ biogas from 20% to 30%	Crop yields +20%	Crop yields -20%	Share of the direct food use crops +20%	Share of the direct food use crops -20%
		%	%	%	%	%	%
Food energy MJ/ha	CS			16	-16	13	-14
Food energy MJ/ha	CSE			16	-16	13	-14
Food energy MJ/ha	AES	9.4	-9.6	15	-15	12	-13
Food energy MJ/ha	AES-LST	-15.6	15.6	18	-18	6	-6
Bioenergy MWh/ha	CSE	-100.0	-100.0	7	-7		
Bioenergy MWh/ha	AES	-27.1	27.1	15	-15		
Bioenergy MWh/ha	AES-LST	-11.7	11.7	7	-7		
Nutrient balance N kg ha^{-1}	CS			-17	17		
Nutrient balance N kg ha^{-1}	CSE			-24	24		
Nutrient balance N kg ha^{-1}	AES	-13.2	13.2	-13	13		
Nutrient balance N kg ha^{-1}	AES-LST	-14.8	14.6	-14	14		
Nutrient balance P kg ha^{-1}	CS			286	-286		
Nutrient balance P kg ha^{-1}	CSE			91	-91		
Nutrient balance P kg ha^{-1}	AES	-24.7	24.7	51	-51		
Nutrient balance P kg ha^{-1}	AES-LST	-21.4	21.4	47	-47		
Portion of recycled N	CS			1	1		
Portion of recycled N	CSE			5	-5		
Portion of recycled N	AES	-27	30	11	-11		
Portion of recycled N	AES-LST	-28	31	12	-13		
Portion of recycled P	CS			0	0		
Portion of recycled P	CSE			3	-3		
Portion of recycled P	AES	-27	32	11	-11		
Portion of recycled P	AES-LST	-32	37	14	-14		
Carbon input kg ha-1	CS			8	-8		
Carbon input kg ha-1	CSE			7	-7		
Carbon input t ha-1	AES	0.9	1.9	4	-4		
Carbon input t ha-1	AES-LST	1.4	1.5	4	-4		

5

Chapter 5

Nested circularity in food systems: A Nordic case study on connecting biomass, nutrient and energy flows from field scale to continent

Kari Koppelmäki, Juha Helenius, and Rogier P.O. Schulte

Based on Koppelmäki, K., Helenius, J., Schulte, R.P.O., 2021. Nested circularity in food systems: A Nordic case study on connecting biomass, nutrient and energy flows from field scale to continent. Resources, Conservations & Recycling. 164, 105218. https://doi.org/10.1016/j.resconrec.2020.105218

Abstract

Although a circular economy promotes economic and environmental benefits, knowledge gaps remain surrounding the application of these concepts to food systems. A better understanding of the connection between different flows of biomass and energy at different spatial scales is needed to facilitate effective transitions towards circular bioeconomies. This study provides a framework for assessing the circularity of food systems, which we exemplify by identifying key steps towards circularity for three contrasting farming regions in Finland. For each of the regions, we quantified the flows of biomass, nutrients and energy. We found large differences in circularity, depending on the chosen indicator. Most biomass and nutrient flows were related to livestock production, which implies that it plays a key role in circular food systems. Current livestock production was found to be connected to national and global food systems through the international feed trade. This trade generates imbalanced nutrient flows between regions and countries, resulting in excess accumulations of nutrients in regions with net imports. In terms of circularity in energy systems, we found that substantial amounts of energy could be produced from manure and plant-based biomasses without causing food-fuel competition in land use. We also observed that, the inclusion of human excreta would further improve recycling but this was significant only in the region with a high population density. Thus, in his study, we propose a concept of nested circularity in which nutrient, biomass and energy cycles are connected and closed across multiple spatial scales.

5.1. Introduction

The concept of circular economy (CE) has been proposed as a promising approach to creating more sustainable agricultural food systems with a great potential for economic and environmental benefits (Ellen MacArthur Foundation 2019). Defined as an industrial system that is designed to be restorative and regenerative at different spatial scales, the concept includes the goal of replacing extract-use-dispose systems with an economic and technological model that is based on principles such as reuse, recycling, reducing and recovering with a shift towards renewable energy (Ellen MacArthur Foundation 2012, Jawahir and Bradley, 2016, Jurgilevich et al., 2016, Kirchherr et al., 2017, Winans et al., 2017). In the context of food systems, it has been proposed that CE includes three stages - food production, food consumption and waste management (Jurgilevich et al., 2016).

The concept of CE has been promoted at multiple policy levels, with the European Union setting ambitious goals, strategies and programmes (European Commission, 2020). EU Member States have taken initiatives accordingly; the Netherlands, for example, ambitiously aims to close cycles of raw materials at the smallest possible scale and to be a world leader in circular agriculture by 2030 (Ministry of Agriculture, Nature and Food Quality of the Netherlands, 2018). Similarly, the government of Finland has worked over the last decade to develop a program which promotes efficient nutrient recycling in agriculture (Ministry of Agriculture and Forestry of Finland, 2011).

Despite its potential to create sustainable systems, the concept of CE has been criticized for setting over-simplified goals that are built upon weak foundations and blurry definitions (Murray et al., 2015; Kirchherr et al., 2017). Furthermore, since current biomass and nutrient flows are far from circular (Buckwell and Nadeu, 2016; Schulte et al., 2019; Parviainen and Helenius, 2020), a large-scale shift towards circular agriculture would require substantial changes to the structure of food systems. Studies that focus on contextualizing this concept to food production are limited (Winans et al., 2017). At present, research has focused either on material and substance flow analyses (Antikainen et al., 2005; van der Wiel et al., 2019; Papangelou et al., 2020) or on the sub-systems level within the agricultural sector, such as the role of livestock (Van Zanten et al., 2019) or nutrient recycling and management (Granstedt et al., 2008; Schoumans et al., 2015; Withers et al., 2015).

Our current food systems have moved away from circularity, in part due to three historical processes: shifts from organic nutrient sources to industrial mineral fertilizers manufactured from virgin sources, specialization of farms and regions to either arable or to livestock farming, and the concentration of food consumption in urban regions. As a result, urban areas are largely reliant on food imports (Fernandez-Mena et al., 2016), while intensive livestock production has created the need for substantial biomass imports for animal fodder (Uwizeye et al., 2016; Spiegal et al., 2020). These local or regional imports of food or feed are commonly associated with substantial negative environmental impacts due to the accumulation, and resulting in harmful emissions, from nutrients (Buckwell and Nadeu, 2016).

Full circularity in food systems, which refers to closed cycles, is practically impossible and is not the ultimate goal. This is because many of the goods that are consumed around the world cannot be grown in all regions (e.g. coffee). Furthermore, the transport of “waste” from cities and livestock farms back to their place of origin is often economically unrealistic (Paudel et al., 2009; Neiva de Figueiredo and Mayerle, 2014). Despite the growing interest in local food production, only limited populations would have the potential to feed themselves with locally produced food (Kinnunen et al., 2020).

The transition towards circularity is further complicated by the simultaneous need to replace fossil fuel usage with renewable energy systems (Haas et al., 2015; Koppelmäki et al., 2019; Sherwood, 2020). This presents challenges and opportunities for agriculture as the sector can be both a consumer and a producer of energy.

Therefore, circular food system design should carefully consider: the multiple linear flows of biomass and nutrients that could be made more circular, the potential spatial scales at which this could be achieved, the role of specialization in farming systems and urbanization, and the role of the bioenergy. Because agroecological and socio-economic conditions vary between the “food environments” (HLPE, 2019), it is not feasible to define a single optimal spatial scale for a circular food system. At the same time, the achievement of circularity becomes increasingly complex as spatial and organisational scales of operations expand. For example, it is more straightforward to examine circularity in primary production alone, compared to the food systems level, which requires the inclusion of food processing and consumption (which increasingly take place at the global scale). There is, therefore, a need for a systems approach which considers the different spatial scales and agroecological contexts where food is produced and consumed.

In summation, there are two contemporary knowledge gaps regarding circular food systems. One of these gaps pertains to the limited systems perspective in defining and measuring circularity which fails to go beyond the concept of nutrient cycling. The second gap refers to a lack of knowledge regarding the spatial scales at which flows of biomass can be made more circular, as well as the way that these flows are connected at the food system level.

In this study, we address the knowledge gaps described above, first by developing a generic framework (Section 2.1) to assess the circularity of food systems and to explore how biomass, nutrient and energy flows are connected at different scales, and secondly, by applying this framework in regional case studies aiming to assess these flows within a food system. The scope of our study is limited to an assessment of biophysical flows and excludes further exploration of the economic or environmental impact categories.

5.2. Materials and methods

5.2.1 Framework for circular food systems

In order to analyse circularity, we first review the interconnectedness of the most integral parts of the food system and the ways that these connections impact the spatial scale at which circularity is applicable. We highlight the most important elements of circular food systems in the context of nested scales. We defined these elements as (1) biomass for food and feed, (2) energy production and consumption, and (3) nutrient cycling (Figure 1).

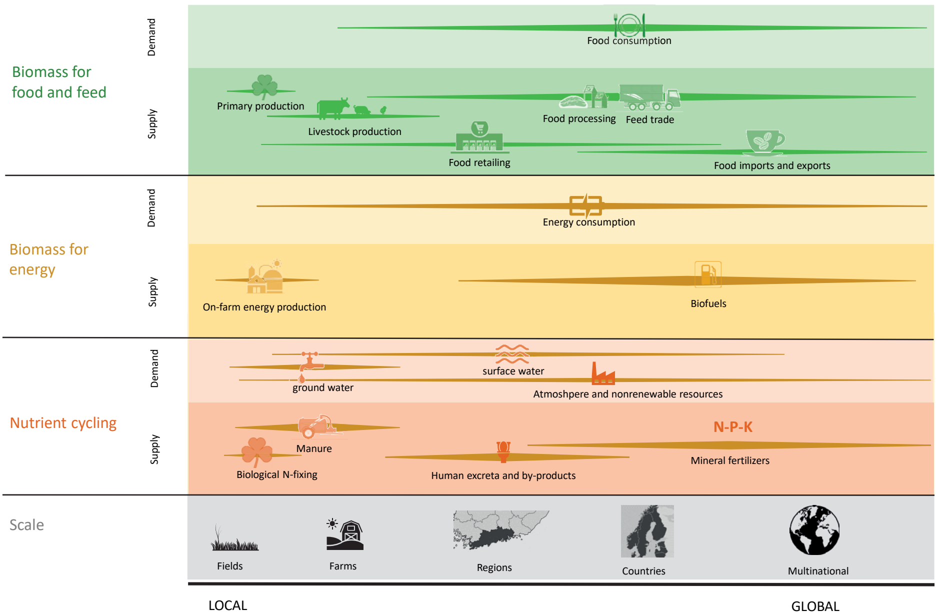

Figure 1. Schematic depiction of the most important elements (biomass for food, feed and energy, and nutrient cycling) of circular food systems illustrating the spatial scale of their supply and demand. The demand for these elements reflects societal and environmental expectations, which may manifest at spatial scales that are different from the scales at which these elements are supplied.

5.2.1.1 Spatial scales of circularity

All food systems are comprised of several subsystems such as primary production, livestock production, food processing, and food consumption that are nested within the complete system (HLPE, 2017). These subsystems range from field scale to global scale and are also linked to other complex systems. Within these nested food systems, the cropping subsystem refers to the agricultural fields that produce biomass. At the farm scale, the system includes all the field parcels, the livestock, and possible energy production. At regional, national, and global levels, the farming system includes all the farms and farmland that serve the food system. Similarly, the subsystems of food processing and consumption range from local to global in their spatial scales. The increase of physical distance between operations from one subsystem to another necessitates the import and export of primary agricultural, food, and feed products.

5.2.1.2 Biomass for food and feed

Primary production inherently takes place on farms, at a very local scale. However, at the agricultural system scale, the cheap transportation of concentrated feeds such as cereals has distanced animal husbandry from local feed production. Furthermore, most crop and livestock products have to be processed before they are delivered for consumption. This increases the geographical scale at which primary products are collected and redistributed.

Demand at the national level is often determined by national food consumption which reflects cultural dietary preferences. Historically, culinary cultures were shaped by the food that could be produced locally. Over the centuries, processes such as globalization have changed food systems—supply, demand, and culture are no longer dictated by spatial scales. In the market-driven system, dietary choice directs food production and can be a major driver of its environmental outcome. For example, livestock production requires more agricultural resources and land than the equivalent plant food production (Van Zanten et al., 2016; Röös et al., 2017).

5.2.1.3 Biomass production for energy

Since food production currently relies heavily on the extraction, transport, and combustion of fossil fuels, the transition from fossil fuel-based energy to renewable energy is an important prerequisite for moving towards circularity (Haas et al., 2015). In this context, biomass production has a dual role because it can both consume and produce renewable energy. Biomass can be transported to industrial sites for production of biofuels, or bioenergy can be produced at the farm scale. In general, biogas is an example of on-farm bioenergy production while biodiesel is an example of biofuel that is produced at the industrial scale. The predominant sources of renewable energy in food systems are manure, crop residues, and bioenergy crops.

5.2.1.4 Nutrient cycling

N and P losses from food production have reduced the quality of groundwaters and surface waters (Schröder et al., 2004; Rockström et al., 2009; Wick et al., 2012). Furthermore, mineral fertilizer manufacturing heavily relies on fossil fuels (Levi and Cullen, 2018). These problems can be mitigated by replacing mineral N with biological nitrogen fixation (BNF) (Crews and

Peoples, 2004), by producing fertilizers that are based on renewable energy, and by recycling nutrients more efficiently (Buckwell and Nadeu, 2016). BNF, an ecosystem service that can be accomplished only at a local scale in agricultural fields, is an alternative to the Haber-Bosch process used (which is the industrial fixation of N by which fertilizer production is consolidated and operates at the national and global scales).

Regardless of the fixation method or the source of the nutrients, recycling within farming through the return of livestock manures to crop production requires implementation at a relatively local scale. This is primarily because low nutrient level per wet-weight unit of livestock manure means that large volumes are required for on-farm use, which increases transportation costs and thus is not economically feasible if the manure is transported long distances (Fealy and Schröder, 2008; Paudel et al., 2009; Neiva de Figueiredo and Mayerle, 2014). As global consumption of animal products increases, manure creates the largest single recyclable flow of plant nutrients.

At the other end of the food chain, nutrients also accumulate as food waste and human excrement are increasingly concentrated spatially due to urbanization. The average human annually excretes about 0.5 kg of phosphorus (P) and 4.5 kg of nitrogen (N) (Vinnerås et al., 2006), which creates an opportunity to substantially reduce nutrient losses from the food system through recycling (van Kernebeek et al., 2018).

5.2.2 Applying the framework in regional case studies

We applied this framework (Figure 1) in assessing circularity in food systems using three contrasting regional case studies. Specifically, we studied how regional food production is connected to the national and global scales through the imports and exports of inputs and outputs in food production. We chose three regions at the NUTS 3 level (Eurostat, 2018) in Finland that differ from one other in terms of population and their agricultural structures (Table 1, Figure 2). The first region, South Savo (GRS-LIV), produces grass-based livestock and has a low population (7.7 inhabitants per km2). The second, South Ostrobothnia (INT-LIV), represents a region with intensive livestock production and also has a low population (13.6 inhabitants per km2). The third region, Uusimaa (URB-CRP) is the location of the capital city of Helsinki and is a more densely populated (103.2 inhabitants per km2) with more crop farms and fewer livestock farms than in the two formerly mentioned study regions. We used agricultural data, including crop and livestock data, input use, and produced agricultural products, from the years 2015–2019. Other relevant food system data, including food consumption and nutrient contents in food processing related wastes or in sewage sludge, were derived from the statistics and literature. Data sources are listed in Table 2.

Table 1. Agricultural characteristics of the study regions. The agricultural land use data (OSF, 2020a) and number of animals (OSF, 2020b) are averaged over the years 2015-2019.

	South Savo (GRS-LIV)	%	South Ostrobothnia (INT-LIV)	%	Uusimaa (URB-CRP)	%
Agricultural land (ha)	69,040	100	240,720	100	177,623	100
Cereals (ha)	*21,580*	*31.3*	*127,280*	*52.8*	*102,080*	*57.5*
Grassland under 5 years (ha)	*35,680*	*51.7*	*68,020*	*28.3*	*30,300*	*17.0*
Oilseed and protein crops	*940*	*1.4*	*8,740*	*3.6*	*12,780*	*7.1*
Potatoes (ha)	*260*	*0.4*	*5,260*	*2.2*	*240*	*0.1*
Horticulture crops (ha)	*734*	*1.0*	*660*	*0.3*	*1,223*	*0.7*
Fallow area (ha)	*8,580*	*12.4*	*29,060*	*12.1*	*28,080*	*15.8*
Other crops (ha)	*1,266*	*1.8*	*1,700*	*0.7*	*4,320*	*2.4*
Number of animals						
Bovine	42,970		111,843		22,425	
Pigs*	13,502		472,487		64,068	
Poultry	162,348		3,573,923		12,164	
Other animals**	8,319		11,003		10,936	

* Number of fattening pigs is calculated by dividing the regional meat production by the average meat production 80 kg per pig (Enroth, 2009) and number of boars and sows is based on statistics (OSF, 2020b)

**Include sheep, goats and horses

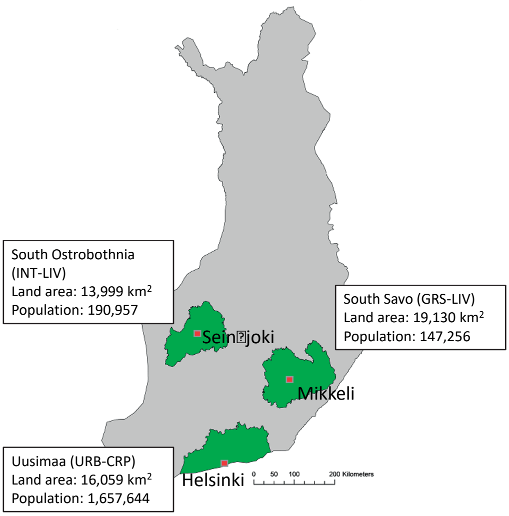

Figure. 2. Case study regions within Finland. Land areas and populations as in 2017 (OSF, 2017). Regional capitals are marked with red squares.

Table 2. Data sources and the methods used to calculate the outcomes in the study

Indicator	Subject	Method of computation	Reference
Biomass for food and feed	Agricultural land area	Derived from the statistics	OSF, 2020a: Utilized Agricultural Area
	Number of livestock	Derived from the statistics	OSF, 2020b: Number of Livestock
	Yields	Dividing the total yield[1] by the cultivation area[2]	OSF, 2020c: Crop Production Statistics
	Crop's protein content	Multiplying the crop's nitrogen content[1] by 6.25[1]	[1]Natural Resources Institute Finland, 2018, [2]Mariotti et al. 2008
	Livestock products' protein content	Multiplying the meat production[1] by the protein contents of livestock products[2]	[1]OSF, 2020d, Meat production by Area, [2]USDA, 2020
	Share of food and feed use	Derived from the statistics	OSF, Cereals balance sheet, 2019
	Feed consumption	Multiplying the study regions' number of animals by the annual feed consumption per animal	Enroth 2009, Huhtamäki, 2019, Suomen broileriydistys ry, 2020 (personal communication), Suomen hevostietokeskus 2020, Atria ltd (personal communication)
	Protein consumption	Multiplying the study region's population by the average annual consumption of protein per capita	Valsta et al. 2018
	Exports and imports between the scales	Subtracting the protein production in crop products[1] and livestock products[2] from the regional consumption. Product exports and imports between Finland and global was derived from the statistics[3].	[1]Natural Resources Institute Finland, 2018, [2]USDA, 2020, [3] 2OSF, 2020e
Biomass for energy	Biomethane potentials for different feedstocks	Multiplying the quantity of volatile solids[1] in each feedstock by the biomethane potentials for different feedstocs[2]	[1]Luostarinen et al. 2017, [2]Seppälä, et al. 2009, Möng-Tegeder et al. 2013, Seppälä et al. 2013, Kafle and Chen, 2016
Nutrient cycling	Mineral fertilizer input	Derived from the statistics	Natural Resources Institute Finland, 2020a
	Manure input	Multiplied by the study region's number of animals[1] by the average nutrient content in manure[2]	[1]OSF, 2020b, [2]Luostarinen et al. 2017
	Biological nitrogen fixation	According to a formula described by Anglande et al. (2015)[1] based on cultivation areas[2] and yields[3]	[1]Anglade et al. 2015, [2]OSF, 2020a, [3]OSF, 2020c
	Nutrient potential in food processing's side streams	Multiplying the quantity of process waste from food processing[1], biodegradable municipal waste[1] by their nutrient content based on literature[1,2,3].	[1]Natural Resources Institute Finland, 2020b, [2]Tampio et al. 2016, [3]Kask et al. 2012,
	Sewage sludge	Multiplying the number of each region's population under industrial wastewater treatment, by the average phosphorus quantity, 0.83 P kg $person^{-1}$ yr^{-1}, in the sewage sludge	Finnish Environment Institute, 2020

5.2.2.1 Indicators for assessing circularity in food systems

To further understand the circular food systems that were outlined in Section 2.1, we created a model for the quantification of biomass production for food and energy, and for nutrient cycling. The following indicators were chosen to evaluate circularity in the case studies:

- Biomass production for food: protein produced (kg ha^{-1}), protein production in relation to consumption (%), connection of biomass flows to national (net balance of produced protein Gg) and global scales (net balance of produced products)
- Biomass production for animal feed: feed self-sufficiency (Dry matter production/consumption), regional cereal feed surplus (protein kg ha^{-1});
- Biomass production for energy: biogas production potential compared to the energy consumption on farms and mineral N and P manufacturing (MWh ha^{-1});
- Nutrient cycling: agricultural field balances (N kg ha^{-1} and P kg ha^{-1}); share of recycled N and P (%).

5.2.2.2 Biomass for food and animal feed

We used protein production as an indicator for food production because proteins are at the biophysical intersection of the nutrient and biomass cycles. Proteins are also essential dietary component for both humans and animals, and it is obtained from both crops and livestock products (Willet et al., 2019). Primary production of the food protein in the study regions was calculated from crop and livestock production for direct human consumption (Table 2). The following crops were included in our analysis: wheat, barley, oats, rye, peas, broad bean and potatoes. Horticultural crops, caraway, sugar beets and other cereals were excluded from the calculation because of their negligible cultivation area (Table 1) and non-significant role in protein production. Honey and fish were outside of the scope, because they do not represent agriculture-based foods in the area. The protein produced was calculated using quantities before processing.

For animal feed production, we first calculated the amount consumed by livestock (bovines, sheep, horse, pigs and poultry) in each region (feed consumption per animal is provided in Appendix 1). We then divided feeds into forage and concentrated feeds which were then further sub-divided into on-farm concentrated feeds such as cereal feed (including cereals, peas, and broad beans) and industrial feedstuff which is always imported to farms. Forage was assumed to be produced entirely within the region, whereas cereal feed production resulted in either a regional surplus or a deficit. In all cases, industrial feeds were assumed to be imported. In addition to feed crops, the calculation also included the by-product of brewery-spent grains due to their substantial area in cultivation. In the URB-CRP, the share of malt barley cultivation area of was 51% of the total barley cultivation area. Corresponding shares for the INT-LIV and GRS-LIV were 1% and 2%, respectively. The connection of each study region to the national scale and further into the global scale is explained in Table 2.

5.2.2.3 Biomass for energy

Biogas generation is a suitable technology for the production of energy from agricultural biomasses and is widely available and used (Börjesson and Berglund, 2006; Weiland, 2010; Möller and Müller, 2012). The sector, however, has not reached its full potential (Winquist et al., 2019). Therefore, we used potential for biogas production, rather than current biomass production, as an indicator. This potential was calculated using the current available agricultural biomasses (manure, green manure leys and nature management fields) that did not compete with food production (Appendix 1). We estimated a parasitic energy consumption of 15% and an energy efficiency of 85% in combined heat and power (CHP) production. The energy quantity produced per hectare was compared to the unrenewable energy consumption on the farms (OSF, 2013), including the energy consumption of manufacturing mineral N (32 MJ kg^{-1}; Hoxha and Christensen, 2019) and P (20 MJ kg^{-1}; Schröder et al., 2010). On-farm energy consumption included the electricity, motor fuel oil, heating fuel oil, fuel for drying of cereals, heavy fuel oil, milled peat, sod peat, and peat pellets.

5.2.2.4 Nutrient cycling

Nutrient balances provide information about the environmental pressure from arable farming (OECD, 2020) whereas the share of secondary nutrients differentiates the nutrients already existing in the systems from the newly imported nutrient inputs. To calculate the nutrient balances and the share of secondary nutrients of the food production's total nutrient input, we considered mineral fertilizers, manure and BNF (Table 2). Potential additional nutrient inputs from recycling were calculated from the food related waste streams, derived from the availabilities of biodegradable municipal waste, side-streams related to food processing, and sewage sludge from industrial wastewater treatment plants (quantities and nutrients are provided in the Appendix 1). We did not include nutrients from the sewage sludge in the total nutrient input because there are no comprehensive data available for agricultural use of sewage sludges.

5.3. Results

5.3.1 Biomass for food and feed

The INT-LIV region produced 59% more food protein per hectare than the URB-CRP region, and 23% more than the GRS-LIV (Figure 3). In both the GRS-LIV and INT-LIV regions, protein was produced mostly in the form of livestock products whereas, in the URB-CRP region, it was mostly produced in the form of crops. As a net balance, the INT-LIV and GRS-LIV produced more food protein than they consumed while the URB-CRP was the most reliant on food protein imports (Figures 3 and 4). In the GRS-LIV, 97% of the livestock-based protein produced was in the form of beef or milk. In the INT-LIV the corresponding proportion for bovine production was 47% and in the URB-CRP it was 78%. Cereals corresponded to 94% of the total protein in food crops in the URB-CRP. In the GRS-LIV and INT-LIVE the corresponding shares for cereals were 75% and 58% respectively. In the INT-LIV and GRS-LIV potatoes produced 42% and 22% of the total food crop protein.

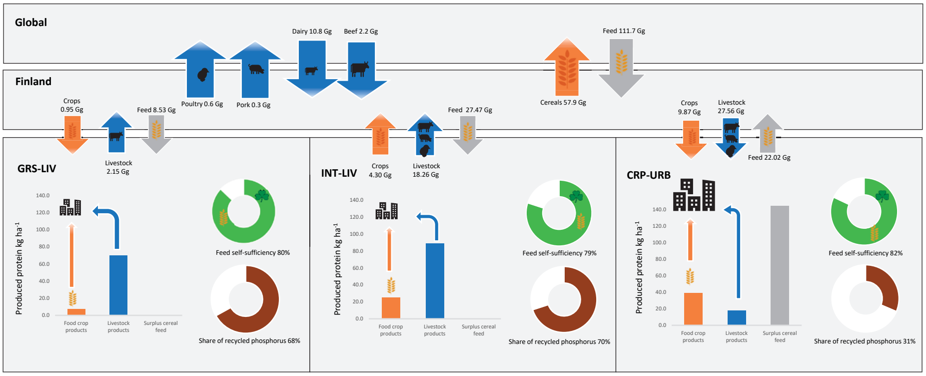

Figure 3. Comparison of agricultural production in the three contrasting regions (Table 1). Food productivity in the study regions in crop and livestock products (as protein kg ha−1) per unit farmland, surplus cereal feed protein (protein kg ha−1), feed self-sufficiency (% of dry matter), and share of recycled P (%). Exports and imports between Finland and Global demonstrate the trade balances in agricultural products in Gigagrams (Gg) per year. The terracotta-coloured arrows represent food crops while blue arrows represent livestock products, and grey arrows represent feeds.

GRS-LIV		INT-LIV		CRP-URB	
Protein production/consumption Food crop products	35%	Protein production/consumption Crop products	322%	Protein production/consumption Crop products	41%
Protein production/consumption Livestock products	180%	Protein production/consumption Livestock products	617%	Protein production/consumption Livestock products	10%
Cereal feed production/consumption	70%	Cereal feed production/consumption	90%	Cereal feed production/consumption	456%
Energy production potential/consumption	66%	Energy production potential/consumption	76%	Energy production potential/consumption	81%

Figure 4. Production in relation to consumption (protein produced / protein consumed;%) of food crops, livestock products, and cereal feeds as well as potential energy production in relation to consumption (%).

Feed self-sufficiency was highest in the URB-CRP region, where on-farm concentrated feeds were produced 52% more than consumed (including the cereals in industrial feeds). The quantity of surplus feed protein (kg ha−1) was 23% higher than the produced food protein in the URB-CRP while in the GRS-LIV and INT-LIV there was a deficit in concentrated feed production (Figure 4.)

5.3.2 Biomass for energy

The highest potential for producing energy from agricultural biomasses was in the URB-CRP region where potential energy production was 81% of energy consumption on farms and mineral N manufacturing (Figure 4 and Table 3). The corresponding rates for the INT-LIV and GRS-LIV were 76% and 66%, respectively. Manufacturing of the mineral fertilizers accounted for 21% of the total energy consumption in the GRS-LIV, 28% in the INT-LIV, and 34% in the URB-CRP. In the INT-LIV and GRS-LIV, the vast majority of energy production potential was in the form of livestock manure, while in the URB-CRP, plant biomass (nature management fields and green manures) provided most of the energy potential.

Table 3. Energy production potential of biogas production from agricultural biomasses and regional energy consumption on the farms and energy consumption of mineral nitrogen (N) manufacturing in the three contrasting study regions.

	GRS-LIV	INT-LIV	URB-CRP
Energy production potential (GWh)	139	541	339
Plant biomass (GWh)	*63*	*206*	*241*
Manure (GWh)	*76*	*335*	*98*
Energy production potential (MWh ha^{-1})	2.0	2.2	1.9
Energy consumption (MWh ha^{-1})	3.1	2.9	2.4
On-farm energy consumption (MWh ha^{-1})	*2.5*	*2.3*	*1.8*
Mineral N manufacturing energy consumption (MWh ha^{-1})	*0.5*	*0.6*	*0.6*

5.3.3. Nutrient cycling

Nutrient surpluses were highest in INT-LIV where the N and P input in mineral fertilizers were also higher than in the GRS-LIV and URB-CRP (Table 4). In the URB-CRP and GRS-LIV, N and P losses were substantially lower as a result of lower mineral fertilizer and manure inputs. The contribution of manure input to total nutrient input was highest in the INT-LIV and GRS-LIV (Table 4), where the share of manure was 42% and 32% of the total N input, and 70% and 68% of the total P input, respectively. In the URB-CRP, the corresponding shares

Table 4. Agricultural field nutrient balances for inputs, outputs and balances of nitrogen (N) and phosphorus (P) in the three contrasting regions of agricultural production (Table 1)

	GRS-LIV	INT-LIV	URB-CRP
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Total N input	133	154	95
Biological nitrogen fixing	*34*	*22*	*19*
N input mineral fertilizers	*57*	*67*	*63*
N input manure	*42*	*65*	*14*
N output (harvested crops)	68	67	56
N Balance	65	87	40
Total P input	12.5	25.2	10.5
P input mineral fertilizers	*4.0*	*7.6*	*7.2*
P input manure	*8.5*	*17.6*	*3.3*
P output (harvested crops)	9.2	9.3	8.2
P balance	3.3	16.0	2.4

were 15% for N and 31% for P. In the GRS-LIV and INT-LIV N input in manure and BNF was 12% and 30% higher, respectively, than the output in harvested biomass. In the URB-CRP, the corresponding share was 59%. P input in manure covered 92%, 189% and 40% of the output in the harvested biomass in the GRS-LIV, INT-LIV and URB-CRP, respectively.

Besides agricultural nutrient inputs (manure and BNF), sewage sludge provided the greatest potential N and P source in the URB-CRP and (though to a lesser extent) in GRS-LIV (Table 5). In the URB-CRP the potential P input was almost exactly same as the P input in mineral fertilizers. In the GRS-LIV, the potential was a third of the mineral P input while in the INT-LIV the corresponding share was 3%. However, In the INT-LIV, waste from food-processing had more potential N and P than did sewage sludge, accounting for 18% of both mineral N and P inputs.

Table 5. Potential nutrient content (kg ha^{-1}) of nitrogen and phosphorus in food-processing related side streams and sewage sludge in the three contrasting regions of agricultural production (Table 1 in the manuscript)

	GRS-LIV	INT-LIV	URB-CRP
Nitrogen			
Food-processing related side streams (kg ha^{-1})	1	12	6
Sewage sludge (kg ha^{-1})	6	1	34
Phosphorus			
Food-processing related side streams (kg ha^{-1})	0.2	1.4	0.8
Sewage sludge (kg ha^{-1})	1.3	0.2	7.3

5.4. Discussion

5.4.1 Regional differences in circularity

In this study, we provided a novel approach to assess circularity in food systems. Through three case study regions, we demonstrated how flows of biomass, nutrients and energy are interconnected at multiple spatial scales and how this interconnectedness varies between regions, signifying different degrees of circularity.

From the circularity perspective, this contrast was greatest between the region characterized by intensive livestock production (INT-LIV) and the region characterized by arable farming (URB-CRP). In the intensive livestock region, feed imports were found to be essential for reaching high levels of both food production and energy production potential (from manure).

Transport of concentrated feeds and the substantial use of industrial feeds have disconnected livestock production from the land where production takes place. One such example is dairy production, in which silage is produced locally, but concentrated feed production is outsourced from other regions and countries (Uwizeye et al., 2020). Our study shows that this separation also takes place between regions within a country. Cereals are grown in southern Finland while livestock is more commonly raised in the western and northern parts. Similarly, monogastric livestock are now increasingly reliant on feed imports from other regions, as well as on global flows of soybean and rapeseed meal (Finnish Food Authority, 2020).

These trades in feed and fertilizer have resulted in positive nutrient balances at the national level in Finland. As a result of lack of circularity, fertilizers that originate from rock phosphate or from synthetic N fixation form the largest nutrient flows that are responsible for this surplus accumulation. These fertilizers are mainly used to grow animal feed (Antikainen et al., 2005) where the spatial proximity necessary for manure recycling is lacking. Feed also accounts for substantial amounts of imported nutrients. Parviainen and Helenius (2020) found that imported feeds accounted for 36% and 15% of the N and P content in manure, respectively. Similar patterns can also be observed at higher spatial levels, such as at the EU level, where more than half of the food system's total P footprint is outsourced to other countries through food and feed imports (Nesme et al., 2016; Schulte et al., 2019)

Transitions to a more circular system would either require livestock production to rely more on local feed production or on transporting nutrients back to the feed production areas (in the form of manure). However, the costs associated with the transportation of manure is distance-dependant, necessitating relatively local management (Paudel et al., 2009; Neiva de Figueiredo and Mayerle, 2014). A livestock production system that relies on local feeds would ultimately result in a reduction in regional specializations of either livestock or grain feed production which could improve nutrient use efficiency, reduce environmental externalities, and provide ecosystem services (Lemaire et al., 2014; Uwizeye et al., 2016; Ryschawy et al., 2017). However, the benefits of the reintegration of arable and livestock systems should be assessed and weighed against the context-specific benefits of spatial specialisation in terms of the suitability of contrasting soils and their contribution to food and feed production (Schulte et al., 2014; Van Kernebeek et al., 2018).

In the arable farming region, food production was relying heavily on mineral fertilizers. Still, the regional nutrient balance was positive, though lower than in the livestock regions. The arable region primarily produced feed-grain crops, thus exporting a significant amount of its nutrients to the livestock regions. These nutrients could not be returned to the soil within the region where they originated (in the form of manure). This accumulation of nutrients in livestock regions was reported previously by Uusitalo et al. (2007).

5.4.2 From regional to national and supranational scales

When we consider only the production of food, the region with the most diverse food production showed the lower degree of circularity while region with specialized food production showed the highest degree of circularity. This indicates that, when striving for circularity, a renewed reliance on resources that are available at the most localised spatial scales may be more important than a diversification of farming systems per se. Put simply, this implies the tailoring of farming systems towards locally available natural resources.

However, when also considering food consumption, the complexity increases. We found that regional food systems are further connected to national and global food systems through the food trade. Because full food self-sufficiency is rarely possible at a regional scale, regions typically function as either net exporters or importers of food. In Finland, about 30 to 40% of the national calorie consumption is derived from imported food (Sandström et al., 2017). Although this includes many commodities that cannot be produced locally, such as coffee and fruits, it also encompasses many products that are indeed also produced locally: pork, for example, was imported in the same quantities as it was exported (Natural Resources Institute Finland, 2020c). Finland is a net-exporter of protein in cereals, whereas dairy and beef imports exceed exports. Overall, both imports and exports of food have increased in Finland over the past 30 to 40 years (Sandström et al., 2017; Parviainen and Helenius, 2020) which indicates further globalization and linearization of the Finnish food system.

5.4.3 The role of food processing

In many food products, the linkage between production and consumption is heavily influenced by food processing. We could not find comprehensive data on the quantity of food that is processed in the same regions where that food was produced. As an example, however, in the case-study region characterized by grass-based livestock production, current local options for dairy processing are negligible which means that most dairy products must be processed outside of the region before they are returned to be sold. Food processing employment statistics (OSF, 2020) indicate that the less-populated (but higher agricultural production) study regions (INT-LIV and GRS-LIV) have fewer options for food processing than the region with a large population (but lower agricultural production). In relation to agricultural land, employment by the food processing industry in the GRS-LIV region was only 19% of its equivalent in the urban region. This implies that the food processing industry tends to gravitate towards regions with higher population densities.

In the absence of a regional food processing industry, this spatial distancing of commodity production and processing creates lock-ins for specialized production structures. This poses challenges to the redesign of farming systems, and suggests the need for a more comprehensive approach to systemic redesign. The equitable distribution of food processing facilities could potentially create more demand for diverse agricultural production. Such an approach has been implemented at the farm scale as part of a pilot project where food production, food processing, and bioenergy-use are integrated in a form of industrial symbiosis called agroecological symbiosis (Koppelmäki et al., 2019).

5.4.4 The role of waste streams

The amount of nutrients in food-processing related wastes was relatively low in each region, which reflected national levels in which P in food-processing related biomass contributed only 4.2% of the total P of all biomass (Marttinen et al., 2017). The arable region's large human population could potentially utilize sewage sludge to replace the mineral fertilizer P input. There is no comprehensive information about the agricultural use of sewage sludge. Official statistics underestimate the agricultural use of sewage sludge in Finland at only 3% (Vilppanen and Toivikko, 2017), whereas data collected from wastewater plant operators in 2016 suggest the agricultural usage as high as 40%. This shows that the role of sewage sludge and food related wastes are context-dependant: in regions with large populations, sewage sludge and food related side-streams can be a significant source of nutrients, with the potential to replace mineral P (Van Kernebeek et al., 2018). To some extent, this is already happening: presently, the majority of waste by-products that could be used as feed are already being used as such. According to Berg (2016), one third of by-products from food processing are recycled as raw materials into feed and organic fertilizer production. One such an example is brewery spent grains originating from beer processing, which provide an additional feed protein source of 29 kg ha−1 from the studied arable region.

Further cycling of by-products as feed is limited by legislative restrictions, the easement of which requires prior food safety examinations (personal communication with the feed industry, 2020). To a lesser extent, this also applies to the use of side streams (mostly from food waste, such as meat bone meal and biodegradable municipal waste) as sources of organic fertilizers (EU, 2019).

From a circularity perspective, it is important to distinguish between nutrient flows that are avoidable and those that are not (Papargyropoulou et al., 2014). Organic waste from food processing is one example of an unavoidable nutrient flow that is inherent to the process. Contrastingly, excess manure from intensive livestock production (in which the manure is not applied back into the production system) is an example of a waste stream that is avoidable, even if it would require considerable systemic change.

5.4.5 The role of bioenergy

Our study showed that a more circular food system offers substantial potential to produce bioenergy without food-energy competition. Generalized to national scale, this potential of agricultural biomass could produce renewable energy in the whole of Finland and cover 86% of the national techno-economical potential of biogas production (Marttinen et al., 2015). The effective integration of biogas and food production at the farm scale has recently been demonstrated by Koppelmäki et al. (2019) in a study that shows the benefits of integrating biogas production into food production in concert with BNF to enhance nutrient recycling within organic farming systems. By using leguminous green manures as the feedstock of anaerobic digestion, the on-farm production of biogas not only contributes to a positive energy balance, but also to more precise fertilization, which reduces the necessary area for green manure (thus leaving more land available for food production). In this light, it is important to consider biogas plants as not only bioenergy producers, but also as recycling facilities. In a CE, biogas plants (which produce renewable energy) are not the end-users of organic wastes and excess biomasses, but rather are necessary for recycling nutrients and disconnecting food production from the use of fossil fuels.

5.4.6 Applicability and limitations of the study

Our case studies represented different agricultural regions in Finland but the framework can be applied similarly to other agricultural contexts and spatial scales. We used openly available data with the limitation on data related to food processing and industrial feed production: there were no data available for agricultural production used in food processing within a region. Similarly, we could not identify data on the regional use of by-products in the feed industry.

5.4.7 Principles for a circular food system

In summary, our case study has demonstrated how flows of biomass, nutrients, and energy are taking place at a range of scales. Current food production systems are connected from the fields to the global level through linear flows resulting in negative environmental impacts such as the accumulation of nutrients in some regions. Thus far, studies on circularity in the food system have focused mostly on recycling of nutrients. In this paper, we have demonstrated that this only captures one dimension of circularity, and that the closing of cycles at local scale is not always possible or even desirable.

Our vision of nested circularity (Figure 5) aims to close not only nutrient cycles, but also biomass cycles and energy flows related to food production, across spatial scales, while maximizing synergies between these components. Achieving circularity in food systems at a global scale requires that these food systems are also compatible with circularity at national, regional, and farm level. In other words, circular food production at the regional scale requires the integration of farm scale cycles, circularity at the national scale requires the integration of regional cycles, while circularity at the global scale requires the integration of national and continental cycles.

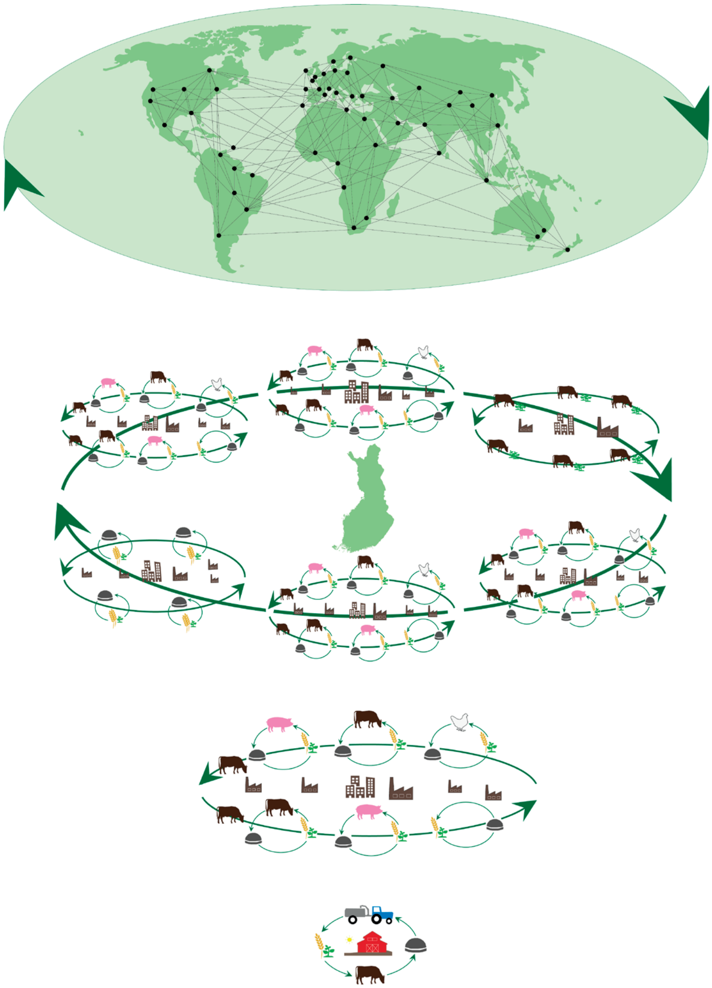

Figure 5. Schematic picture of nested circularity at different geographical scales. The bottom picture illustrates circular farms which, together and in conjunction with food processing and food consumption at the regional scale, form the circular food system. Circularity at the national scale occurs as a result of circularity within the different regions of which it is comprised. Achieving circularity requires compatibility across the scales.

From our case studies, we have derived the following principles for nested circularity in the food system:

1) The role of livestock and energy production based on agricultural biomass is context-specific and depends on both the demand for plant-based food production and on the specific agroecological system. In some regions, livestock production is the only option for producing food. Circularity requires that the scale and intensity of livestock production be set by the local capacity to produce feed, in order to avoid nutrient surpluses as well as the competition for land with direct food production;

2) Biomass, nutrients, and energy constitute multiple, interlocked dimensions in circular food systems. Increasing circularity requires that the use of non-renewable, imported inputs is reduced through improved nutrient recycling and increased multifunctionality in biomass production, for example, integrating energy production into food production;
3) While food production is localized (i.e. relying on local nutrient inputs, feed production, and energy production) at smaller spatial scales, processed food is imported and exported across the scales.
4) Recycling nutrients in biomasses that are concentrated in urban areas, such as sewage sludge and biodegradable municipal waste, provides substantial resources required for closing nutrient loops in densely populated agricultural regions

Furthermore, we identified additional elements that are essential to the transformation towards circular food systems which were not included in this study but deserve further study:
1) The impacts of a possible transition to more plant-based diets, as proposed by reports such as EAT-Lancet (Willett et al., 2019) on circularity in the food system;
2) The addition of economic values at different scales in circular food systems. This may involve, for example, a more direct linkage between food production and processing, and the value derived from distributed energy production systems;
3) The optimal use of waste biomasses such as sewage sludge in order to increase nutrient recycling.
4) The role and participation of multiple local actors, at a range of spatial scales, that are required in a transition towards circular systems (O'Sullivan et al., 2018).

5.5. Conclusions

Circularity is considered a promising approach for creating more sustainable food systems. However, current farming systems have actually moved away from circularity. In order to facilitate a transition toward CE in food systems, we need to develop a better understanding of current biomass, nutrient, and energy flows within these systems, and how these flows are connected at different spatial scales. In this paper, we presented a framework for circularity in food systems and applied the framework to three case studies in Finland. Through these case studies, we demonstrated how biomass and nutrient flows related to livestock production play a key role in current food systems. As a result of food consumption, more densely populated areas, which can be seen as analogous to intense livestock production, offer significant nutrient resources which could be circulated back to food production. Achieving circularity requires that the food production be based on local resources. This means, for example, that the capacity to produce feed determines the scale and intensity of livestock production. Because biomass production, nutrient flows and energy use are interlinked, a multifunctional use of biomass could provide options for improving nutrient recycling as well as allowing for bioenergy production which does not compete with food production. The introduced concept of ‘Nested circularity’ provides a vision for localizing food systems by closing nutrient, biomass, and energy cycles at multiple scales. Achieving this vison would require further studies about system-level transition including changes to transition pathways towards agricultural production that is aligned to context-specific agroecological conditions.

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Supplementary material

Supplementary Table 1. Feed useper animal

	Dairy cows[1]	Heifers[2]	Suckler cows[2]	Bulls[2]	Sheep[2]	Horse[3]
	kg DM yr^{-1}	kg DM yr^{-1}	kg DM yr^{-1}	kg DM yr^{-1}	kg DM yr^{-1}	kg DM yr^{-1}
Silage	3,758	2,150	3,225	1,403	224	-
Pasture	2,60	247	1,455	-	258.02	-
Hay	-	-	-	34.4	122.12	2,511.2
Grain	1,233	110	305	1,079.3	132.44	627.8
Industrial feed	1,858	224	64.5	113.52	-	172.65
	Fattening pigs[4]	Sows and piglets[4]	Laying hen[2]	Broilers[5]	Turkey[6]	
	kg DM lyr^{-1}	kg DM yr^{-1}	kg DM yr^{-1}	kg DM yr^{-1}	kg DM yr^{-1}	
Grain	175.2	1116	24.8	2.45	19.6	
Industrial feed (concentrate)	64.8	744	6	1.05	8.4	

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[6] Suomen siipikarjaliitto ry. www.siipi.net (accessed 21 April 2020)

Supplementary Table 2. Biomethane potentials (BMP) for different feedstocks

Feed	BMP Nm^3 CH_4 t VS^{-1}	Reference
Grass*	322	Seppälä et al. 2009
Cow slurry**	212	Seppälä et al. 2013
Pig slurry**	180	
Laying hens and poltry (deep	425	Kafle and Chen (2016)
Horse (deep litter)	142	Mönch-Tegeder et al. (2013)
Sheep and goat	242	Kafle and Chen (2016)

Supplementary Table 3. Grains used for food and feed

Grain used for food and feed	Food %	Feed %	Seed %	Energy %	Other use %	Protein content g/100 g DM
Wheat	28.4	62.7	7.2	0.4	1.4	12.26
Rye	91.5	1.9	5.2	0.7	0.8	9.86
Barley	0.9	70.8	7.8	0.4	20.1	10.64
Oats	9.4	82.0	7.6	1.0	0.1	11.65
Broad bean*	6.5	87	7			26.88
Peas**	-	-	-	-	-	20.61

* own estimation

** Based on regional data from the years 2018 and 2019 (Official Statistics of Finland, 2020)

Supplementary Table 4. Quantities and nutrient contents of food related wastes from agriculture, municipalities and food processing industry (Biomass atlas, 2020)

	South Savo	South Ostrobothnia	Uusimaa	N	P
	Quantity t yr-1	Quantity t yr-1	Quantity t yr-1	%	%
Animal-tissue and processing waste	109	78785	1697	3.2	0.4
Plant-tissue waste from the primary production	-	46665	1413	0.78	0.1
Primary production's other waste	8	3166	4	0.78	0.1
Other waste from the sugar-processing	2858	-	-	0.8	0.5
Dairy-product-industry's materials unsuitable for consumption or processing	1341	-	-	0.3	0.06
Beverage industry's raw-materials-processing-sludges	-	-	228	0.8	0.5
Municipal separately-collected edible-oil-and-fat-waste	9	-	113	0.16	0
Biodegradable municipal waste	10356	13483	115320	0.78	0.1

6

Chapter 6

Food-energy integration in primary production and food processing results in a more equal distribution of economic value across regional food systems. Nordic case study from circular perspective

Kari Koppelmäki, Maartje Hendriks, Susanna Kujala, Juha Helenius, and Rogier P.O. Schulte

Abstract

Circular food systems have been proposed as an alternative to the current dominant linear food chain structures. Biomass production for food and energy, and nutrient recycling have been defined as the most important elements of circular food systems. Thus far, the potential role of food processing as a large biomass and energy user has gained little attention in studies of the circular bioeconomy. In this study, we explore how compatible bioenergy production is with the energy consumption of regional food processing and how such integrated systems may impact on the economic value created in regional food systems. We applied the Nested circularity framework to three contrasting regions to study from an economic perspective the economic value created in primary production, food processing and bioenergy production. In addition to this, we also calculated the value of external nutrient and energy inputs used in food production. Our results showed how energy production from agricultural biomasses can provide enough energy for food processing on a regional scale, but that this would require integrating food processing with primary production. As a result of this integration, the economic value created in food processing decreased substantially in two of the case study regions while the value increased in the third region but at national level the overall value remained the same. We suggest that regionalized food processing is an integral element of circular food systems, as it plays an important role in closing local and regional cycles of nutrients, food and energy.

6.1 Introduction

The structure of the food chain, including primary production, food processing and food consumption, has an important role in determining the economic and biophysical performance of the food systems. The modern food chain mainly follows a so-called linear model (Jurgilevich et al., 2016) where primary production, food processing and food consumption are operating at and increasingly global scale. This pattern is not only unsustainable in terms of the environment, but it also bypasses economic opportunities for rural regions (European Commission, 2020).

One of the main consequences of the current food system has been that primary production has become detached from the land and regions where food is processed and consumed (Hendrickson, 2015; Nyström et al., 2019). This detachment has increased dependency on external inputs (Gladek et al., 2017; Sims et al., 2015). For example, livestock production in Europe is heavily dependent on feed imports from outside of Europe (Wang et al., 2018). As a result of the increased geographical scale at which food is produced and processed, emissions that are embedded in the products are traded across different spatial scales (Uwizeye et al., 2016). This regional specialization in farming coupled with the consolidation of the food industry, and the globalization of the production chains have made it increasingly challenging to reach the goals of circularity in food sector because food value chains now typically transcend the spatial scales at which accountability and legislative compliance is administered (O'Sullivan et al., under review).

Nested circularity

Aiming to address these challenges with food system redesign, previous studies on a circular bioeconomy have called for more localized food production by better cycling of nutrients (Harder et al., 2021; Kahiluoto et al., 2021). However, the desired outcomes of such reintegration of local supply and demand for food must be considered carefully against the benefits of a diversified diet that global trade of food items has allowed.

In response, Koppelmäki et al. (2021) introduced the concept of "Nested Circularity", which considers the interconnected flows over spatial scales of biomasses and products, and plant nutrients, and the benefits from integrating bioenergy production in the food systems. Nested circularity encompasses an optimized food system that maximizes cycling of, and synergies between these components. The result is more local food production systems that also allow for food products to be imported and exported across different spatial scales.

In addition, we must consider with renewed urgency the need for a transition in the role of agriculture from a net consumer of fossil fuels into a producer of bioenergy. The use of agricultural land for energy production is contested because of possible food-fuel competition from the land area that is required to produce feedstock for energy production (Rosegrant and Msangi, 2014). However, agricultural biomasses that do not compete with food production provide an untapped potential for bioenergy production which could replace the use of fossil fuels, and to increase the overall economic value created in food systems without the introduction of new external inputs (Koppelmäki et al., 2019, 2021b; Scarlat et al., 2018)

Integrated food and energy production

Koppelmäki et al., (2016; 2019) introduced Agroecological Symbiosis (AES) as a model that makes the Nested Circularity concept tangible via a consideration of the spatial scale of food and energy production. In the AES, primary production, food processing and energy production are re-arranged to function in a spatial proximity that enables efficient nutrient recycling, and the multifunctional use of biomass to produce food and energy. In this model, energy is produced from agricultural biomasses such as green manure crops, crop residues and manure, and by-products of food processing. After energy production, the nutrient-rich digestate is returned back to the fields as a fertilizer. The resulting enhanced nutrient cycling has been shown to increase the potential primary production of food while simultaneously enhancing nutrient recycling within the farming system (Koppelmäki et al., 2019, 2021b), thus overcoming food-fuel competition.

While the AES model allows for agriculture to become a net producer of energy, the spatial scale of this energy production is restricted. This is because long-distance transport of these biomasses or energy produced is not economically feasible (Neiva de Figueiredo and Mayerle, 2014; Paudel et al., 2009; Torquati et al., 2016) and local energy demand does not match energy production. This is a challenge, especially in rural areas where biomasses are readily available, but the demand for energy, apart from electricity, is often limited to a farm's own electricity and heat consumption. In the AES model, the food industry partner that is located in the spatial proximity creates a constant demand for the bioenergy.

Knowledge gaps

In previous studies, we analyzed Nested Circularity and the AES model primarily from an environmental point of view (Helenius et al., 2020; Koppelmäki et al., 2021a, 2021b, 2019) without considering the role and compatibility of food processing with energy production from locally available biomasses. Partial decentralization of food processing would mean potentially substantial changes to the structure of the current food system and would impact on how economic value is aggregated and distributed across regions.

As such, a food system design aligned with Nested circularity and the AES concept would result in food production operations taking place at a smaller spatial scale than that at which the current linear food system operates (Figure 1). Primary production, energy production and food processing would take place at local and regional scales allowing for exports and imports of food products from local to global scales. This design would result in the spatial re-distribution of the economic value in the food system.

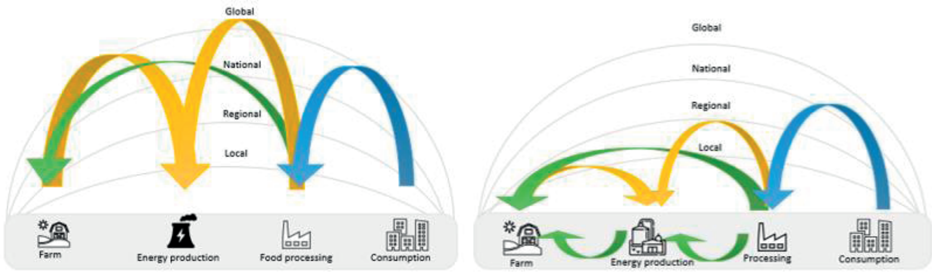

Fig 1. Value flows in linear (left) and circular (right) food systems. Yellow arrows represent value flows for energy, green arrows are value flows for raw materials, and blue arrows represent economic value flows for processed goods

The scope

In this manuscript, we aim to fill the knowledge gap in understanding the economic impacts of such a transformation and to explore the feasibility of the regional integration of primary production with food processing, and integration of these with bioenergy production. To do this, we apply the Nested Circularity framework (Koppelmäki et al., 2021a) to three regions in Finland, to study the accrual and distribution of economic value related to biomass production, nutrients, and energy. First, we assess the compatibility of bioenergy production with the energy consumption of regional food processing, while negating food-fuel competition. Second, we examine how integrated primary production and food processing impact the distribution of economic value across primary producers and food processors in regional food systems.

6.2 Material and Methods

6.2.1 Scenario descriptions

We modeled how economic value is being created in the current food system (CFS) vs. a regionalized food system (RFS) scenario (Figure 2). In the CFS scenario, we modelled the current system at the regional levels using the year 2019 as the reference year. The RFS scenario represented the concept of AES (Koppelmäki et al. 2019; Helenius et al. 2021) where farming, food processing and bioenergy production is integrated at the regional scale. In the RFS scenario, we assumed that food from primary production in a region was also processed into food products within that same region. This scenario (RFS) was contrasted with the current situation (CFS), where factors other than origin of the primary agricultural products define where food processing industries are located. We included the following agricultural products: food cereals, milk, meat and agricultural land use related to producing these products (Supplementary Table 1). In both scenarios, produced feed was assumed to be consumed by the livestock in the same regions. Possible feed surpluses and exports were included in the economic value created in a given region. In addition to the value of food production and processing, in the RFS scenario we included the value of energy production from potential biomasses that did not compete with food or feed production.

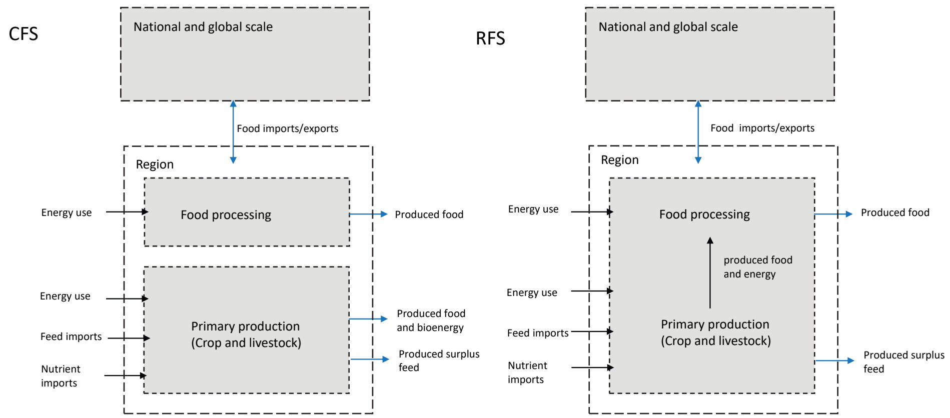

Figure 2. Current food systems (CFS) and Regional food system (RFS) scenario. Black arrows represent imported inputs to the system and blue arrows represent food exports from the system. Grey arrows represent food exports and imports between the studied system and national/global food system.

Data collection

We used official statistics about agricultural production and enterprise structure in Finland combined with data based on the literature. Agricultural data used in the study included crop production data and data about inputs used in food production from the years 2016-2020. For livestock production and food processing, we used data from 2019. The data for food processing were obtained by data request from Structural Business and Financial Statement Statistics (Statistics Finland, 2021a).

Case study regions

We used three contrasting regional food systems in Finland as case study regions. These regions were defined by the Centres for Economic Development, Transport and the Environment (ELY Centres). The case study regions were South Savo (GRS-LVS), characterized by grass-based livestock agriculture, South Ostrobothnia (INT-LVS) of intensive livestock production, and Uusimaa (URB-CRP), a more urban region with predominantly arable crop production. As a result, the case study regions contrast each other by type of food production and the size of population (Figure 3). The biophysical circularity of these regions was previously analyzed by Koppelmäki et al. (2021a).

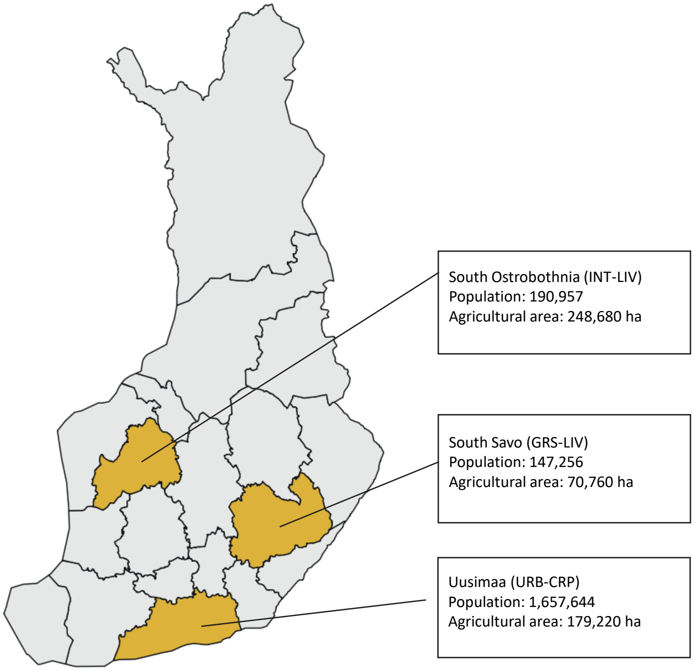

Figure 3. The location, population and agricultural land area of three case study regions in Finland. The data for population year 2020 (OFS, 2021a). The agricultural land area includes the average cultivated and fallow land areas over a five-year period.

6.2.2 Analyses

In order to calculate how economic value is created in primary production and food processing, we analyzed the economic value in absolute values and per hectare of utilized agricultural land within each of the regions. The values of taxes and subsidies were not included. In addition to regional scale calculations, we analyzed how case study regions were connected to the national food system through food exports and imports.

Primary production

The value of primary production was calculated by multiplying the quantity of produced agricultural food products by the producer prices (Table 1) and the value of produced energy. For agricultural food products, we included cereals that were used for food production, dairy, and meat products and eggs. These products were chosen for two reasons: they require food processing, and they have a high importance in terms of land use corresponding to 96% of the cultivation area in each of the case study regions. We excluded from the calculation the value of horticultural plants, potatoes, and special crops such as caraway. We acknowledge their high economic value per hectare, but these crops were excluded from this study because they require less processing or have a small significance in terms of land use in the case study regions.

Table 1. Producer prices of cereals, dairy, meat and eggs, and feed (OSF, 2021b).

	Value
Cereals for food	euro t^{-1}
Wheat	173
Rye	166
Barley	167
Oats	186 *
Dairy	cent $litre^{-1}$
Milk	39.18
Meat and eggs	euro kg^{-1}
Beef	3.05
Pork	1.52
Lamb	3.16
Poultry	1.36
Eggs	1.08

For energy production, we calculated both the economic value and quantity of produced energy. We included the current biogas production in the case study regions in the CFS and the potential energy production from biomasses that do not compete with current food or feed production in the RFS scenario. These biomasses used as feedstock for energy production were livestock manure, grass biomass from green manure and nature management fields. In addition to energy production from primary production, we also included the quantity and value of food processing related waste and biowaste. The biomethane potentials for these biomasses as well as the available quantities are provided in the Supplementary Table 2.

The current quantity of biogas production was our own estimation based on available information from the current biogas operations (OSF, 2021c). In this study, we assumed that food processors used one third of the energy produced in the form of electricity and two thirds in the form of fuel (OSF, 2021d; Valio, 2020). For electricity generation we considered 63% conversion loss (Tateishi, 2016). The economic value of energy production, 82 MWh^{-1}, was based on the market value of natural gas (50 euros MWh^{-1}) and electricity (147 euros MWh^{-1}) which was our own estimation based on the energy prices in 2019 (OSF, 2021e). We acknowledge the increased energy prices at the time of writing this paper and will discuss the impact this on price volatility in the discussion.

Food processing

The current value of food processing in the study regions was derived directly from the statistics which included data from the year 2019. We used the *gross value of production (GV)* and value *added at factor cost (VA)* as indicators for our analysis (Statistics Finland, 2021b). The GV of production measures the actual production output of food processing including production for personal use and production for an enterprise's other establishments. The VA is the result when the costs of goods and services used in production are deducted from the GV (Statistics Finland, 2021b). Thus, these indicators were selected to demonstrate two different economic aspects: the GV to describe the value of total food processing output and the VA to describe the total value added generated in food processing in the study regions. The current GV of the products included in the study made 83.5% of the total food GV of food processing in GRS-LIV, 95.7% in INT-LIV and 59.1% in URB-CRP. In URB-CRP, the lower percentage is explained mostly by its large coffee and confectionery industries. The value of egg packing is not included due to a lack of data. We refer to the Supplementary Tables for the specific food processing classifications.

In the RFS scenario, we calculated the GV and VA of food processing indirectly by calculating the share of agricultural products (food cereals, milk, meat) produced in each case study region in relation to the total production of these products in Finland. This share was multiplied by the current total GV and VA of food processing for the corresponding product category in Finland. In other words, if a region would produce X% of the total nationwide milk production, the total GV or VA of dairy processing at the national scale was multiplied with the same percentage. In addition to the case study regions, we calculated the GV and VA for all ELY-Centre regions in Finland to better understand the role of food processing in the case study regions as a part of the Finnish food system at the national scale. This was calculated in the same way that the GV and VA for the case-study regions were calculated. We refer to Supplementary Table 3 for the total GV and VA of each product category at the national scale.

The market value of external inputs

To calculate biomass and energy costs related to agricultural production, we included the market value of imported feed, nitrogen (N) and phosphorus (P) fertilizers, and energy consumption on the farms and in food processing. The value of imported feed included the market value of industrial feed, 350 euro t^{-1}, and, when the regional feed cereal production was not sufficient to cover the feed cereal requirement of livestock, it also included the value of grain cereals at 150 euro t^{-1} (OSF, 2021b), These values were then multiplied by the feed usage of each region, which is reported in the Supplementary Tables. Number of animals is reported in the Supplementary Table 4. Feed use per animal is reported in Koppelmäki et al. (2021a).

The current quantity of imported mineral N and P was derived from data on regional nutrient balances. These quantities were multiplied by the price of N and P in fertilizers, 0.95 euro kg^{-1} and 1.7 kg^{-1}, respectively (Natural Resources Institute Finland, 2021). For the RFS scenario, we calculated the reduction in fertilization costs by assuming that, in comparison to CFS, rates of nutrient recycling were increased at the expense of the use of industrial mineral fertilizers. This increased recyclable nutrient quantity, in the RFS, resulted from biogas production using grass biomasses that do not compete with food production. For this we included biomass from green manure leys and nature management fields.

The value of regional on-farm energy consumption was calculated by multiplying the energy consumption of agriculture and horticulture in GWh in the study regions by the energy prices (OSF, 2021e). The value of imported feed and on-farm energy consumption remained the same in both scenarios, as agricultural production remains unchanged in the RFS scenario.

To represent energy consumption in food processing, we used the following processing activities; milling and baking for cereal processing, milk and cheese for dairy processing, and cutting, deboning and chilling for meat processing. The energy consumption costs were calculated for the RFS scenario by multiplying the energy consumption in food processing (Table 2) with the quantities of potential biomass produced in the region for food processing. Then this result was converted to MWh, and finally multiplied by the same energy price used to calculate the value of energy production. In the CFS, the value of energy consumption was calculated indirectly as we did not have data regarding the quantities of raw material used in food processing. We used ratios for each product group (Supplementary Table 5) which we calculated by dividing the GV of food processing in the RFS by the GV of food processing in the CFS. These ratios were then multiplied by the RFS energy consumption costs.

Table 2. Energy consumption (MJ kg-1) in food processing (Ladha-Sabur et al., 2019a).

	Electricity*	Fuel	Total
Flour			1.23
Bread			7.5
Milk	2.7	1.8	4.5
Cheese	3.1	3.94	7.1
Meat**			2.5

*Gross energy required to produce electricity. (We assumed 35% energy conversion efficiency)

** Includes cutting, deboning, and chilling

Regarding the quantities of biomass used in food processing, we simulated that 88% of the primary milk production is used for 'table' milk production and 12% is used for cheese production. We based these factors on statistics of the current production of milk products in Finland (OSF, 2021f). Furthermore, for baking we assumed that from 1 kg of grain, 0.6 kg flour is produced and that from 1 kg of flour, 1.5 kg of bread is produced.

Connection to national and global scale through food imports and exports

In order to understand the role of trade for Finnish food processing, we calculated the quantities of international imports and exports of raw materials, as well as the value of exported and processed food. We assumed that the imports and exports of primary produce and each processed food commodity remained the same in both scenarios. We included corresponding products with primary production and food processing and made a distinction between raw materials and processed food (Supplementary material). Data about the import and export between Finland and global were derived from the statistics (OSF, 2021g; Supplementary Table 6).

6.3 Results

6.3.1 Economic value in primary production

The current value of primary production in INT-LIV was 32% higher than in GRS-LIV and 241% higher than in URB-CRP when the value was measured per ha of utilized agricultural land (Figure 4). In each study region, the most value in primary production was created in livestock products which corresponded to 65% of the total value of primary production in URB-CRP, 97% in INT-LIV and 98% in GRS-LIV. Dairy was the most economically significant line of production in GRS-LIV with 70% share of value generated, and in URB-CRP this value vas 42%. In INT-LIV the meat production corresponded 59% of the total value generated.

In the CFS, the value of energy production was less than 1% in all study regions. In the RFS, the bioenergy production increased the share of the economic value of energy production up to 30% in URB-CRP. The corresponding values for INT-LIV and GRS-LIV were 15% and 17%, respectively. The main sources of energy production were manure in GRS-LIV and INT-LIV, corresponding to 45% and 50% of the total energy production, respectively, in contrast to URB-CRP where the main energy source was plant biomass, corresponding to 64% of the total energy production.

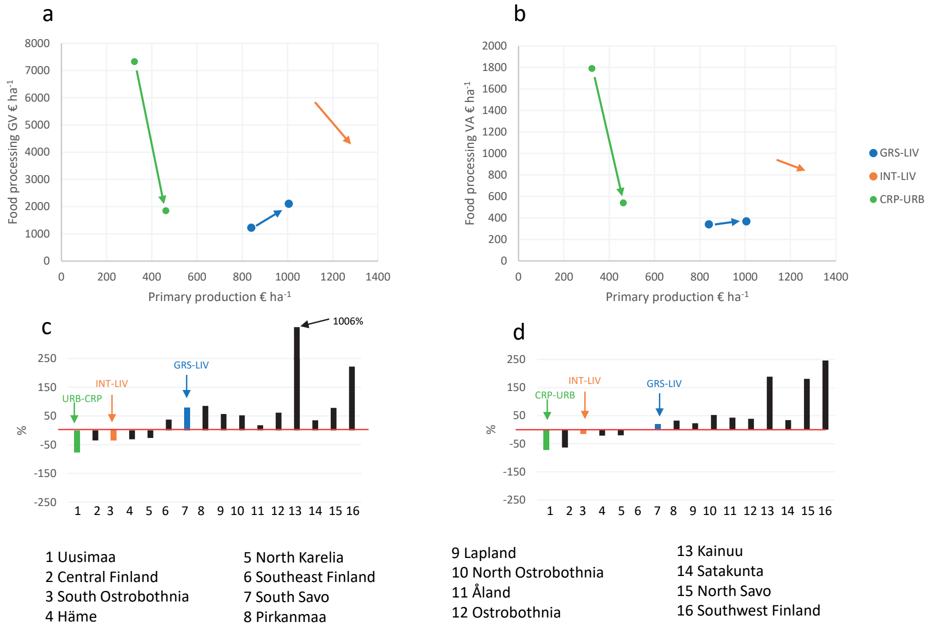

Figure 4. The value of primary production (food and energy) and gross value in food processing (a), and the value of primary production (food and energy) and added value in food processing (b) in the three case study regions. The arrow between the points shows the change from the current food system (CFS) scenario to the regional food system (RFS) scenario. The change (%) of the gross value (c) and value added (d) in food processing in the RFS scenario in all regions in Finland.

6.3.2 Economic value in Food processing

In the CFS, the absolute GV of food processing was highest in INT-LIV and smallest in GRS-LIV (Supplementary material), while when the value was divided by utilized agricultural land, the highest value was created in URB-CRP which was almost six-fold the value for GRS-LIV (Figure 4). Like in primary production, most of the GV in food processing was generated in livestock products, which corresponded to 62% of the total GV of food processing in URB-CRP, 63% in GRS-LIV and 98% in INT-LIV. However, VA yielded opposite results for URB-CRP and GRS-LIV where the share of cereal products corresponded 54% in both regions. These contrasting results can be explained by the share of VA per product group which was the highest for cereal products, namely between 34% - 41%, while for livestock products this was between 12% - 20%.

Compared to the CFS scenario, the GV of food processing in the RFS scenario decreased in INT-LIV and URB-CRP, while in GRS-LIV the value increased. This increase resulted from increased processing within dairy production, covering 70% of the total GV of food processing. Although in INT-LIV the GV on cereals had more than quadrupled, the total GV of food processing still decreased due to the halving of the GV on livestock products. In URB-CRP, the GV on all product groups declined, especially on livestock products which decreased by 87%. However, again different results were observed in the VA. The increase in the VA of food processing in GRS-LIV was 8%, while the value decreased in INT-LIV by 14% and in URB-CRP by 70%. Absolute values in food processing are reported in the Supplementary material.

6.3.3 Energy integration between primary production and food processing

In the CFS, energy produced from biomasses originating from farms, food processing and biowaste was negligible compared to energy production in the RFS (Figure 5). In the RFS, energy production was 107% higher than consumption in GRS-LIV, 136% in INT-LIV and 165% in INT-LIV. Dairy processing corresponded to 87.5% of the total energy consumption in INT-LIV and 70% in CRP-URB. In GRS-LIV nearly all energy consumption in food processing took place in cereal processing.

Compared to the CFS, energy consumption in food processing in the RFS scenario decreased by 41% in INT-LIV and 77% in URB-CRP, while it increased with 591% in GRS-LIV (Figure 5). Moreover, when the value was divided by utilized agricultural land, GRS-LIV had the highest value of energy consumption in food processing (185 euro ha^{-1}), followed by INT-LIV (147 euro ha^{-1}) and URB-CRP (88 euro ha^{-1}).

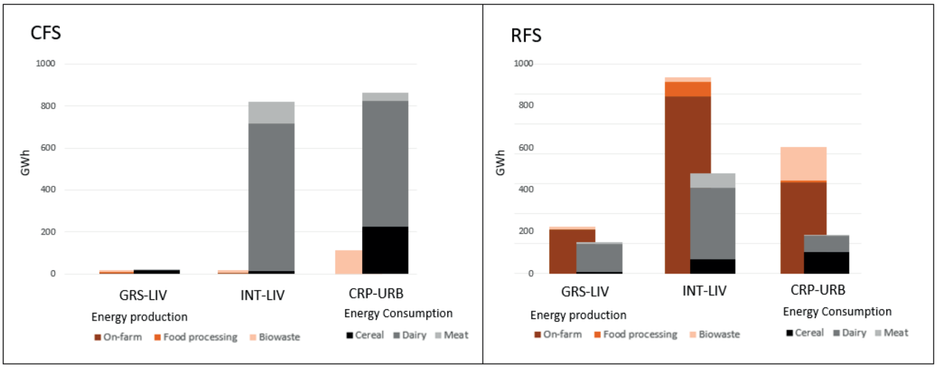

Figure 5. Energy production potential (GWh) and energy consumption (GWh) in food processing in the current food system (CFS) and regional food system (RFS) scenarios in the three case-study regions (Figure1).

6.3.4 Value of external inputs in primary production

In the CFS, URB-CRP had the highest costs on N and P fertilizers per ha, followed by GRS-LIV and INT-LIV (Table 3). In the RFS scenario, URB-CRP remained the region with the highest costs on N and P fertilizers per ha, followed by GRS-LIV and INT-LIV, but the cost of fertilizer input per hectare decreased around 15-18% in each region compared to the CFS. The absolute costs of energy consumption in primary production were the highest in INT-LIV, while when the value was measured by utilized agricultural land, the highest costs were found in GRS-LIV (351 euro ha^{-1}), followed by INT-LIV (329 euro ha^{-1}) and URB-CRP (136 euro ha^{-1}).

Table 3. Energy, mineral nitrogen (N) and phosphorus (P), and feed costs (euro ha^{-1}) in primary production. The negative value for feed imports indicates that the value of feed exports from the region is bigger than the value of imports.

	GRS-LIV		INT-LIV		URB-CRP	
	CFS	RFS	CFS	RFS	CFS	RFS
Energy cost € ha^{-1}	343	343	315	315	135	135
Mineral N € ha^{-1}	46	38	63	56	70	61
Mineral P € ha^{-1}	5	4	9	8	11	9
Feed imports € ha^{-1}	151	151	173	173	-70	-70

6.3.5 Connection to national and global scales through food imports and exports

The economic value of exported raw materials used in food processing was higher than the corresponding value of imported raw materials (Table 4). In the processed food, the value of dairy exports was 3% higher than the value of imports, whereas cereal products and meat were imported substantially more than exported.

Table 4. Average economic value of imports and exports between Finland and Global 2016-2020.

	Import (1000e)	€ ha^{-1}	Export (1000e)	€ ha^{-1}	Balance (1000e)	€ ha^{-1}
Raw materials						
Cereals for food	9,844	4	245,223	109	235,379	105
Processed food						
Cereal products	413,950	185	123,672	55	-290,278	-129
Dairy	386,414	172	396,139	177	9,725	4
Meat	312,704	139	132,240	59	-180,464	-80

6.4 Discussion

In this study, we explored a design towards a more circular food system from the economic perspective. We investigated the compatibility of energy production using biomasses from primary production with the energy consumption of food processing, following the concept of AES (Koppelmäki et al. 2019; Helenius et al. 2021). We aimed to determine how such an integrated system of primary production, food processing and bioenergy production would impact on the economic value in regional food systems. Our findings demonstrated that energy production from agricultural biomasses can provide enough energy for food processing at a regional scale, but that this would necessitate integrating food processing with primary production. Such a system design would, however, redistribute and equalize the economic value of the agri-food industry across regional food systems.

6.4.1 Integrated food and energy production

A prominent catalyst for such integrated food-energy systems is the need to replace the use of fossil fuels in food processing to reduce climate emissions, and secure energy-sovereignty. The utilization of energy from agricultural biomasses that do not compete with food production requires the relocation of food processing to be closer to bioenergy suppliers. Our results showed that primary production can indeed provide enough energy for food processing at a regional scale. Results also highlighted the central role of dairy production and processing in this rebalancing of energy production and consumption. Dairy processing is more energy intensive compared to cereal and meat processing (Ladha-Sabur et al., 2019)

In our study, we compared the potential energy production to energy consumption at the regional scale. However, the actual scale at which energy production matches energy consumption is more local. The unit size of the operation in food processing determines the share of energy needs that could be met by locally available biomasses, as transporting biomasses long distances for biogas production is not economically feasible (Paudel et al., 2009; Neiva de Figueiredo and Mayerle, 2014; Torquati, 2016). It is also important to consider a farms' own energy consumption. Specifically, the use of electricity or fossil fuels for heat generation in primary production could be replaced with bioenergy. However, the technology required for fueling farm machinery with biogas, or fueling tractors with electricity has not yet matured. Although no data on energy consumption between different production groups were available, the energy consumption per hectare in the livestock production regions was more than twice that of the crop production region. Dairy farms in particular consume a lot of energy (Rajaniemi et al., 2017). This suggests that successfully integrating dairy processing with biogas production would necessitate the use of additional biomasses, such as multi-purpose N-fixing, soil conditioning, nutrient recycling bioenergy leys (Koppelmäki et al. 2021b), in energy production in addition to manure, as farms are likely to prioritize their own energy use first.

The biggest energy production potential from agricultural biomasses in Finland lies in grass biomass and crop residues (Koppelmäki et al., 2019; Marttinen et al., 2015). In our study, we included only grass biomass, but inclusion of other crop residues would significantly increase the energy production. For example, the techno-economical potential of straw is almost 70% compared to grass biomass (Marttinen et al. 2015). The use of grass biomass and crop residues in biogas production enables the multifunctional utilization of biomass. In addition to contributing to energy production, the use of perennial grasses in biogas production would allow the system to fix nitrogen and maintain soil quality (Koppelmäki et al. 2019; Koppelmäki et al. 2021b). By integrating biogas production into food production, mineral fertilizers can be in part replaced by digestate which also includes nutrients from grass fallows that were not otherwise used in production. Replacing external nutrient inputs to a greater extent than was achieved in our study, would require integrating more nitrogen-fixing plants, such as green manure leys, to biogas production.

6.4.2 Economic significance of integrated primary production and food processing

In our study we showed how integrating food processing and energy production from agricultural biomasses would require disaggregation of the current centralized structure of the food processing industry. In the current system, the economic value of primary production and food processing varied between case study regions depending on the structure of these elements. Currently, regional food processing and primary production were not regionally interdependent. For example, in the region with its highest value created in dairy farming, almost all milk was exported to other regions before being processed into dairy products and adding value. As a result, the region with high crop production created, somewhat paradoxically, the highest value in food processing from dairy products. Also, the total value of food processing in relation to the total agricultural land use was the highest in the most densely populated region, but this did not impact the value of primary production which was clearly lower than in other regions. Concentration of food processing industries around big cities and in densely populations regions close to big food markets is a well-known and often problematic phenomenon (Hendrickson, 2015). This phenomenon presents a challenge for rural regions because potential economic benefits are displaced to other regions.

In our RFS system, the integration of food processing into regional primary production had a substantial impact on the value of food processing in the study regions and also at the national level. In most regions, we saw an increase in the economic value of food processing; a decrease in economic value was only observed in the few regions where the food processing sector is currently concentrated. This realignment resulted in a more equitable distribution of economic value among regions. In addition, the economic value of energy production increased extensively in all case study regions as current biogas production is negligible.

In our study, the value of food processing was a zero-sum game at the national scale which meant that our regional food production scenario did not impact the overall value of food processing. However, the requirement that food production rely on local resources constrains the maximum potential of biomass throughput in the agri-food system, and therefore, it also constraints the maximum potential value that can be created indigenously within the foodscape at the regional scale. To industry, such constraints as limiting the production to rely on local resources are often seen as a valid reason to call such a change in the system unfeasible; it creates hesitation within companies as this is perceived as an impediment to economic growth, and thus one of main barriers to a transformation towards a circular bioeconomy (Gladek et al., 2017; Kirchherr et al., 2017). At the same time, the increased bioenergy production in the RFS reduced imports, and therefore costs, of fossil fuels at a national scale, resulting in a net economic cost reduction. These results suggest that incentivization, whether monetary or otherwise, of a more circular reconfiguration of the processing industry may be warranted.

6.4.3 Connection to national and global scales

Our RFS was connected to the national and global scales through the use of external inputs, and food exports and imports. In the case study regions, the value of food imports was relatively low in relation to the value of regional food processing. This indicates high self-sufficiency in food production. It is, however, important to acknowledge that we only included food types that are important in terms of land use in Finland. According to Sandström et al. (2017) the deficit between imports and exports was over 200,000 ha of cropland which corresponds about 10% of the total agricultural area in Finland.

Our redesigned system represented a more local food system as food processing was integrated with regional primary production and bioenergy production reduced the need for external energy inputs. It is important to note that in this system food commodities are still exported and imported allowing for diverse diets in food consumption. If all non-processed raw materials (cereals for food, milk and meat) would be processed in Finland, the value of food processing would increase further.

6.4.4 The impact of remarkable increase of energy and fertilizer prices

In this study, we used energy and fertilizer prices from the year 2019. At the time of writing this article there is a lot of volatility in these prices. Natural gas prices are at an all-time high as a result of the war in Ukraine at the time of writing this article. For example, the price of natural gas has increased four-fold in a few years and the price of fertilizers has tripled in less than a year. In fact, currently there is even a risk of shortages in fertilizers and uncertainties related to the limited availability of natural gas.

In this study the value of potential energy production from biomasses that did not compete with food production varied from 15% to 30% between the case study regions. The value of energy production depends on the end use of the produced energy. However, any substantial increase in energy prices will make biogas production more attractive option either from perspective of increasing energy self-sufficiency on a farm level or increasing the overall value of primary produce. Increases in fertilizer prices, in turn, will have an impact on which crops are grown and to the share of fallow land, thus having indirect impacts on commodity prices as well. However, the use of recycled nutrients becomes more economic option.

6.4.5 Applicability of the results and future research questions

Our study included three case study regions representing different agri-food chain structures in the context of the Finnish food systems. It is likely that similar results can be found in other regions where the consolidation of food industry has taken place. However, the role of biomass in energy production is more context specific. It depends on the overall demand for available biomass, and on the local potential to produce biomass that does not compete with food production. For example, in drier climates other renewable energy production options may provide a more feasible option than producing biogas from crop residues and rotational fallows.

In nested circularity, the local production of biomass for food, feed and energy, and the added value of local food processing is based on the availability of local resources (Koppelmäki et al. 2021a). Studying the economic value of food systems from a circular perspective requires separating the total value of food production into the value of food produced from regional resources and the value that is created by using imported inputs that are produced outside of the studied region. Our study included the role of food processing, but a better understanding of circularity would require also studying the changes in food production. This would, for example, mean balancing the intensity of livestock production with the regional feed production, which would likely result in substantial changes to the amounts of food produced.

Finally, a transition towards RFS would not only result in the redistribution of the economic activity across regional food systems, it would also result in wider regional economic impacts for other sectors. Multiplier effects of food production on regional output can be almost the same size as the direct affect (e.g. Kujala et al., 2021; Schmit et al., 2016). In addition, the total regional economic impact of biogas production can also be bigger than the direct impact (Peura et al., 2018). These wider economic and employment impacts of a regionalized food system would be valuable for underpinning transitions towards regional hubs for the production and processing of food and energy.

6.5 Conclusions

Our study demonstrated the role of food processing in creating value in regional food systems. This value varies between regions depending on the population of these regions and on their current consolidation of the food industry. We suggest that regionalized food processing is an integral element in circular food systems, given its important role in creating demand for primary production, both in terms of food and energy. RFSs are a contrast to concentrated and globalized food systems that have resulted in many negative environmental and socio-economic challenges. Especially for rural regions, circular food systems could provide new economic opportunities.

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Supplementary material

Supplementary Table 1. Cereals for food, dairy and meat products included in primary production and food processing. Classification by Statistics Finland (2021a).

Group	Primary production	Food processing
Cereals for food	Wheat Rye Barley Oats	Manufacture of grain mill products Manufacture of bread Manufacture of rusks and biscuits Manufacture of macaroni, noodles, couscous and similar farinaceous products
Dairy	Cows' milk	Operation of dairies and cheese making
Meat and eggs	Beef Pork Poultry Turkey Lamb Eggs	Processing and preserving of meat Processing and preserving of pork meat Production of meat and poultry meat products

Supplementary Table 2. The average quantities and biomethane potentials for plant-based biomass, manures, and biodegradable waste from food processing of each case study region 2016-2020.

Feedstock	Biomethane potential	References
	BMP Nm^3 CH_4 t^{-1} TS^{-1}	
Plant biomass		
Fallows	290	Seppälä et al. 2009
Manures	BMP Nm^3 CH_4 t^{-1} VS^{-1}	
Dairy cows, suckler cows, heifers, calves, bulls	212	Luostarinen et al. 2019, Seppälä et al. 2013
Sows, boars, fattening pigs	300	Møller et al. (2004)
Laying hens and poultry	425	Kafle and Chen (2016)
Horse	142	Mönch-Tegeder et al. (2013)
Sheep	242	Kafle and Chen (2016)
Food processing	BMP Nm^3 CH_4 $m^{3\ -1}$	
Biodegradable waste from food processing	400	Kask et al. (2012)

Supplementary Table 3. The current gross value and value added at factor cost of food processing of each product category in Finland of year 2020 (Statistics Finland, 2021a)

Product category	Gross value of production (1000 euros) yr^{-1}	Value added at factor cost (1000 euros) yr^{-1}
Cereals for food	1,473,431	514,389
Manufacture of grain mill products		
Manufacture of bread		
Manufacture of rusks and biscuits		
Manufacture of macaroni, noodles, couscous and similar farinaceous products		
Dairy	2,195,686	326,710
Operation of dairies and cheese making		
Meat	2,525,904	503,807
Processing and preserving of meat		
Processing and preserving of poultry meat		
Production of meat and poultry meat products		

Supplementary Table 4. Feed use (imported and regionally produced) of each case study region 2016-2020 (OSF, 2021)

Feedstock	GRS-LIV	INT-LIV	URB-CRP
Feed use (t DM yr^{-1})			
Grain (incl. pulses)	31,377	223,434	27,598
Industrial feed	29,549	138,883	20,066

Supplementary Table 5. The food processing energy consumption ratios to calculate the value of energy consumption in the current system. The ratios were calculated by dividing the gross value of food processing in the regional food system scenario with the gross value of food processing in the current food system. The ratios were then multiplied by the energy consumption in the regional food system scenario.

Product group	GRS-LIV	INT-LIV	URB-CRP
Cereals for food	2.11949	0.18513	1.92120
Dairy	0.00011	2.04131	7.39680
Meat	1.70461	1.89927	8.66603

Supplementary Table 6. Average quantities of imports and exports between Finland and Global 2016-2020. Raw materials and processed food that still can be used as input by food processors. (OSF, 2021)

	Import t yr^{-1}	Export t yr^{-1}	Balance t yr^{-1}
Raw materials			
Cereals for food	34,923	624,099	589,176
Processed food			
Flour and other milled product	35,748	41,163	5,415
Milk	10,908	57,593	46,685
Butter	1,046	34,593	33,533
Meat	53,270	63,475	10,205

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7

Chapter 7

General Discussion

Kari Koppelmäki

7.1 Introduction

It is said that the only thing that is constant is change. Indeed, throughout the first years of my PhD, I thought that my topic was a bit abstract, and that the relevance of my study was only understood by a limited number of stakeholders working on the food systems. However, since I started my PhD, the world has changed dramatically. First, the global pandemic raised awareness regarding the food system's resilience. Furthermore, at the time of writing this thesis, Russia has launched a full-scale war in Ukraine, which has, in addition to causing a humanitarian disaster, resulted in widespread awareness of the vulnerability of our food systems. Although the sustainability of the global food system has been challenged before, these events have put sovereignty in food production into a new context. The societal demand for moving away from the use of fossil fuel driven food systems has never been so high.

The aim of this thesis was to propose a design for circular food production that utilizes the interconnected biomass-nutrients-energy nexus. I studied the biophysical and economic impacts of this integrated food and energy production design at different spatial scales in the context of the Finnish food system. At the farm scale (Chapter 2), we demonstrated through a case study how food and energy production can be integrated in a synergistic way, and we introduced the model of Agroecological symbiosis (AES). AES integrates food and energy production. Food processing also plays a role in an AES model as an integrated part of the system creating demand for locally produced bioenergy and primary produce. In this case study, the integration of food and energy production increased food production and reduced nutrient losses while converting the whole system from an energy consumer to a net energy producer.

The model of AES was elaborated further in Chapter 3. In this concept paper we argued for the use of AES as a generic model to redesign food production at the food system level. This chapter deepened the theoretical foundations of this model by presenting the main principles of the concept and how it contributes to sustainability in terms of efficiency, sufficiency, and consistency. In addition to the biophysical perspective, we introduced the co-creative process of forming the first AES at Palopuro, Finland. We also discussed the role of people who live in the landscapes where food is produced, as active food citizens.

Chapter 4 studied the spatial scale of the system where the AES model was applied at a larger scale to cover a larger area (municipality). In this study, we showed how increasing complexity through the multifunctional use of biomass (nitrogen fixing, food, feed, energy) in the system increased the supply of ecosystem services. Biomasses that did not compete with food production provided substantial feedstock for energy production. The most complex system design included integrating crop and livestock production which resulted in the highest increase in food production within the system and reduced the externalities.

In Chapters 2 and 4, we focused on horizontal (spatial proximity of the actors) integration in primary production and showed how utilizing locally available resources can convert farming system from energy consumer to energy producers. In Chapters 5 and 6, we broadened the scope towards the regional food system level to include also cycles that cannot be closed at the farm level and how those cycles interlock at the system level. In chapter 5, we presented a framework to study circularity in the context of food systems. Under the concept of Nested Circularity, we defined the most important elements of circular food systems, namely biomass for food and feed, biomass for energy, and nutrient recycling. Through three case studies we showed that, while livestock production played a central role in food production in all three case study regions, there were profound differences in how the regions contributed to livestock production; either producing livestock products or producing feed for export. While the AES model is a tangible system to redesign food system elements on a farming system scale, the concept of Nested Circularity defines the circularity in the context of food systems across spatial scales.

In Chapter 6, we applied the Nested Circularity framework from the economic perspective to the same case studies presented in Chapter 5. We specifically focused on the role of the food processing industry as the prime catalyst for adding and distributing value through the food system in the integrated food and energy production system. We showed how bioenergy production can substantially increase in the economic value from primary production while integration of primary production and food processing resulted in substantial redistribution of economic value created in food processing across the food system.

In this thesis, I have outlined a design for a circular food and energy production across spatial scales. This novel conceptualization is what I have termed *Nested Circularity*. In the following sections, I will discuss the implications of the main findings presented in the previous chapters. First, I will discuss how this research process was upscaled from a co-created farm level pilot project to the regional food system level. Then, based on the results of the previous chapters, I present my conceptualization of the building blocks needed to make a circular design in food production, and I suggest the future research needs. Finally, I will conclude the results by presenting the required steps in transforming the current food system towards circularity.

7.2 Co-created design for circular food and energy production

A common approach to food system related studies focuses on modelling the outcomes of different future scenarios, created by scientists, describing the desired state of the studied system. In this top-down approach, the modelled outcomes serve as visions or goals that are aimed at guiding the process of food systems transformation. Furthermore, these studies often focus on modelling outcomes at the global scale which may reduce the level of deployment of these studies in practice, thus creating need for more practical approaches (Slade et al., 2014). Loos et al. (2014), states that global analyses often do not acknowledge – apart from the obvious food production – the other ecosystem services that agricultural land provides. While food systems studies conducted on a global scale may gain more attention, contextualized studies focusing on smaller spatial scales provide a complement understanding of complexity in food systems and thus are potentially valuable for society (Kline et al., 2016; Slade et al., 2014).

In this thesis, I used an approach that reversed this common top-down approach. I started at the farm level by introducing a real-life initiative that represents a circular food production system. The Palopuro AES pilot project served as an inspirational model for a circular design, which was upscaled from the farm to a regional scale.

The pilot project of Palopuro AES was introduced in Chapter 2. This model is part of the Global Network of Lighthouse Farms, which is a network of farms that represents radical solutions for addressing sustainability challenges. The network demonstrates systems that can be achieved within the bio-physical and socio-economic solution spaces (Valencia et al., 2022). The pilot AES in Palopuro was created and designed in a co-creative process between local actors and other stakeholders including research institutes (Chapter 3). The participants on the research side had a central role in studying the feasibility and environmental sustainability of the initial system design.

Upscaling from the farm to the food system scale

Drawing on the results of the pilot study, we have suggested AES as a generic model for re-arranging primary production and food processing to achieve a sustainable food system (Chapter 3). In this model, food producers and processors operate in close spatial proximity enabling multifunctional biomass production for fixing nitrogen to the system, recycling nutrients efficiently, and producing renewable energy. The AES model emerged from a bottom-up co-creational process (Chapter 3), but the scalability of this model was studied through scenario analyses in Chapters 4, 5 and 6. AES was used as a grounded inspirational model and was applied in different scenarios to explore the solution space for synergistic integrated food and energy production systems from the farm to regional scale. The regional scale in my thesis represents a feasible scale for circular food production that enables both vertical (different actors in the food chain) and horizontal (spatial proximity of the actors) integration of the most important elements of circular food production.

7.3 Building blocks for circular food production

Our bottom-up exploration of circularity through a range of spatial scales allowed us to identify the essential building blocks for circular food production. In this section, I will delineate from the results of previous chapters, the most central elements needed for circular system design.

7.3.1 Integration of biomass-nutrient-energy

The guiding principle for circular design proposed in this thesis originates from the goal of making better use of resources that are currently available within a system. In Chapter 2, we described a bioenergy production design that challenged the underlying assumptions employed in the food-fuel debate regarding the pitfalls of using agricultural land to produce bioenergy. In this design, instead of competition, the synergies were achieved by biomass-energy-nutrient integration. In the AES model, green manures are not ploughed into soil, but instead used for anaerobic digestion. This enables the production of bioenergy, and the process of producing bioenergy concentrates the nutrients into a digestate, which can be applied as an organic fertilizer more precisely according to soil and crop requirements.

As shown in Chapter 2, by integrating energy production into nutrient recycling, food production was increased by up to 40% while bioenergy production converted the system from an energy consumer to net energy producer. This case study represented organic crop farming in a region with limited manure availability. The yield increase was based on more efficient nutrient recycling within the system without importing new nutrient inputs. In organic crop production this allows for reducing the area of green manure required, and for leaving more land available to produce food crops.

Aside from the biophysical effects, biomass-nutrient-energy integration can also be assessed from an economic perspective. When bioenergy is produced from biomass and is not competing with food production, the overall economic value generated from biomass production is increased (Chapter 6). This can create new economic opportunities for farmers but also decreases their dependency on external inputs. Winquist et al. (2019) interviewed biogas produces who recognized that, in addition to direct economic benefits, biogas production includes several nonmarket benefits which increased the value of investments. At a systems level biogas production may result in more evenly distributed economic value compared to the use of fossil fuels, as bioenergy is inherently more evenly disturbed across the globe (Dale et al., 2016).

Reflections on food-feed-fuel competition

Although agricultural land use for bioenergy production has been criticized, dismissing the potential for using agricultural biomasses for energy production works against sustainability goals. Schulte et al. (2021) argues that competition between food and energy production is a false dichotomy, which prevents developing a focus on designing regenerative and climate-resilient food and energy production systems. History demonstrates that the food-fuel competition argument is erroneous because, in the past, rather than dedicating all agricultural land to the production of food, a part of this land was typically used to produce feed for the farm-animals who carried out the physical activities on the farm now done by tractors and other farm machines (Schulte et al., 2021; Smil, 2017).

However, it must be acknowledged that current agricultural land use has often resulted in competition between food and energy production (Lark et al., 2022; Rosegrant and Msangi, 2014; Searchinger et al., 2008; Tenenbaum, 2008). In this thesis, I showed that synergetic solutions to this problem exist (Chapter 2-6). Understanding how synergistic land use can be achieved in the context of food-feed-fuel competition requires considering the context of specific agricultural land use demands while also acknowledging the spatial and temporal dimensions related to this demand.

First, the amount of land available for energy production depends on the demand for food production, and other ecosystem services making the question of food-feed competition very context dependent differing based on the demand for biomass that is produced in each specific food system. For example, although most agricultural land could provide food directly to humans, there is not currently enough demand to warrant the use of all available agricultural land for producing food. Given the current demand, it is not economically feasible to produce food or feed on all agricultural land, and there are other societal demands for agricultural land.

As a result, current agricultural land area that is not used for food or feed has a substantial energy potential without food-feed-energy competition. That is, we could be taking advantage of the 'living solar panels' formed by agricultural crop plants for producing biomass for energy production. Producing biomass directly from photosynthesis differs from the industry using non-renewable resources to manufacture products as photosynthesis uses solar energy which—in geological time scales—is an inexhaustible energy source. However, the volume of sustainable biomass production possible without compromising the other ecosystem services, is limited by the biophysical potential of the specific agroecosystems that produce that biomass (Chapter 3).

Second, the future demand for agricultural land use is mainly affected by population growth and by dietary change (Gerbens-Leenes et al., 2010; Marques et al., 2018). These drivers largely determine the pressure on agricultural land and on production. Global biomass production is estimated to be sufficient to feed the growing population but it may require allocating more of this produced biomass to direct human uses (Cassidy et al., 2013). As such it is often argued that arable land should be used for human food production to avoid food-feed competition

(Muscat et al., 2021; Zanten et al., 2018). Consequently, a shift in diets towards consumption of less livestock products might be needed to achieve circularity at the EU level (van Selm et al., 2022). In the context of the Finnish food system, a lower demand for livestock production would reduce pressure on agricultural land and open new opportunities for other purposes as about 80% of the cultivate land is currently used for livestock (OSF, 2021). This would make integrating perennial leys—as proposed in this thesis—into food and energy production even more feasible.

7.3.2 Multifunctional use of perennial grasslands

Increasing productivity while reducing nutrient losses was enabled by the multifunctional use of perennial nitrogen fixing leys, and marginal grasslands as main feedstocks in biogas production. Through Chapters 2 and 4, we demonstrated the important role of perennial leys in multifunctional biomass production and use. They fix nitrogen from the atmosphere into the farming—and food—systems, producing feedstock either for livestock or bioenergy production, and providing mobile nutrients after bioenergy production. When energy is produced from grass or crop residues, a biogas plant has, in terms of nutrient cycling, the same function as livestock. Just as ruminant livestock leave nutrients in manures, a biogas plant leaves the nutrients in the digestate. As a result, biomass and nutrients are concentrated in one location enabling for reallocation of those nutrients to nutrient demanding crops.

The use of green manure leys is not unique to organic farming, as conventional farms are also including green manure leys in their crop rotation for economic and agronomic reasons. In Finland in 2021, almost 10% of the utilized agricultural area was either fallows, nature management fields, or green manure leys (OSF, 2021). In crop production regions, the share of these grass biomasses that are not harvested for feed is higher than in the livestock production regions, thus providing a substantial underutilized resource for energy production. Marttinen et al (2015) estimated that grass biomass corresponds to almost half of the theoretical biogas potential in Finland. However, it must be noted that extensive use of fallows in biogas production may result in trade-offs with biodiversity which was not included in this study. In the context of Baltic agriculture Valujeva et al. (2022), showed the multifunctional outcomes of taking the abandoned farmland back to food production. They found that there is space for optimization to simultaneously increase the supply of primary production, carbon regulation and habitat for biodiversity.

We demonstrated the multifunctional use of these biomasses in Chapter 4. The introduction of perennial leys for biogas production to the currently arable farming region increased the provision of ecosystem services. We showed how the supply of ecosystem services (food, nutrient cycling, and climate mitigation) was increased by applying different scenarios where grass biomass was used either directly as a feedstock in biogas production or first fed to livestock which, in the scenario, were re-introduced to the region before using manure as a feedstock in biogas production. The incremental increase of complexity in the system increased the supply of ecosystem services. Integrating crop production and livestock production resulted in the best performance with the lowest externalities while still having a moderate trade-off with energy production compared to using grass biomass directly in biogas production. The research has supported similar synergies discovered in this thesis between providing biomass for energy while also providing other ecosystem services such as maintaining soil quality, lowering nitrogen losses, and promoting biodiversity by employing perennial leys in bioenergy production (Asbjornsen et al., 2014; Tilman et al., 2006; Werling et al., 2014).

A system embracing similar bioenergy production methods to those of the AES concept was reported by Dale et al. (2016) who presented a farming system level example from northern Italy where farms produced biogas by applying a double cropping system to extend the growing season. In this system cover crops were used to produce biomass outside of the growing season while also fixing nitrogen from the atmosphere. These examples shows that synergies can be found, but it is important to acknowledge that the appropriate design is always place-specific. Therefore, we need to design a diversity of AES systems for contrasting environments and production systems. For example, in Northern Europe the short growing season limits the use of double cropping as a main feedstock in biogas production. However, in Southern Finland undersown cover crops can provide an additional feedstock as we demonstrated in Chapter 3.

7.3.3 Horizontal and vertical integration

Circularity in food production has traditionally focused on nutrient flows in primary production. However, organizing nutrient management requires that, in addition to primary production, it also address vertical integration in the food system. How the processing industry, food consumption and waste management are organized at the system level also have a substantial impact on nutrient flows and energy use. In this thesis, I have introduced a design that considers both horizontal and vertical integrations. This design gives principles for farm scale primary production but also recognizes how circular systems need to be compatible across spatial scales and actors.

From the biophysical point of view, the most important factors that impact circularity are how primary production is organized, where food is processed and where consumption takes place. How these elements are organized has an impact on the amount of food produced within the system, how closed the system is in terms of nutrient flows and energy use, and how much economic livelihood the system creates at the regional food system level.

Regional imbalances in the current structure

Chapters 5 and 6 show how the current structure of the food system works against the goals of circularity. We demonstrated and discussed how integrating the most important elements of a circular system (biomass production for food, feed and energy, and nutrient cycling) requires a smaller spatial scale than that of the current food system.

I argue that the current food system structure disables the transition to circular food systems. For example, as shown in Chapters 4, 5 and 6, regional specialization in livestock production, and the resulting high livestock densities, result in entire regions relying on imported feed, and lead to nutrient surpluses which carry increased environmental impacts. At the same time, arable production regions that are producing the feed grains that are exported to the livestock regions (Chapter 5), without a return flow of plant nutrients, need to rely on virgin, industrial mineral fertilizers, which are associated with depletion of the natural resources. From a circularity perspective, these challenges stand in the way of achieving the ambitious objectives set by European Union and Finnish government (European Commission, 2018; Ministry of Agriculture and Forestry, 2017; Ministry of Economic Affairs and Employment, 2019) regarding the transformation of food systems towards circularity and carbon neutrality.

The role of food processing

The role of the food processing industry has gained little attention in studies related to food system structure in the context of the localization of the food industry. In this thesis, I increase the knowledge base related to the role of food processing creating demand for primary production (both food and energy). Successful integration of energy production to agricultural land use requires considering the demand for the energy that is produced. In this thesis, I propose integrating food processing with regional food and bioenergy production to increase resilience and decrease dependence on fossil fuels in the food processing industry. We showed that the supply of energy from agricultural biomasses is compatible with the energy consumption of the food processing industry in our case study regions (Chapter 6). This result is consistent with the relationship between estimated biogas production potential and consumption in food processing at the national level. Marttinen et al (2015) estimated the biogas production potential from agricultural biomasses to be approximately 10 TW yr^{-1} whereas the end-user consumption in food processing was about 4 TW yr^{-1} in 2020 (OSF, 2020). However, integrating food processing with bioenergy production would require food processing to decentralize their operations in contrast to current centralized operations in the industrialized food system.

The concept of *Nested Circularity* allows for food products to be exported and imported across the regions (Chapter 5). Similarly, in the *AES* concept (Chapter 3), individual symbiosis would create a network producing food suitable for that specific agroecosystem but still allowing for food exports and imports. As a result of integrating food processing with agricultural primary production in accordance with the *AES* concept, this scenario projects a remarkable impact on the economic value created from food processing. We demonstrated this by calculating the value of food processing at the regional scale in a scenario where food processing would use the cereals and livestock products produced within the same region. As a result, the economic value is projected to be distributed more equally across the regions.

The current structure of the food system has caused a lock-in and resulted in a situation where it is challenging for individual actors to initiate change. For example, farmers might have available biomasses to produce bioenergy, but there is no demand for the energy. The food industry does not see a reason to regionalize food processing if there is no bioenergy production available. To overcome this "chicken-egg" dilemma would require a co-participatory approach that involves not only farmers and food processors but also other stakeholders that could support such transition.

Functional scale for circularity

Based on the results of my thesis, I propose that the regional food system scale is the most functional spatial scale for initiating the transition towards a circular food production design, which enables both the horizontal and vertical integration of the most important elements related to food production. However, within this structure the spatial scale for each sub-system is not the same (Figure 1). At the smallest scales, we find products with a high-water content and low value per kg. Transportation of these types of biomasses, such as manure, is prohibitively expensive. For example, in nutrient recycling the functional scale of these operations is determined by the economic distance of transportation of non-concentrated feedstocks (i.e., grass) for livestock or energy production and applying manure or digestate back to food production. At the larger scale, we find high-value products, such as processed food, where the transport costs represent only a small share of total production costs. This is supported by Granstedt (2000) who argues that synergies between productivity and efficient nutrient recycling can be achieved by integrating crop and livestock production whereas van der Wiel et al. (2019), argues that an appropriate scale for organizing nutrient management covers all the subsystems in spatial proximity.

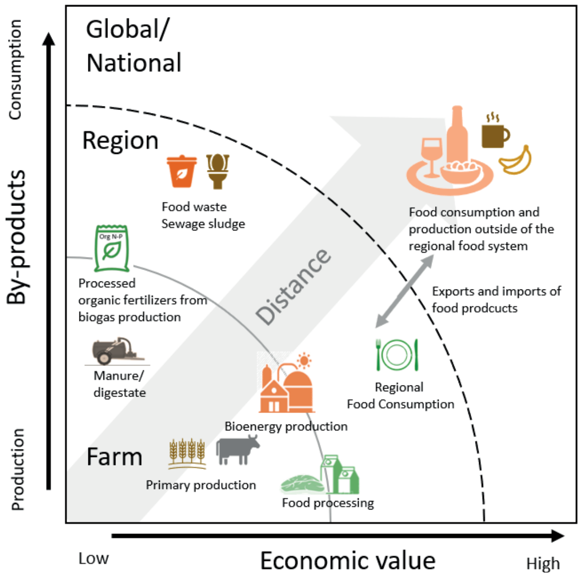

Figure 1. Spatial scales for different sub-systems in a functional circular food system. The scale of bioenergy production, food processing, and processed organic fertilizers from biogas production located at the intersection of the farm and regional scale implies that, in a circular system, these elements operate at a scale that enables efficient recycling of nutrients back to primary production.

For sake of clarity, we must emphasize that the concepts introduced in this thesis, are based on developing more localized food production without localizing food consumption. Localizing food production, that is, production including primary production and processing from locally available resources eliminates negative environmental impacts resulting from the use of external inputs. Localizing food consumption reduces only the environmental impacts associated with the transportation of products. Furthermore, most people in the world cannot rely on local food (Kinnunen et al., 2020). On the other hand, as many regions can produce more food than is needed for local consumption (Erb et al., 2009), producers in these regions need to export food in order to remain economically viable. However, the acceptance of food production systems among consumers cannot be overlooked (Augustin et al., 2016). More localized food systems, such as the ones presented in this thesis, that form a regionalized food production system which is attached to local land, enable interaction between different stakeholders and allows people to have a greater role in food production as active food citizens.

7.4 Future research needs

In this thesis, I studied circularity mostly assuming a continuation of the current scenario of agricultural land use, which limits the degree of nutrient recycling. Better understanding the full potential of circular systems would require studying the potential of optimizing farming systems. This would include optimizing agricultural land use and livestock production in different demand scenarios (van Selm et al., 2022).

A relevant research question from a circular perspective would examine the role of livestock production in the future. What will the impact of required dietary change (van Selm et al., 2022) on demand for primary production be in the context of the Finnish food system. A central question here is whether the role of agricultural systems is to provide food for people's diets at the national level or to supply biomass that is optimally sustainable for a specific agro-ecological system. For example, Lehikoinen et al. (2019) suggested designating water-intensive production, such as dairy production, to water-rich regions to produce livestock products for export to regions with less water resources. Furthermore, reducing livestock production would allow for either increasing crop production directly for human use and increasing bioenergy production from agricultural biomasses.

Facilitating this transition would require further research about possible policy incentives for breaking out of the lock-ins associated with the current food system structure. This would include for example conducting regional scale think-do-gap analysis to better identify the gaps that need to be bridged between the present systems and the envisioned future (O'Sullivan et al., 2018). This would also necessitate studying the roles of different food system actors, political interventions and subsidies needed in the transition towards circularity.

7.5 Conclusions

In this thesis, I have proposed a circular design for localized food production in a globalized world using the context of the Finnish food system. Through case studies ranging in scale from a farm to a regional food system, I have presented the main elements of a circular food production system and demonstrated how they are connected across spatial scales. In this design, the biomass-energy-nutrients integration takes place at a feasible spatial scale that enables efficient nutrient recycling and integrated energy production.

It is suggested by scholars that dietary change is required to achieve a sustainable food system that can feed a growing global population. Several studies suggest multiple environmental benefits of redesigning food production to provide more food directly to humans (e.g. Poore & Nemecek, 2018; Röös et al., 2017; van Hal et al., 2019; Zanten et al., 2018). However, we emphasize the importance to acknowledging that food producers, both farmers and food processors, supply food to meet the current demand. When aiming to transform food systems towards circularity, considering the current demand for biomass production in the specific agroecosystem is required.

Thus, the current demand for primary production serves as a baseline for redesigning processes. It is important to understand that the world is constantly changing, and that these changes can be guided by political intervention and participation via active food citizenship (Chapter 3). Some changes require broader participation by different actors, some changes need to be implemented over a long timeline, and others can be implemented at the present time. However, as addressed by Kuokkanen et al. (2017) it is important to orchestrate the transition towards sustainability at the system level. This requires the simultaneous implementation of different measures and sufficiently flexible polices that consider different place-specific contexts.

At present, farmers supply food for current demand and are locked into the current system. *Nested circularity* is a concept that proposes a radical redesign of the food system to negate the negative externalities of the current food system while allowing for trade and a nutritious and varied diet throughout the year. Individual actors in food production cannot be expected to “adopt” this new system, because it requires all actors to redesign their own roles in the food system simultaneously. This requires careful initiation and coordination with supporting policies. To help actors to build integrated food and energy production systems, based on the idea of Agroecological Symbiosis, I propose the following steps (figure 2) to move towards circularity in the context of Finnish food systems.

1. Biological nitrogen fixing instead of mineral nitrogen. Adding more nitrogen fixing crops and perennial leys to crop rotation reduces the need for external nitrogen inputs and to increase feed self-sufficiency while simultaneously reducing indirect energy consumption in food production. This can be implemented by farms but may also require support form agri-environmental polices and the food industry.

2. Localized livestock production. The scale and intensity of livestock production is determined by the regional capacity to produce feed. This requires changes in livestock feeding practices and may result in decreases in the amount of food produced in some regions with intense livestock production. However, in the regions with surplus feed production this would mean an increase in livestock production resulting in improved balance at the system level.

Changes in feeding practices and adjusting the number of livestock can be implemented by farmers but additional support from agri-environmental policies may be needed. Large-scale implementation requires transition towards mixed crop and livestock production systems and balancing the livestock production more evenly across the regions. In the long term, this would require support through appropriate agricultural policies. A more evenly distributed food processing industry would create demand for more localized livestock production.

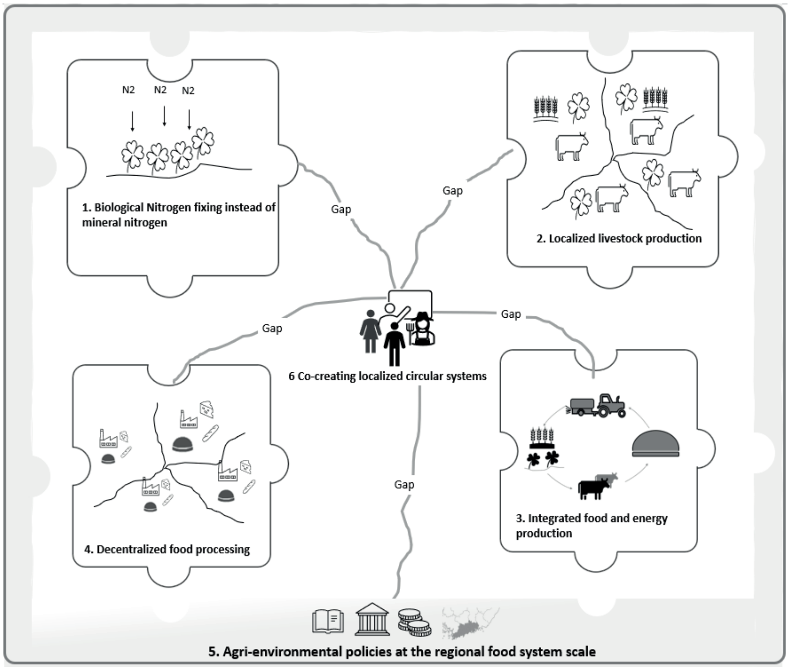

Figure 2. Combination of different required measures in the transition towards circular food systems. The lines between the pieces illustrate the paths with different gaps (knowledge, technological, political, economic) illustrating obstacles on the way towards the desired system. The measures are explained with details in the main body of the text.

3. Integrated food and energy production to enhance nutrient recycling within the farming system, and to reduce the dependence on fossil fuels in the food production. This measure can be implemented by farms but requires support for high capital-demand investments and possible price support to compete with the price of fossil fuels. In particular, the other industrial sectors such as food industry can play an important role by creating demand for produced energy.

4. Decentralizing food processing to a more regional scale closer to the origin of the biomasses it uses in order to enable energy integration with biogas production from food system biomasses, and to distribute the added economic value created by food processing more evenly across the regions. This would require strong regional food and economic policies to support decentralized regional food processing.

5. Agri-environmental policies at the regional scale. Revision of agri-environmental and economic policies to enable a regional approach to designing circular systems at the regional food system scale. The current system is highly subsidized which means that re-allocating these economic resources could provide a central tool in supporting a transition in the desired direction. A revision of the current subsidy system is also needed because the outcomes of the current system have been criticized for low environmental results and cost-effectiveness (European Court of Auditors, 2021; Hyvönen et al., 2020)

6. Co-create circular localized food systems together with all stakeholders at a spatial scale where people share similar goals for food production. These co-created food systems also create regional food cultures to support the localization of food system.

7.7. Acknowledgements

I thank Juha Helenius and Rogier Schulte for their constructive comments on an earlier version of this chapter.

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Summary

In most parts of the world, food production has developed from land use relying on local resources to the current fossil fuel driven globalized food production systems. This transition has occurred for several reasons. The spatial scale of both food consumption and food production have increased. Food consumption has detached from the land where the food is grown. This has also happened with livestock production which is increasingly relying on imported feed resulting in imbalances global nutrient flows. The use of fossil fuels and external nutrient inputs in food production have created a structure that works against the sustainability goals set for food production. In the future, there is a need for systems which will produce enough food for a growing population while simultaneously reducing the environmental impacts from food production. In order to move towards sustainability, the relatively short history of fossil fuel use in food production needs to be left in the past and food production returned to a reliance on renewable energy without food-fuel competition. Thus, demand for such food production systems, with the aim of reducing the use of fossil-based inputs, is higher than ever.

With the objective of addressing these challenges, in chapter 1, I explore the role of biomass-energy-nutrient nexus in food production, and present research questions and methodology I'm using in this study. The aim of this thesis is to propose a design for a circular food production system which acknowledges the interconnected nexus of biomass-nutrients-energy. I study the biophysical and economic impacts of such an integrated food and energy production design at different spatial scales in the context of the Finnish food system.

In chapter 2, through a case study, I show how food and energy production can be integrated to enhance productivity and nutrient recycling at the farm scale. In this Chapter, I used the case of Palopuro Agroecological symbiosis (AES), located in Southern Finland, to study how biogas production from on-farm feedstocks that do not compete with food production can be used to enhance nutrient cycling and food production, and to calculate how much energy could be produced from the within-system feedstocks. The results demonstrated substantial potential for increasing yields and reducing nutrient losses in organic crop production by enhancing nutrient recycling withing the systems. This was achieved through the production of renewable energy by using green manure leys as a main feedstock in biogas production which enabled the better allocation of nutrients in time and space compared to the conventional use of green manures where they are ploughed into soil. In addition, the biogas production from on-farm biomasses produced 70% more energy than the system consumed and converted the system from energy consumer to net energy producer.

In chapter 3, the concept of AES is proposed as a generic arrangement for re-configuring primary production and food processing and forming a network of localized food systems to work

towards system-level sustainability. This chapter deepened the theoretical foundations of this model by presenting the main principles of the concept and laying out how they contribute to sustainability in terms of efficiency, sufficiency and consistency. In addition, the co-creative process of forming the first AES at Palopuro, Finland is explained. Also, the role of people who live in the landscapes where food is produced, as active food citizens, is discussed.

In chapter 4, the spatial scale of the system where the AES model was studied was broadened to the municipality scale. I conducted a scenario analysis in which energy production was integrated into food production to different extents in three different scenarios. In each scenario the complexity of the system increased. In the first scenario, only biomasses (fallow, manure) that were not currently competing with food production were used in biogas production whereas, in the second scenario, clover-leys were applied to crop rotations to produce additional biomass for energy production and to fix nitrogen to the system. In the third scenario, this biomass from green manure leys was used first to fed livestock and the livestock manure then used in biogas production. I used a multicriterial framework to assess 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 scenarios compared to the current system. The results showed potential synergies in integrating food and energy production. Biogas production was substantial in each scenario without having a significant impact on food production. The biggest synergies in the supply of ecosystem services were found when livestock production was integrated with biomass and energy production. Simultaneously, the environmental externalities were reduced compared to the current system.

In chapter 5, I expanded the spatial scale to the regional scale. In this chapter, I provided a novel approach to assessing a food system's circularity which goes beyond nutrient recycling and acknowledges the spatial connections of biomass flows. Under the concept of Nested Circularity, I defined the most important elements of circular food systems as biomass for food and feed, biomass for energy, and nutrient recycling. I applied the Nested Circularity framework to three contrasting farming regions in Finland and calculated the biomass (food and feed) and nutrient flows for these regions. For energy, I calculated the current energy use in primary production and then potential to produce energy from food system biomasses that did not compete with food production. The results showed large differences in circularity between regions. Livestock production played a central role in each region. Biomass production was related to either livestock production or to feed production. In each region, substantial amounts of energy could be produced from manure and plant-based biomasses without the food-fuel competition. Manure provided the biggest recyclable nutrient resources whereas food system by-products and human excreta provided a significant nutrient resource only in the region with a high population. In this chapter, I propose a concept of Nested Circularity in which nutrient, biomass and energy cycles are connected and closed across multiple spatial scales.

In chapter 6, I expanded the vertical dimension by including the role of food processing from an economic perspective in a regional food system. I also studied how compatible the energy production potential from agricultural biomasses is with the energy consumption in food processing. I applied the Nested Circularity framework, which was introduced in Chapter 5, to the same three case study regions. I calculated the economic value created in primary production (food and energy), food processing, and the value of nutrient and energy costs related to food production in the current system and in a regional scenario where it was assumed that all biomass produced in these regions was either processed into food products or used to produce biogas within that region. The results showed how energy production from agricultural biomasses can provide enough energy for food processing on a regional scale, but that this would require integrations of food processing and primary production. Essentially, with this chapter, I am suggesting that regionalized food processing is an integral element of circular food systems because it plays an important role in regional biomass flows and energy use.

In chapter 7, the general discussion, I discuss the results and implications of my work. I propose that a circular food production system design is built from the following elements 1) the integration of biomass-nutrient-energy, 2) the multifunctional use of perennial leys, and 3) the horizontal and vertical integration of actors and operations at the food systems scale which is functional both from the biophysical and physical perspective. To transform the current food system towards circularity, I propose six steps to be taken simultaneously. These steps consider the role of farmers, food processors and policy makers in the context of regional food systems. To support this transition, I suggest further research into the potential of land use optimization from a circular food system perspective, how projected dietary change may impact agricultural land use in the future, and what policy interventions are needed.

Acknowledgements

Life is full of surprises. For me, one of the biggest was starting a PhD. I would not have been able to go through the process of this PhD without the support of several people.

First and foremost, I would like to thank my supervisors, Rogier Schulte and Juha Helenius, who guided me through this process. Juha, thank you for encouraging me to start a PhD. In addition to the great supervision, I am also grateful for our inspiring discussions about sustainability. Rogier, thank you for your guidance during this process. I am still always impressed by your visionary thinking and how you chair the group. Thank you for letting me be part of this group. Juha and Rogier, I have learned a lot from both of you and I really appreciate your knowledge and special supportive attitude towards students and colleagues. I am also grateful for another surprise in my PhD process, when you agreed in the car on the way to Palopuro that I could do a double degree between the University of Helsinki and Wageningen University. Hopefully, our collaboration will result in more positive surprises in the future as well. I would also like to thank my co-supervisor Hannu Mikkola. I have always really enjoyed our conversations, especially at the beginning of my PhD.

I would like to give a special thanks to my neighbours on the Knehtilä farm. Markus, Minna, all the other important Knehtilä people, and those people involved in the Palopuro pilot. You have provided an inspirational environment from a research and community perspective. I am looking forward to new adventures in developing sustainable food production with all of you.

I am grateful to be part of the Global Network of Lighthouse Farms. I would like to express my gratitude to all the wonderful farmers and researchers that I have met through this network. My special thanks go to the coordinators of the network—Annemiek and Mariana—it has been a pleasure and so much fun to work with you.

Doing a degree between two universities has the advantage of getting an opportunity to meet many amazing colleagues. I would like to thank all my colleagues in the agroecology group and other groups in the department of plant science at the University of Helsinki Viikki Campus. This includes Hanna, Irina, Jana, Johan, Jure, Mari, Marjaana, Miriam, Natasha, Niko, Priit, Sari, Rachel, Sari, Venla, Yumi. I am sure there are some you that have inadvertently overlooked when putting together this list. I also would like to thank my co-authors Elina, Maartje, Marjukka, Susanna and Tuure. Also, a special thanks to Sophia for being a dynamic co-author, who always went out of her way to be helpful in editing and proof-reading. Anna, thank you for your concrete and sharp comments on my work. I would also like to thank Ari-Matti, Iiris, Jeroen, Maartje and Xianya whose master’s theses I had a chance to supervise. Thank you all for sharing your knowledge and for the countless chats while we were having our coffee and lunch breaks. It was these moments and the friendship and inspiration found in them that made it worthwhile to travel to the office.

I am also grateful to my colleagues at the Ruralia Institute in Mikkeli and Seinäjoki. Sami and Torsti, thank you for trusting my skills and for creating such a warm and inspiring work environment at Ruralia. Thank you to all Ruralia people in Mikkeli and Seinäjoki. I would also like to thank Anne, Heli, Milla Sari, Sirpa at the Finnish Organic Research Institute. All the people I would like to thank here is too long to list here individually, but you know who you are.

To my colleagues the Farming Systems Ecology group, thank you for always making me feel welcome when was in Wageningen. My special thanks go to Gemma, who I met already on my first visit to Wageningen. You have been such a big help during this process. Special thanks also to Blair, who I also met on my first visit. In addition to helping me with many practical issues, I also feel grateful for the opportunities to participate in lectures in Wageningen. Thanks for all staff and PhD candidates in the group, Carl, Clark, Dirk, Elsa, Felipe, Felix, Fogelina, Hannah, Hennie, Ichani, Jeroen, Jiali, Jonas, Katie, Kees, Kristine, Laci, Lenora, Lilian, Lizzy, Loekie, Merel, Pablo, Qingbo, Renée, Roos, Stella, Tharic, Vena, Vivian, Walter, Wolfram, Wendy. I had more interaction with some of you than others. Hopefully there will be new opportunities to get to know you better in the future. Especially those who I forgot to mention.

I am grateful to all of you for sharing your knowledge and for always having time and energy for inspirational discussions. Thanks also for the social life and the drinks every then and now!

Thank you to my graduate schools and PhD offices in both universities for helping to make this dual degree possible. I would also like to thank my colleagues at LUKE, SYKE, LUT, and the other organizations where I have been lucky enough to collaborate.

Last, but certainly not least, I would like to thank my parents and my family—Lilja, Oiva and Päivi,—for their love and support during this process.

About the author

Kari Koppelmäki was born in Muurame, Finland, on December 27, 1979. He first became interested in food production and sustainability in 2003 while studying sustainable development and resource use at the University of Applied Science in Hyvinkää. He did his internship at the regional Centre for Environment in Uusimaa—Finland's capital region. For the 8 years after his studies, he worked with farmers in different agri-environmental projects that aimed to reduce the nutrient leaching caused by agriculture. During this period Kari started a small farm with his wife in Hyvinkää, where they produce honey and organic vegetables.

Between 2013–2016, Kari completed an MSc in Agroecology at the University of Helsinki. During his studies he was actively involved in developing a more sustainable food model in his home village, Palopuro. This project was undertaken in conjunction with his neighbors and his supervisor, professor Juha Helenius. This model for localized food production is called Agroecological Symbiosis (AES). The concept was designed and piloted from 2015–2017, during the Palopuro AES project. This project was funded by the Finnish Ministry of Environment. Kari served as a project coordinator for this project.

During the AES project Kari became more interested in research and in the Autumn of 2017, he decided to begin his PhD. The Palopuro AES project attracted many visitors, including Professor Rogier Schulte from Wageningen University. It was during Dr. Schulte's visit in 2017, that Kari's PhD project was expanded to also be conducted at Wageningen University. In 2020, Kari started working for the Ruralia Institute of the University of Helsinki. His work involves several different projects that aim for the development of a more sustainable food system.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (5 ECTS)

- Integrating biogas production to nutrient recycling in localized food production

Post-graduate courses (10.6 ECTS)

- Soils and climate change; University of Helsinki (2019)
- World soils and their assessment; ISRIC (2019)
- The future of the bioeconomy: circular and ecosystem services-aware; University of Helsinki/NOVA network (2020)
- Introduction to R; University of Helsinki (2020)
- Landscape ecology, spatial pattern analysis; University of Helsinki (2021)

Invited review of (unpublished) journal manuscript (2 ECTS)

- Ecohydrology & Hydrobiology: carbon and nutrient recycling ecotechnologies (2020)
- Journal of Industrial Ecology: symbiosis between food and energy systems (2020)

Competence strengthening / skills courses (5 ECTS)

- Scientific writing; University of Helsinki (2018)
- Grant writing; University of Helsinki (2018)
- Popularisation of science; University of Helsinki (2021)
- Learning to visualize data; University of Helsinki (2021)

Scientific integrity/ethics in science activities (1 ECTS)

- Research ethics; University of Helsinki (2021)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.5 ECTS)

- PE&RC First years weekend (2017)
- PE&RC Last years weekend (2021)

Discussion groups / local seminars or scientific meetings (4.8 ECTS)

- SURVEG project; University of Helsinki (2018-2021)
- Ville project, a project about mitigating to climate change in the agricultural sector in Finland; University of Helsinki (2018-2022)
- AGFOREE seminars sustainable use of renewable natural resources; University of Helsinki (2018-2022)

- Unknown food system discussion meetings; University of Helsinki (2019)
- Biokaasusta elinvoimaa project, a feasibility project about biogas production in the municipality of Lapinjärvi, Finland; University of Helsinki (2020-2021)
- EIP-AGRI Enhancing production and use of renewable energy on the farm; University of Helsinki
- Livestock's role in sustainable food system workshops; University of Helsinki (2021)

International symposia, workshops and conferences (4 ECTS)

- 3rd European Sustainable Phosphorus Conference; poster presentation; Helsinki, Finland (2018)
- 6th Farming Systems Design Symposium; oral presentation; Montevideo Uruguay (2019)
- 28th General Meeting of European Grassland Federation; online; Helsinki, Finland (2021)

Societally relevant exposure (1 ECTS)

- Three blog writings https://blogs.helsinki.fi/hy-ruralia/ (2020-2021)

Lecturing/supervision of practicals/tutorials (0.9 ECTS)

- Exploring the future of food and farming; Wageningen University (2020-2021)
- Ecological farming methods; University of Helsinki (2021)

BSc/MSc thesis supervision (12 ECTS)

- Optimization of the farming system
- Optimization of the nutrient use at the farm scale.
- Economic assessment of regional food production system
- Optimizing a circular food and energy production system

Funding

The research described in this thesis was financially supported from the Finnish Ministry of the Environment's Programme (RAKI2) to promote the recycling of nutrients and improve the ecological status of the Archipelago Sea, the South Savo Regional Council, The Finnish Foundation for Technology Promotion, and Maa- ja vesitekniikan tuki ry.

Financial support from Wageningen University for printing this thesis is gratefully acknowledged.

Cover design by Katri Oikarinen
Printed by Proefschriftmaken on FSC-certified paper