Nested circularity

Localized Food in a Globalized World

Kari Koppelmäki

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Chapter 1

General Introduction

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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 14th-16th 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.

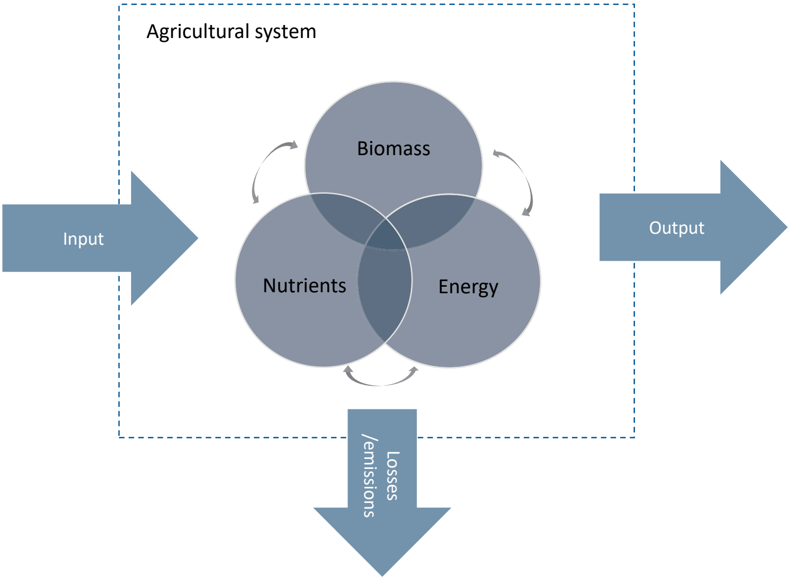

Figure 1. The nexus of biomass, nutrients and energy. In an agricultural system biomass production requires both nutrients and energy while biomass can also be used as a recycled nutrient source for plants and to produce energy. In most systems biomass (feed), nutrients (fertilizers), and energy (fossil 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 20th 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

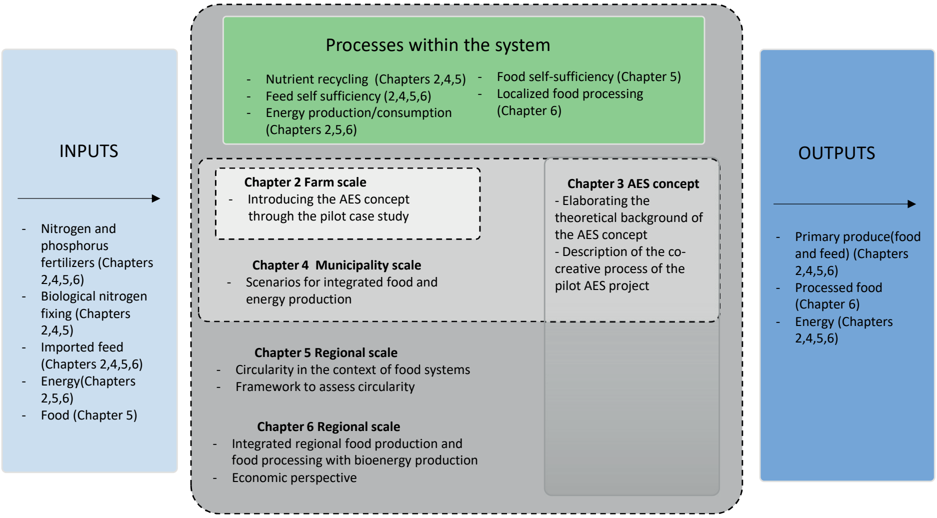

Figure 2. Outline of my thesis structure including the system boundaries for each chapter, and the focus of each chapter.

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

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Chapter 2

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

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Chapter 3

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

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Chapter 4

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

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Chapter 5

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

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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

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.

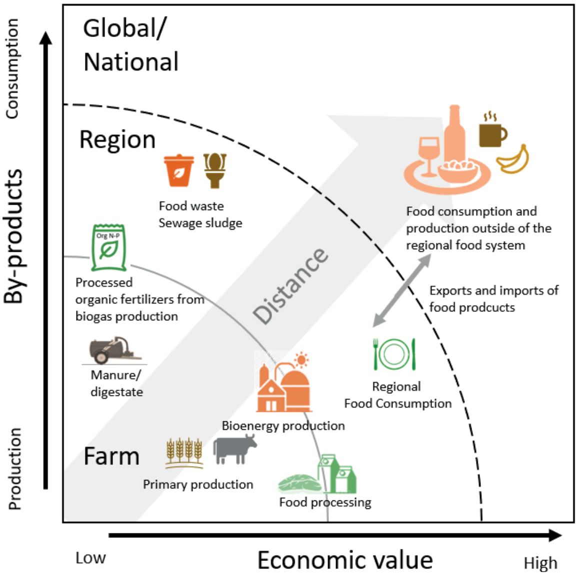

Figure 1. Spatial scales for different sub-systems in a functional circular food system. The scale of bioenergy production, food processing, and processed organic fertilizers from biogas production located at the intersection of the farm and regional scale implies that, in a circular system, these elements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

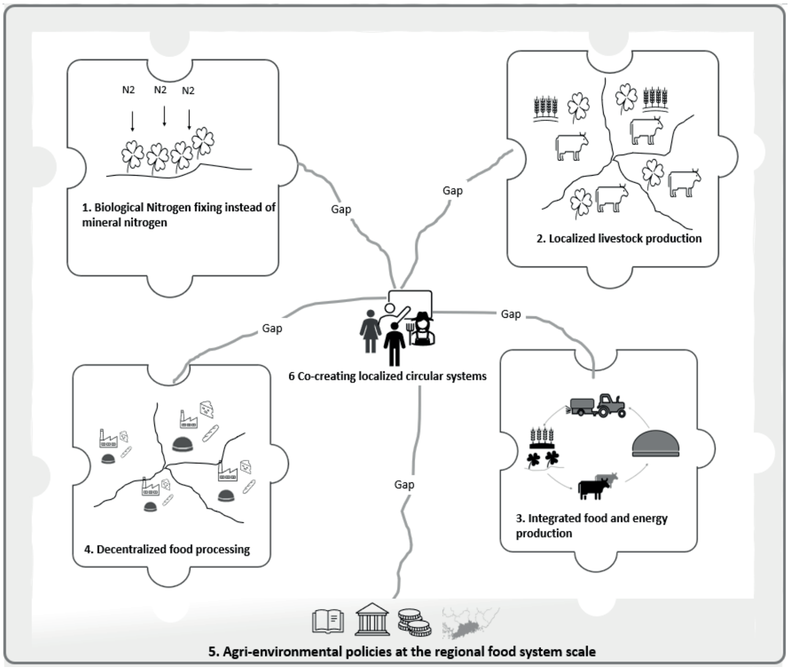

Figure 2. Combination of different required measures in the transition towards circular food systems. The lines between the pieces illustrate the paths with different gaps (knowledge, technological, political, economic) illustrating obstacles on the way towards the desired system. The measures are explained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

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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.

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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

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