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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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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.

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

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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 bio-physical flows and excludes further exploration of the economic or environmental impact categories.

2. Materials and methods

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 (Fig. 1).

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.

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).

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.

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

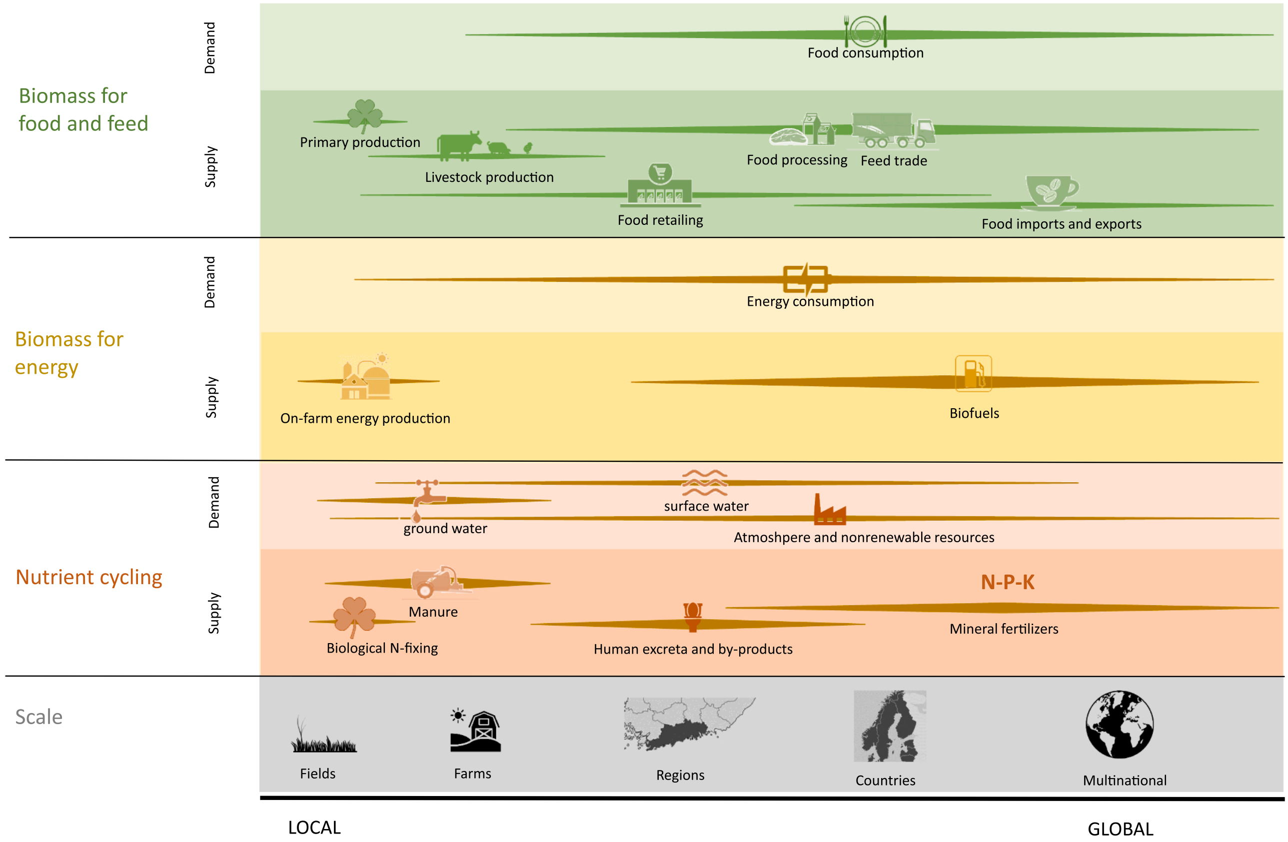


Fig. 1. Schematic depiction of the most important elements (biomass for food, feed and energy, and nutrient cycling) of circular food systems illustrating the spatial scale of their supply and demand. The demand for these elements reflects societal and environmental expectations, which may manifest at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

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).

2.2. *Applying the framework in regional case studies*

We applied this framework (Fig. 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

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*	*8740*	*3.6*	*12,780*	*7.1*
Potatoes (ha)	*260*	*0.4*	*5260*	*2.2*	*240*	*0.1*
Horticulture crops (ha)	*734*	*1.0*	*660*	*0.3*	*1223*	*0.7*
Fallow area (ha)	*8580*	*12.4*	*29,060*	*12.1*	*28,080*	*15.8*
Other crops (ha)	*1266*	*1.8*	*1700*	*0.7*	*4320*	*2.4*
Number of animals						
Bovine	42,970		111,843		22,425	
Pigs*	13,502		472,487		64,068	
Poultry	162,348		3573,923		12,164	
Other animals**	8319		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.

their agricultural structures (Table 1, Fig. 2). The first region, South Savo (GRS-LIV), produces grass-based livestock and has a low population (7.7 inhabitants per km^2). The second, South Ostrobothnia (INT-LIV), represents a region with intensive livestock production and also has a low population (13.6 inhabitants per km^2). 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 km^2) 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.

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 (%).

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.

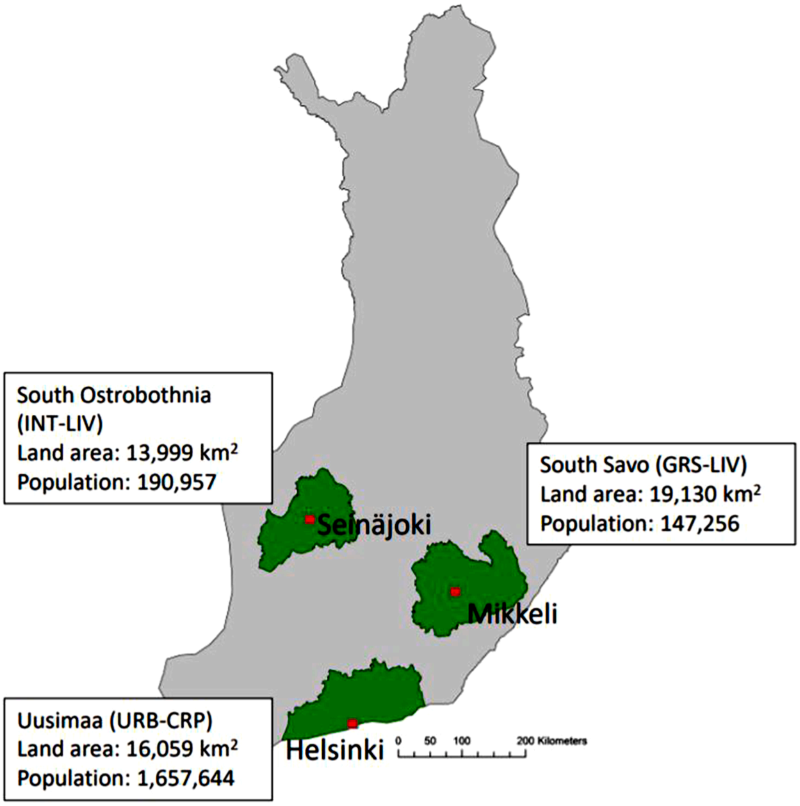


Fig. 2. Case study regions within Finland. Land areas and populations as in 2017 (OSF, 2017). Regional capitals are marked with red squares. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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, Mönch-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[5,6,7].	[1]Natural Resources Institute Finland, 2020b, [5]Tampio et al., 2016, [6] Kask et al., 2012,
	Sewage sludge	Multiplying the number of each region's population under industrial wastewater treatment[1,] by the average phosphorus quantity, 0.83 P kg person^{-1} yr^{-1}, in the sewage sludge[2]	Finnish Environment Institute, 2020

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.

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.

3. Results

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 (Fig. 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 (Figs. 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

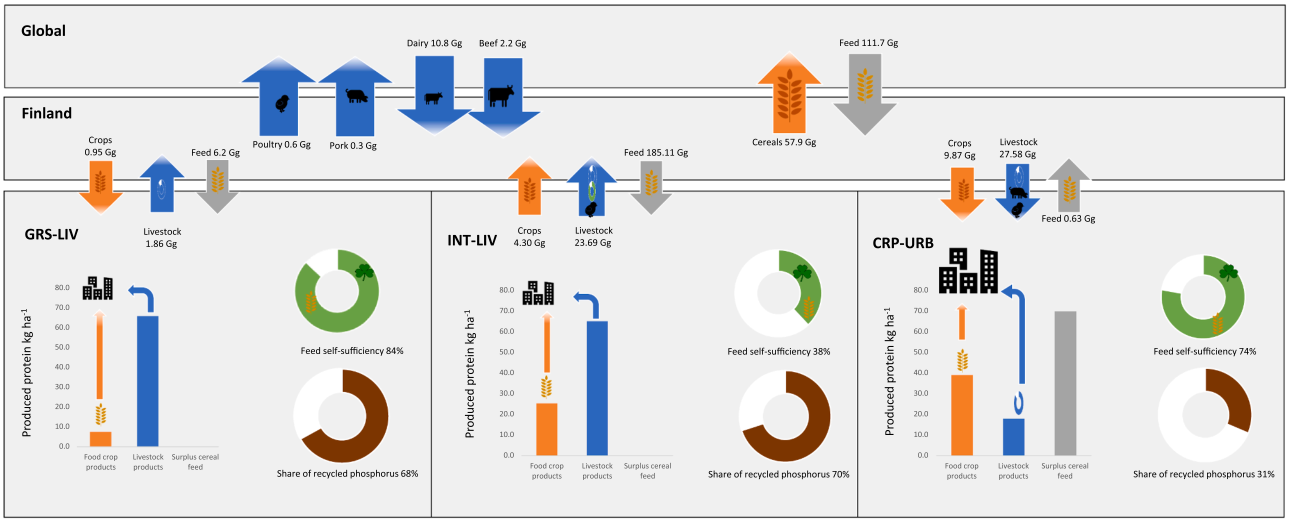
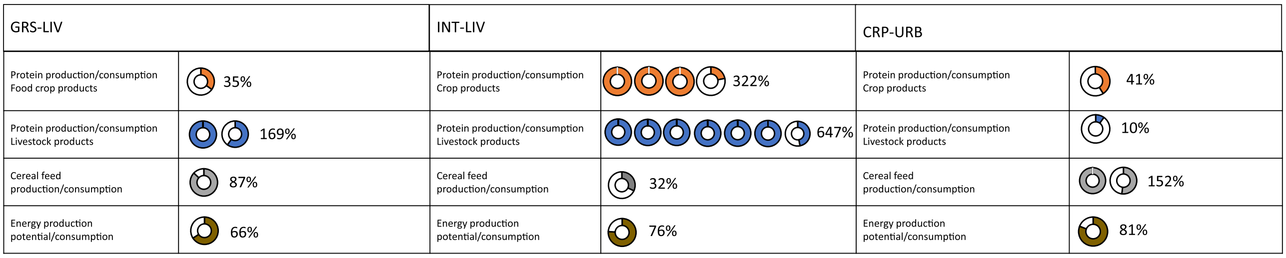


Fig. 3. Comparison of agricultural production in the three contrasting regions (Table 1). Food productivity in the study regions in crop and livestock products (as protein kg ha^{-1}) per unit farmland, surplus cereal feed protein (protein kg ha^{-1}), feed self-sufficiency (% of dry matter), and share 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



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	169%	Protein production/consumption Livestock products	647%	Protein production/consumption Livestock products	10%
Cereal feed production/consumption	87%	Cereal feed production/consumption	32%	Cereal feed production/consumption	152%
Energy production potential/consumption	66%	Energy production potential/consumption	76%	Energy production potential/consumption	81%

Fig. 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 (%).

produced 42% and 22% of the total food crop protein.

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 (Fig. 4.)

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 (Fig. 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*

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 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

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 kg ha^{-1}	INT-LIV kg ha^{-1}	URB-CRP 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

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.

4. Discussion

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).

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

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).

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.

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).

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.

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.

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.

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** (Fig. 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.

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;

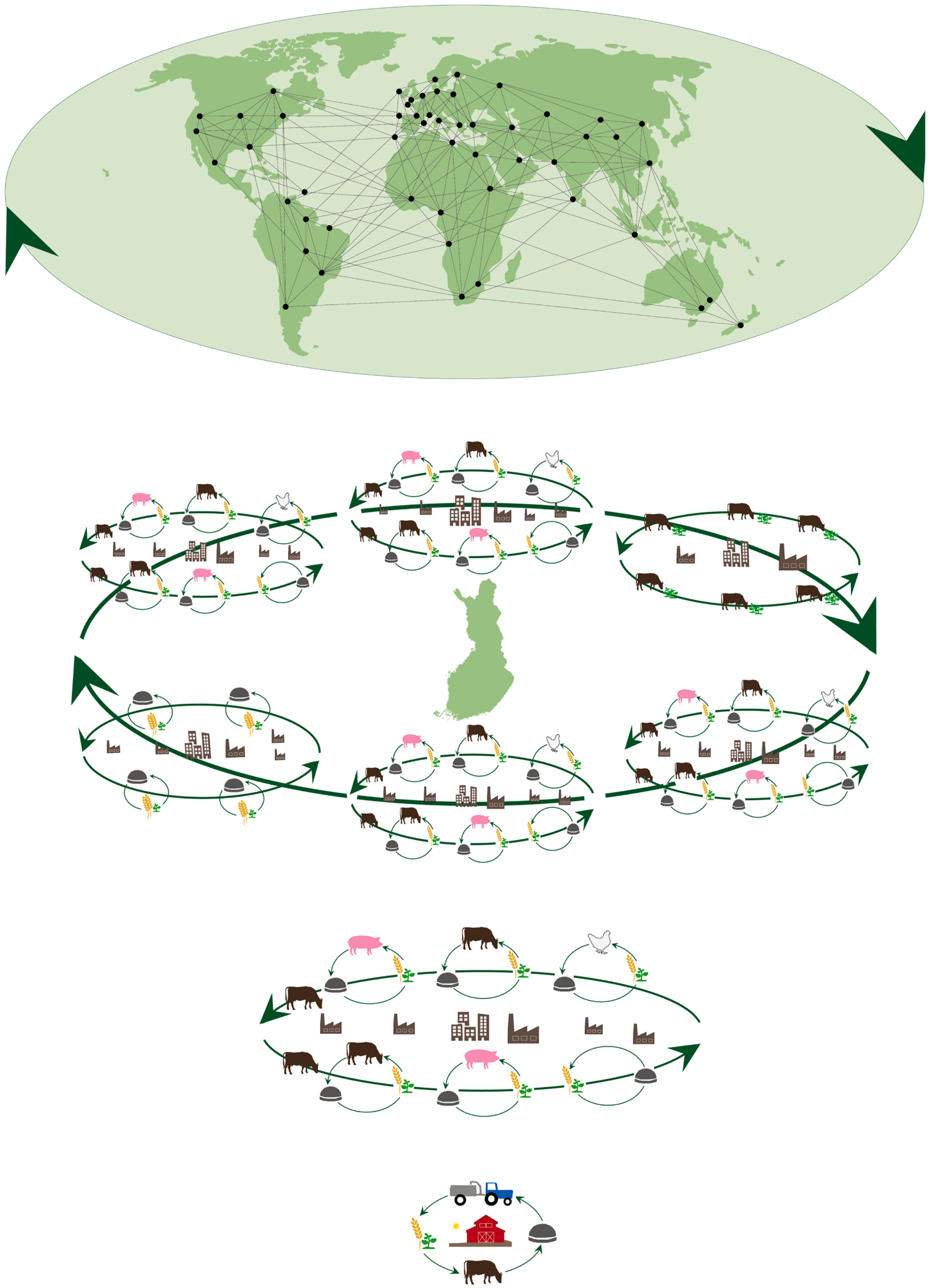


Fig 5. Schematic picture of **nested circularity** at different geographical scales. The bottom picture illustrates circular farms which, together and in conjunction with food processing and food consumption at the regional scale, form the circular food system. Circularity at the national scale occurs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

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. 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.

CRediT authorship contribution statement

Kari Koppelmäki: Conceptualization, Data curation, Formal analysis, Methodology, Investigation, Writing - original draft, Visualization. **Juha Helenius:** Writing - review & editing, Supervision. **Rogier P.O. Schulte:** Conceptualization, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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References

Anglade, J., Billen, G., Garnier, J., 2015. Relationships for estimating N_2 fixation in legumes: incidence for N balance of legume-based cropping systems in Europe. Ecosphere 6, 1–24. https://doi.org/10.1890/ES14-00353.1.

Antikainen, R., Lemola, R., Nousiainen, J.I., Sokka, L., Esala, M., Huhtanen, P., Rekolainen, S., 2005. Stocks and flows of nitrogen and phosphorus in the Finnish food production and consumption system. Agric. Ecosyst. Environ. 107, 287–305. https://doi.org/10.1016/j.agee.2004.10.025.

Berg, J. (2016). ETL:n jäte- ja sivuvirtaselvitys 2016. 36. http://www.etl.fi/media/aineistot/raportit-ja-katsaukset/etl-jate_ja_sivuvirtaselvitys_2016.pdf (accessed 2 June 2020).

Buckwell, A., Nadeu, E., 2016. Nutrient Recovery and Reuse (NRR) in European Agriculture. A Review of the Issues, Opportunities, and Actions. RISE Foundation, Brussels.

Börjesson, P., Berglund, M., 2006. Environmental systems analysis of biogas systems-part I: fuel-cycle emissions. Biomass Bioenergy 30, 469–485. https://doi.org/10.1016/j.biombioe.2005.11.014.

Crews, T.E., Peoples, M.B., 2004. Legume versus fertilizer sources of nitrogen: ecological tradeoffs and human needs. Agric. Ecosyst. Environ. 102, 279–297. https://doi.org/10.1016/j.agee.2003.09.018.

Ellen MacArthur Foundation, 2012. Towards the circular economy: economic and business rationale for an accelerated transition. Available at. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf.

Ellen MacArthur Foundation, 2019. Cities and circular economy for food. Available at. https://www.ellenmacarthurfoundation.org/assets/downloads/insight/CCEFF_Full-report_May-2019_Web.pdf (accessed 3 May 2020).

European Commission, 2020. A new Circular Economy Action Plan For a cleaner and more competitive Europe. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN (Accessed 3 May 2020).

EU, 2019. Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 https://eur-lex.europa.eu/eli/reg/2019/1009/oj (Accessed 30 May 2020).

Enroth, A., 2009. Mallilaskelmia Maataloudessa 2009. ProAgria Keskusten Liiton Julkaisuja Nro 1081. Hakapaino Oy, HelsinkiFinland, 47550.

Eurostat, 2018. Regions in the European Union. Nomenclature of territorial units for statistics - NUTS 2016/EU-28. https://doi.org/10.2785/475524.

Fealy, R., Schroder, J.J., 2008. Assessment of manure transport distances and their impact on economic and energy cost. In: Proceedings 642, International Fertiliser Society. York, p. 28.

Fernandez-Mena, H., Nesme, T., Pellerin, S., 2016. Towards an agro-industrial ecology: a review of nutrient flow modelling and assessment tools in agro-food systems at the local scale. Sci. Total Environ. 543, 467–479. https://doi.org/10.1016/j.scitotenv.2015.11.032.

Finnish Environment Institute, 2020. https://www.ymparisto.fi/fi-fi/kartat_ja_tilastot/vesihuoltoraportit/Yhdyskuntien_jatevesien_kuormitus_vesiin (accessed 10 April 2020.

Finnish Food Authority, 2020. Feed imports statistics https://www.ruokavirasto.fi/yritykset/rehu–ja-lannoiteala/rehut-ja-rehualan-toimijat/tilastot-ja-raportit/ (in finnish) (accessed 3 May 2020).

Granstedt, A., Schneider, T., Seuri, P., Thomsson, O., 2008. Ecological recycling agriculture to reduce nutrient pollution to the baltic sea. Biol. Agric. Hortic. 26 (3), 279–307. https://doi.org/10.1080/01448765.2008.9755088.

Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European union and the world in 2005. J. Ind. Ecol. 19 (5), 765–777. https://doi.org/10.1111/jiec.12244.

HLPE, 2017. Nutrition and Food systems. A report By the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. http://www.fao.org/3/a-i7846e.pdf. accessed 20 May 2020.

HLPE, 2019. Agroecological and Other Innovative Approaches For Sustainable Agriculture and Food Systems That Enhance Food Security and nutrition. A report By the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. http://www.fao.org/3/ca5602en/ca5602en.pdf. accessed 20 May 2020.

Hoxha, A., Christensen, B., 2019. The Carbon Footprint of Fertilizer Production: Regional Reference Values, 1. International Fertilizer Society, pp. 1–21.

Huhtamäki, T., 2019. Ruokinta tuotosseurantatiloilla vuonna 2018. ProArgia 505. https://www.proagria.fi/sites/default/files/attachment/tuotosseurantakarjojen_rehustus_vuonna_2018_huhtamaki.p506pdf. accessed 21 April 2020.

Jawahir, I.S., Bradley, R., 2016. Technological elements of circular economy and the principles of 6R-based closed-loop material flow in sustainable manufacturing. Procedia CIRP 40, 103–108. In: https://doi.org/10.1016/J.PROCIR.2016.01.067.

Jurgilevich, A., Birge, T., Kentala-Lehtonen, J., Korhonen-Kurki, K., Pietikäinen, J., Saikku, L., Schösler, H., 2016. Transition towards circular economy in the food system. Sustainability 8, 1–14. https://doi.org/10.3390/su8010069.

Kafle, G.K., Chen, L., 2016. Comparison on batch anaerobic digestion of five different livestock manures and prediction of biochemical methane potential (BMP) using different statistical models. Waste Manage. (Oxford) 48, 492–502. https://doi.org/10.1016/j.wasman.2015.10.021.

Kask, Ü., Andrijevskaja, J., Kask, L., Heinla, P., Hüüs, M., Rasi, S., Heino, E., Ahonen, S., & Marttinen, S., 2012. From waste to traffic fuel (W-Fuel). http://www.mtt.fi/mttraportti/pdf/mttraportti53.pdf.

Kinnunen, P., Guillaume, J.H.A., Taka, M., D'Odorico, P., Siebert, S., Puma, M.J., Jalava, M., Kummu, M., 2020. Local food crop production can fulfil demand for less than one-third of the population. Nature Food 1, 229–237. https://doi.org/10.1038/s43016-020-0060-7.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/J.RESCONREC.2017.09.005.

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. Agric. Syst. 170, 39–48. https://doi.org/10.1016/j.agsy.2018.12.007.

Lemaire, G., Franzluebbers, A., Carvalho, P.C.de F., Dedieu, B., 2014. Integrated crop-livestock systems: strategies to achieve synergy between agricultural production and environmental quality. Agric. Ecosyst. Environ. 190, 4–8. https://doi.org/10.1016/j.agee.2013.08.009.

Levi, P.G., Cullen, J.M., 2018. Mapping global flows of chemicals: from fossil fuel feedstocks to chemical products. Environ. Sci. Technol. 52, 1725–1734. https://doi.org/10.1021/acs.est.7b04573.

Luostarinen, S., Grönroos, J., Hellstedt, M., Nousiainen, J., & Munther, J., 2017. Finnish normative manure system system documentation and first results. http://urn.fi/URN:ISBN:978-952-326-443-4.

Mariotti, F., Tomé, D., Mirand, P.P., 2008. Converting nitrogen into protein - beyond 6.25 and jones' factors. Crit. Rev. Food Sci. Nutr. 48, 177–184. https://doi.org/10.1080/10408390701279749.

Marttinen, S., Tampio, E., Sinkko, T., Timonen, K., Luostarinen, S., Manninen, K., 2015. Biokaasulaitokset - syötteistä lopputuotteisiin. Luonnonvara- ja biotalouden Tutkimus 14/2015. Luonnonvarakeskus (Luke), Helsinki. http://urn.fi/URN:ISBN:978-952-326-013-9.

Marttinen, S., Venelampi, O., Iho, A., Koikkalainen, K., Lehtonen, E., Luostarinen, S., Rasa, K., Sarvi, M., Tampio, E., Turtola, E., Ylivainio, K., Grönroos, J., Kauppila, J., Koskiaho, J., Valve, H., Laine-Ylijoki, J., Lantto, R., Oasmaa, A., & Zu Castell-Rüdenhausen, M., 2017. Kohti ravinteiden kierrätyksen läpimurtoa - Nykytila ja suositukset ohjauskeinojen kehittämiseksi Suomessa. Available at. http://urn.fi/URN:ISBN:978-952-326-437-3.

Ministry of Agriculture and Forestry of Finland, 2011. Suomesta ravinteiden kierrätyksen mallimaa. http://urn.fi/URN:ISBN:978-952-453-649-3 (accessed 12 May 2020) (in Finnish).

Ministry of Agriculture, Nature and Food Quality of the Netherlands, 2018. Agriculture, nature and food: valuable and connected The Netherlands as a leader in circular agriculture. https://www.government.nl/ministries/ministry-of-agriculture-nature-and-food-quality/vision-anf (accessed 12 May 2020).

Murray, A., Skene, K., Haynes, K., 2015. The circular economy: an interdisciplinary exploration of the concept and application in a global context. J. Bus. Ethics 140, 369–380. https://doi.org/10.1007/s10551-015-2693-2.

Möller, K., Müller, T., 2012. Effects of anaerobic digestion on digestate nutrient availability and crop growth: a review. Eng. Life Sci. 12 (3), 242–257. https://doi.org/10.1002/elsc.201100085.

Mönch-Tegeder, M., Lemmer, A., Oechsner, H., Jungbluth, T., 2013. Investigation of the methane potential of horse manure. Agric. Eng. Int. 15, 161–172.

Natural Resources Institute Finland, 2018. Feed tables and nutrient requirements of farm animals used in Finland. https://portal.mtt.fi/portal/page/portal/Rehutaulukot/feed_tables_english (accessed 15 February 2020).

Natural Resources Institute Finland, 2020a: Statistics Database: nitrogen and Phosphorus balance. https://stat.luke.fi/en/uusi-etusivu (accessed 12 May 2020).

Natural Resources Institute Finland, 2020b: Biomass-atlas. https://www.luke.fi/biomassa-atlas/en/ (accessed 12 May 2020).

Natural Resources Institute Finland, 2020c: Foreign trade in agri-food products. https://stat.luke.fi/en/foreign-trade-in-agri-food-products (accessed 2 May 2020).

Neiva de Figueiredo, J., Mayerle, S.F., 2014. A systemic approach for dimensioning and designing anaerobic bio-digestion/energy generation biomass supply networks. Renew. Energy 71, 690–694. https://doi.org/10.1016/j.renene.2014.06.031.

Nesme, T., Roques, S., Metson, G.S., Bennett, E.M., 2016. The surprisingly small but increasing role of international agricultural trade on the European Union's dependence on mineral phosphorus fertiliser. Environ. Res. Lett. 11. https://doi.org/10.1088/1748-9326/11/2/025003.

OECD, 2020. Nutrient balance (indicator). Available at. https://data.oecd.org/agrland/nutrient-balance.htm (accessed 2 February 201).

OSF, 2013. Natural Resources Institute Finland, Energy consumption of agriculture and horticulture https://stat.luke.fi/en/energy-consumption-agriculture-and-horticulture-2013_en (accessed 2 June 2020).

OSF, 2017. Official Statistics of Finland. Preliminary Population Statistics [e-publication]. ISSN=2243-3627. December 2017, Preliminary population and population growth by region 2017 . Helsinki: Statistics Finland [referred: 7.5.2020]. Access method: http://www.stat.fi/til/vamuu/2017/12/vamuu_2017_12_2018-02-15_tau_001_en.html. Accessed 2 June 2020.

OSF, 2019: Natural Resources Institute Finland, Cereals balance sheet. https://stat.luke.fi/en/cereals-balance-sheet (accessed 10 March 2020).

OSF, 2020: Natural Resources Institute Finland, Utilized agricultural area. https://stat.luke.fi/en/utilised-agricultural-area (accessed 11 April 2020).

OSF, 2020: Natural Resources Institute Finland, Number of livestock. https://stat.luke.fi/en/number-of-livestock (accessed 11 April 2020).

OSF, 2020: Natural Resources Institute Finland, Crop production statistics. https://stat.luke.fi/en/crop-production-statistics (accessed 10 May 2020).

OSF, 2020: Natural Resources Institute Finland, Meat production by area. https://stat.luke.fi/en/meat-production-by-area (accessed 10 May 2020).

OSF, 2020: Natural Resources Institute Finland, Foreign trade in agri-food products. https://stat.luke.fi/en/foreign-trade-in-agri-food-products (accessed 10 May 2020).

OSF, 2020: Regional statistics on entrepreneurial activity. https://www.stat.fi/til/alyr/index_en.html (accessed 29 April 2020).

O'Sullivan, L., Wall, D., Creamer, R., Bampa, F., Schulte, R.P.O., 2018. Functional land management: bridging the think-do-gap using a multi-stakeholder science policy interface. Ambio 47 (2), 216–230. https://doi.org/10.1007/s13280-017-0983-x.

Papangelou, A., Achten, W.M.J., Mathijs, E., 2020. Phosphorus and energy flows through the food system of Brussels Capital Region. Resour. Conserv. Recycl. 156. https://doi.org/10.1016/j.resconrec.2020.104687.

Papargyropoulou, E., Lozano, R., K. Steinberger, J., Wright, N., Ujang, Z.bin., 2014. The food waste hierarchy as a framework for the management of food surplus and food waste. J. Clean. Prod. 76, 106–115. https://doi.org/10.1016/J.JCLEPRO.2014.04.020.

Parviainen, T., Helenius, J., 2020. Trade imports increasingly contribute to plant nutrient inputs: case of the finnish food system 1996–2014. Sustainability 12. https://doi.org/10.3390/su12020702.

Paudel, K.P., Bhattarai, K., Gauthier, W.M., Hall, L.M., 2009. Geographic information systems (GIS) based model of dairy manure transportation and application with environmental quality consideration. Waste Manage. (Oxford) 29, 1634–1643. https://doi.org/10.1016/j.wasman.2008.11.028.

Rockström, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., Gerten, D., 2009. Future water availability for global food production: the potential of green water for increasing resilience to global change. Water Resour. Res. 45, 1–16. https://doi.org/10.1029/2007WR006767.

Röös, E., Bajželj, B., Smith, P., Patel, M., Little, D., Garnett, T., 2017. Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures. Global Environ. Change 47, 1–12. https://doi.org/10.1016/j.gloenvcha.2017.09.001.

Ryschawy, J., Martin, G., Moraine, M., Duru, M., Therond, O., 2017. Designing crop–livestock integration at different levels: toward new agroecological models? Nutr. Cycling Agroecosyst. 108, 5–20. https://doi.org/10.1007/s10705-016-9815-9.

Sandström, V., Kauppi, P.E., Scherer, L., Kastner, T., 2017. Linking country level food supply to global land and water use and biodiversity impacts: the case of Finland. Sci. Total Environ. 575, 33–40. https://doi.org/10.1016/j.scitotenv.2016.10.002.

Schoumans, O.F., Bouraoui, F., Kabbe, C., Oenema, O., van Dijk, K.C., 2015. Phosphorus management in Europe in a changing world. Ambio 44, 180–192. https://doi.org/10.1007/s13280-014-0613-9.

Schröder, J., Cordell, D., Smit, A., Rosemarin, A., 2010. Sustainable Use of Phosphorus. Report 357. Plant Research International, Wageningen. http://ec.europa.eu/environment/natres/pdf/sustainable_use_phosphorus.pdf. Accessed 16 September 2020.

Schröder, J.J., Scholefield, D., Cabral, F., Hofman, G., 2004. The effects of nutrient losses from agriculture on ground and surface water quality: the position of science in developing indicators for regulation. Environ. Sci. Policy 7, 15–23. https://doi.org/10.1016/j.envsci.2003.10.006.

Schulte, R.P.O., Creamer, R.E., Donnellan, T., Farrelly, N., Fealy, R., O'Donoghue, C., O'hUallachain, D., 2014. Functional land management: a framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. Environ. Sci. Policy 38, 45–58. https://doi.org/10.1016/j.envsci.2013.10.002.

Schulte, R.P.O., O'Sullivan, L., Vrebos, D., Bampa, F., Jones, A., Staes, J., 2019. Demands on land: mapping competing societal expectations for the functionality of agricultural soils in Europe. Environ. Sci. Policy 100, 113–125. https://doi.org/10.1016/J.ENVSCI.2019.06.011.

Seppälä, M., Paavola, T., Lehtomäki, A., Rintala, J., 2009. Biogas production from boreal herbaceous grasses - specific methane yield and methane yield per hectare. Bioresour. Technol. 100, 2952–2958. https://doi.org/10.1016/j.biortech.2009.01.044.

Seppälä, M., Pyykkönen, V., Väisänen, A., & Rintala, J., 2013. Biomethane production from maize and liquid cow manure – effect of share of maize, post-methanation potential and digestate characteristics. 107, 209–216.

Sherwood, J., 2020. The significance of biomass in a circular economy. Bioresour. Technol. 300. https://doi.org/10.1016/j.biortech.2020.122755.

Spiegal, S., Kleinman, P.J.A., Endale, D.M., Bryant, R.B., Dell, C., Goslee, S., Meinen, R.J., Flynn, K.C., Baker, J.M., Browning, D.M., Mccarty, G., Bittman, S., Carter, J., Cavigelli, M., Duncan, E., Gowda, P., Li, X., Ponce-campos, G.E., Cibin, R., … Cruces, L., 2020. Manuresheds : advancing nutrient recycling in US agriculture. 182. https://doi.org/10.1016/j.agsy.2020.102813.

Suomen hevostietokeskus, 2020. Webpage. https://www.hevostietokeskus.fi/ (Accessed 10 April 2020).

Tampio, E., Salo, T., Rintala, J., 2016. Agronomic characteristics of five different urban waste digestates. J. Environ. Manage. 169, 293–302. https://doi.org/10.1016/J.JENVMAN.2016.01.001.

USDA, 2020. Food Data Central https://fdc.nal.usda.gov/ (Accessed 10 April 2020).

Uusitalo, R., Turtola, E., Grönroos, J., Kivistö, J., Mäntylahti, V., Turtola, A., Lemola, R., Salo, T., 2007. Finnish trends in phosphorus balances and soil test phosphorus.

Agric. Food Sci. 16, 301–316. Vol.Issue. https://doi.org/10.2137/145960607784125339.

Uwizeye, A., Gerber, P.J., Schulte, R.P.O., De Boer, I.J.M., 2016. A comprehensive framework to assess the sustainability of nutrient use in global livestock supply chains. J. Clean. Prod. 129, 647–658. https://doi.org/10.1016/j.jclepro.2016.03.108.

Uwizeye, A., de Boer, I.J.M., Opio, C.I., Schulte, R.P.O., Falcucci, A., Tempio, G., Teillard, F., Casu, F., Rulli, M., Galloway, J.N., Leip, A., Erisman, J.W., Robinson, T. P., Steinfeld, H., Gerber, P.J., 2020. Nitrogen emissions along global livestock supply chains. Nat. Food 1, 437–446, 2020. https://doi.org/10.1038/s43016-020-0113-y.

Valsta, L., Kaartinen, N., Tapanainen, H., Männistö, S., & Sääksjärvi, K., 2018. Ravitsemus Suomessa - FinRavinto 2017 -tutkimus. Nutrition in Finland - The National FinDiet 2017 Survey. http://urn.fi/URN:ISBN:978-952-343-238-3%0Ahttp://www.julkari.fi/handle/10024/137433.

van der Wiel, B.Z., Weijma, J., van Middelaar, C.E., Kleinke, M., Buisman, C.J.N., Wichern, F., 2019. Restoring nutrient circularity: a review of nutrient stock and flow analyses of local agro-food-waste systems. Resour. Conserv. Recycl. 3, 100014. https://doi.org/10.1016/j.rcrx.2019.100014.

Van Kernebeek, H., Oosting, S., Van Ittersum, M., Ripoll-Bosch, R., De Boer, I., 2018. Closing the phosphorus cycle in a food system: insights from a modelling exercise. Animal 12, 1755–1765. https://doi.org/10.1017/S1751731118001039.

Van Zanten, H., Meerburg, B., Bikker, P., Herrero, M., De Boer, I., 2016. The role of livestock in a sustainable diet: a land-use perspective. Animal 10, 547–549. https://doi.org/10.1017/S1751731115002694.

Van Zanten, H.H.E., Van Ittersum, M.K., De Boer, I.J.M., 2019. The role of farm animals in a circular food system. Glob. Food Sec. 21, 18–22. https://doi.org/10.1016/J.GFS.2019.06.003.

Vilppanen, M., Toivikko, S, 2017. Yhdyskuntalietteen Käsittelyn Ja Hyödyntämisen Nykytilannekatsaus. Vesilaitos yhdistyksen moniste sarja nro 46, Suomen Vesilaitosyhdistys ry, Helsinki.

Weiland, P., 2010. Biogas production: current state and perspectives. Appl. Biochem. Biotechnol. 85, 849–860. https://doi.org/10.1007/s00253-009-2246-. Vinnerås, B., Palmquist, H., Balmér, P., & Jönsson, H., 2006. The characteristics of household wastewater and biodegradable solid waste - A proposal for new Swedish design values. Urban Water Journal. 3, 3–11. https://doi.org/10.1080/15730620600578629.

Wick, K., Heumesser, C., Schmid, E., 2012. Groundwater nitrate contamination: factors and indicators. J. Environ. Manage. 111, 178–186. https://doi.org/10.1016/J.JENVMAN.2012.06.030.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., 2019. Food in the Anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. Lancet North Am. Ed. 393, 447–492. http://dx.doi.org/10.1016/S0140-6736(18)31788-4.

Winans, K., Kendall, A., Deng, H., 2017. The history and current applications of the circular economy concept. Renewable Sustainable Energy Rev. 68, 825–833. https://doi.org/10.1016/J.RSER.2016.09.123.

Vinnerås, B., Palmquist, H., Balmér, P., Jönsson, H., 2006. The characteristics of household wastewater and biodegradable solid waste - a proposal for new Swedish design values. Urban Water J. 3, 3–11. https://doi.org/10.1080/15730620600578629.

Winquist, E., Rikkonen, P., Pyysiäinen, J., Varho, V., 2019. Is biogas an energy or a sustainability product? - Business opportunities in the Finnish biogas branch. J. Clean. Prod. 233, 1344–1354. https://doi.org/10.1016/j.jclepro.2019.06.181.

Withers, P.J.A., van Dijk, K.C., Neset, T.S.S., Nesme, T., Oenema, O., Rubæk, G.H., Schoumans, O.F., Smit, B., Pellerin, S., 2015. Stewardship to tackle global phosphorus inefficiency: the case of Europe. Ambio 44, 193–206. https://doi.org/10.1007/s13280-014-0614-8.