



Why is nutrient cycling in food systems so limited? A case study from the North-Netherlands region

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Abstract Identifying pathways to circular agriculture requires a profound understanding of nutrient flows and losses throughout the food system, and of interactions between biophysical conditions, land use, food production and food consumption. We quantified nitrogen (N) and phosphorus (P) flows of the food system of the North-Netherlands (NN) region and of its 30 subregions varying in biophysical and socio-economic conditions. The food system included agriculture, food processing, consumption, and waste processing. Nitrogen use efficiency (NUE), phosphorus use efficiency (PUE) and the nutrient cycling counts were calculated. Results show a low NUE (25%) and PUE (59%) of the food system. External inputs were used to maintain high yields and production. Nutrient cycling was very limited with losses from agriculture ranging from 143 to 465 kg N ha⁻¹ y⁻¹ and 4 to

11 kg P ha⁻¹ y⁻¹. Food system losses ranged from 181 to 480 kg N ha⁻¹ y⁻¹ and from 7 to 31 kg P ha⁻¹ y⁻¹ and varied with biophysical conditions, population density and farming systems. Large losses were associated with livestock farming and farming on drained peat soils. Food system efficiency was strongly associated with the utilization of produce. We conclude that increasing circularity requires tailoring of agriculture to local biophysical conditions and food system redesign to facilitate nutrient recycling. Steps towards circularity in NN include: matching livestock production to feed supply from residual flows and lands unsuitable for food crops, diversifying crop production to better match local demand and increasing waste recovery.

Keywords Food system · Nutrients · Local · Circular agriculture · Land use · Nutrient use efficiency

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Introduction

Today's food system has a significant impact on the planet (Crippa et al. 2021; Mueller et al. 2012; Pereira et al. 2010). Currently food systems heavily rely on external resources including energy, mined nutrients and chemicals (Kuokkanen et al. 2017). Various factors enhance this input dependency. The disconnection of food production and consumption leads to losses of nutrients in the system from urban

areas. On-farm and regional specialization in agriculture with de-coupled crop and livestock production (Garrett et al. 2020; Martin et al. 2016; Schut et al. 2021) has resulted in inefficient use of nutrients (Tan et al. 2022) with manure excess in areas of intensive livestock production (Bai et al. 2022; de Vries et al. 2021). Furthermore, the utilization of less suitable soils for intensive agriculture comes with substantial nutrient losses and greenhouse gas (GHG) emissions, the latter in particular from degradation of organic soils (Crippa et al. 2021). The theory of circular agriculture provides a guideline to resolve several of these issues and is increasingly seen as an important means for a sustainable food future.

The concept of circularity has been applied to agriculture (de Boer and van Ittersum 2018), food systems (Jurgilevich et al. 2016) and the biobased economy (Muscat et al. 2021). Muscat et al. (2021) argue that the foremost principle of circular agriculture is to safeguard the health of (agro)ecosystems by not exceeding the regenerative capacity of natural resources. In addition, they emphasize the importance of efficient resource use by avoiding non-essential products and residual flows of essential products, prioritizing biomass use for human needs, and by recycling of unavoidable residual flows. Finally, they propose that the external energy requirement of the system can be decreased by working with nature and by maximising the utility of materials and recycling (Bergen et al. 2001; Muscat et al. 2021). By following these principles of circularity, food systems could in theory transition from a linear extract-consume-discard system to a more circular one in which resource loops are closed to prevent depletion of mineral and fossil resources and reduce emissions to the air, water and soil (Muscat et al. 2021).

Circularity of resource flows in the food system requires a food systems lens to quantify and eventually optimize flows between food system components in order to minimize resource use and environmental impacts at the level of the entire food system. This goes beyond resource use efficiency of individual agricultural sectors or production chains. Circular food systems also require spatial reconfiguration of production to enhance re-coupling of nutrient flows with limited biomass transport and to stay within local environmental carrying capacities (Bai et al. 2022; Koppelmäki et al. 2021). Furthermore, production may need to be coupled to food demand on

more local or regional scales to limit nutrient imbalances between regions and to minimize energy use and GHG emissions from transportation. However, the feasibility of recoupling nutrient flows locally is strongly tied to the local biophysical production conditions which determine the suitability for and efficiency of food production. The scale at which striving for circularity in food systems is feasible is therefore determined by the biophysical context affecting the ability to produce food, but also by the processing capacity of agricultural products, food demand and the availability of consumer waste.

Several studies have quantified biomass and/or nutrient flows at farm (de Vries et al. 2018; Schröder et al. 2003), regional (Hanserud et al. 2016; Le Noë et al. 2017; Theobald et al. 2016; Vingerhoets et al. 2023), national (van Selm et al. 2022) or global (Crippa et al. 2021; Willett et al. 2019) levels with the aim of more circular resource use. However, such studies either focus on the entire food system with a subnational region as the smallest spatial unit, or on agriculture in its local context but with limited attention for the complexity of agriculture as part of the food system. Hence, it is still poorly understood how the biophysical production environment, type and productivity of production systems and local food demand interact with nutrient flows, losses and circularity of the food system.

To improve our understanding of these interrelationships, the objective of this study was twofold. First, we aimed to quantify nitrogen (N) and phosphorus (P) flows and to evaluate differences in efficiency between subsystems of the food system and between subregions within the 'North-Netherlands' (NN); and second to benchmark the circularity of the current food system and provide a deeper understanding of nutrient cycling, losses and inefficiencies in this highly specialized, food exporting region. We compared four subregions that strongly differed in soil type as a proxy for the biophysical conditions, production volumes of crop- and animal products as an indicator of specialization and population as a proxy for consumption. Three subregions had suitable sandy- and clay soils. Of these Achtkarspelen was characterized by predominantly intensive husbandry and low population density, Veendam-Pekela by arable farming and low population density and Assen by mixed farming and high population density. Subregion de Fryske Marren was characterized by predominantly

peat soils with dairy farming and a low population density. Nitrogen use efficiency (NUE) and phosphorus use efficiency (PUE) were evaluated at subsystem level and for the entire food system. A cycling count indicator (van Loon et al. 2023) was used to evaluate the degree of nutrient recycling in the current food system and to identify opportunities to enhance circular resource use. We hypothesized that subregional differences in indicators of efficiency and circularity of the food system are directly linked to the biophysical characteristics of the production environment and associated agricultural specialization and to local food demand and thus to import and export.

Method

A mass flow analysis was conducted to quantify nitrogen (N) and phosphorus (P) flows in the food system of the North Netherlands region and of constituent subregions for the years 2015–2019. Total flows and losses as well as nutrient use efficiency and the nutrient cycling count of the current food system were calculated.

Delineation of case study

Region description

The North Netherlands (NN) region covers an area of 8,292 km² land and includes the provinces of Friesland, Groningen, and Drenthe with in total 1,7 million inhabitants. The population density of 216 inhabitants km⁻² is much lower than the Dutch average of 517 inhabitants km⁻², yet is still far above the EU27 average of 118 inhabitants km⁻² (CBS 2020; EUROSTAT 2021). However, NN is relatively land abundant with 0.31 ha of cultivated land per capita, which includes cropland, grassland, and horticulture (CBS 2022a, b). This is way more than the 0.06 ha cultivated land per capita for the Netherlands and 0.22 ha cultivated land per capita for the EU27 (The World Bank 2020), highlighting the role of NN as a food producing region. About 70% of the land in NN is used for agriculture, including 45% for livestock farming and 19% for cropping (CBS 2018, 2022b). Main crops are: winter and spring wheat, barley, sugar beets and seed, ware and starch potatoes. The livestock sector consists mainly of dairy cattle with a smaller number

of pig and poultry farms (Smit et al. 2017). Horticulture takes up about 1% of total agricultural land (Smit et al. 2017). There is an ongoing trend of specialization and increasing farm size, in line with wider European trends (Schut et al. 2021; Smit et al. 2017). The NN is a strong exporting region producing for the EU and world markets (CBS 2016). The region includes a wide variety of bio-physical conditions, with different soil types and ground water levels. NN is an important region for biodiversity conservation, and supports large populations of migratory birds (Reneerkens et al. 2005) and has unique habitats for various animal and plant species (Aptroot et al. 2012; Peeters and Reemer 2003). It also borders the Wadden sea, the largest tidal flats in the world that provide a unique habitat for numerous species (Wortelboer 2010).

We divided NN into 30 constituent subregions that contrasted in predominant soil type, agricultural specialization and population density (Fig. 1). Soil type was chosen as a proxy for variations in the biophysical production environment, as it is the most important determinant of the suitability for and the nutrient efficiency of the production of different crops in the region. Agricultural specialization determines what is produced, processed and exported from a subregion. Variation in population density is directly related to consumption and the availability of recyclable consumer waste. These proxies for the biophysical environment, specialization and consumption together give insight in the potential for and possible pathways to circularity in a local or regional food system.

Definition of the food system and substance flow model

This case study focused on the food system within mainland NN. The subsystems included were: agriculture, food- and feed processing, (human) consumption and waste processing. A substance flow model was developed to analyse annual nitrogen (N) and phosphorus (P) in- and outflows of the system, including flows within and between the different subsystems (Supplementary Material; Fig. S1). The selection of flows was based on earlier studies on comparable food systems (Smit et al. 2010; van der Wiel et al. 2020, 2021) and adapted to region-specific conditions. Where possible, flows were quantified by using publicly available data from

Calculation of flows

A complete overview of all flows, their main data sources and calculation is given in the Supplementary Material (Fig. S1; Table S1). The entire calculation procedure has been made available online (DOI: <https://doi.org/10.4121/8899e893-c68a-4fe1-813e-6af228eb0ef1>). Below we provide an outline of the calculation procedure for the main components in the food system.

Agriculture

Agriculture was restricted to arable crop and livestock production, (greenhouse) horticulture was excluded. Livestock included dairy and beef cattle, pigs, poultry, and sheep. Livestock from hobby farms were excluded as these were not included in the agricultural census.

Most internal flows in the subsystem agriculture were calculated using the INITIATOR model (de Vries et al. 2023; Kros et al. 2019). INITIATOR calculates spatially explicit N, P and C fluxes in agriculture, including the supply of N, P and C in the form of fertilizer, animal manure, deposition and N fixation, the N and P discharge by the crop and the emissions of methane (CH₄), ammonia (NH₃), nitrous oxide (N₂O) and nitrogen oxides (NO_x) to the atmosphere. The model uses detailed spatial data that largely came from available national datasets, such as the geographically explicit agricultural census data, including crop type, cropping area, livestock numbers and housing type at farms. INITIATOR was used to calculate manure excretion on farm level as well as gaseous N losses from animal housing and manure storage. Manure was distributed over the fields of the farm, up to the legal application limit for animal manure per hectare. Any excess manure was initially divided over the agricultural area within each (aggregated) municipality. Any remaining excess was subsequently exported to regions of NN with a manure shortage, i.e. where more manure could be applied within the legal limit. Similarly, if the legal application limit was not reached, manure was imported from other regions of the Netherlands with excess manure. In the Netherlands, legislation enforces that excess manure needs to be exported as manure or in processed form to farmers in manure deficient areas

who get rewarded for manure application on cropland. Gaps between effective N and P applied with animal manure and the legal total effective application limits were assumed to be filled up with artificial fertilizers and compost. This is a reasonable assumption, because fertilizer inputs are cheap relative to product prices in the Netherlands and farmers utilize the entire application norm (Langeveld et al. 2007; Reijneveld et al. 2010). In addition N and P inputs from atmospheric deposition were taken into account. The INITIATOR soil module was used to calculate the amounts of nitrogen fixation and decomposition of organic matter as well as crop uptake and losses from manure storage, fertilizer application, leaching, runoff and denitrification per hectare. Loss fractions differed between soil types and groundwater levels (de Vries et al. 2023).

The crop offtake of kg N ha⁻¹ and kg P ha⁻¹ and crop area obtained from INITIATOR were multiplied to obtain production per subregion. Crops in INITIATOR output were grouped into: potatoes, sugar beet, wheat, other cereals, grass, silage maize and miscellaneous crops. We segregated the production of crop groups into individual crops by estimating for each subregion the production ratio between each crop in a group. To this aim crop areas and yields from (CBS 2022b) and crop nutrient content obtained from experimental studies in the Netherlands were multiplied to provide N and P production per crop (de Ruijter et al. 2020; Ehlert et al. 2009). The total mass of N and P in consumed feed was calculated using the average fodder and feed concentrate consumption per animal per feed group reported by (CBS 2019) and the livestock numbers from the agricultural census (CBS 2022b). It was assumed that all fodder was produced in the region. In most cases the production of fodder crops did not exactly match the calculated consumption by livestock. Such discrepancies were resolved by adjusting the grass nutrient content, as this was a major source of uncertainty. The feed concentrate requirement was filled with residual flows from the processing and waste processing industries and supplemented with feed imports if needed (see Sects. 2.2.3 and 2.2.5). Animal production was calculated by multiplying livestock numbers by production per animal and the N and P content of various animal products (CBS 2019). Nutrient balances were maintained, i.e. nutrients in feed supply exactly matched offtake with animal products and excreta.

Food processing

Food processing included processing of raw products from agriculture in each subregion and NN only. The fraction of each raw crop and animal product that was processed was derived from literature (Supplementary Material; Table S1). The remaining produce was assumed to be consumed in unprocessed form. Crop and animal products were converted into food products and residual flows using transfer coefficients (TCs). TCs were derived either directly from processing industries in the region or from Dutch sectorial sources (Supplementary Material; Table S1). The most common application of each residual flow was obtained from industry reports or directly from processing companies. Applications of processing output were grouped as: food, livestock feed, soil amendment and other flows that left the food system. In case flows had multiple applications a best-case scenario was assumed where application as livestock feed was preferred over application to soil, which in turn was preferred over applications outside the food system. Food, feed, and soil amendments that were not exported were designated as inputs to consumption and agriculture respectively (see 2.2.5). We assumed that seed potatoes and non-food cash crops (e.g. fiber hemp) were exported as whole products from the region without further processing. Losses from processing to the environment were not quantified because of data limitations.

Food consumption

Consumption included the food consumption of the human population in the region, excluding their pets and recreational animals. Food consumption was calculated from regional and municipal demographic data (CBS 2022a) and consumption per capita. Per capita consumption of products in different food groups was derived from the Dutch Food Consumption Survey (van Rossum et al. 2020). An overview of food groups is given in (van Rossum et al. 2020). One average diet was assumed for the entire population, based on the average diet of males and females between the ages of 1 and 79, weighed by the population composition of NN (van Rossum et al. 2020). The N and P contents per food item were obtained from the Dutch Food Composition Database and averaged for all products in a food group (RIVM 2021).

The amount of food waste was estimated based on the food waste survey by (CREM Waste Management 2017). Human body mass changes were ignored, and it was therefore assumed that all consumed N and P in food was excreted.

Waste processing

Waste processing included organic waste arising from the food system only, thus including food waste and human excreta but excluding garden waste. All human excreta were assumed to be treated at a typical communal wastewater treatment plant (WWTP), since 99.7% of Dutch households is connected to the communal sewer (Oosterom and Hermans 2013). N and P from human excreta were allocated to sludge, emissions to the air and to surface water (Rijkswaterstaat 2019; WSBD 2018). In the Netherlands nutrients are currently not recovered from sludge in any significant quantity and were therefore considered lost from the system (Regelink et al. 2017). Food waste went to incineration, landfilling, livestock feed, composting or anaerobic digestion in ratios derived from (Soethoudt and Vollebregt 2020). All incinerated and landfilled food waste was considered lost from the food system. Compost, digestate and livestock feed were returned to agriculture.

Retail: Food and feed import- and export

A net balance approach was used to estimate food and feed imports and exports at subregional and at NN regional level. Livestock N and P requirements were met with local roughage and co-products from processing industries and waste processing and were supplemented with feed imports. Local food demand for each food group was filled with produce from the subregion or NN region and supplemented with food imports. Consumed horticulture products were part of the food imports, as horticulture was not included in this study due to its small acreage in the region. Products that were produced but not consumed were assumed to be exported. Summed totals of import and export were used to calculate the net import/export balance over all food groups. This is an approach that determines the highest possible degree of local consumption rather than actual local consumption, used to compensate for the lack of trade data at the sub-national level. Losses from retail were ignored as

losses from supermarkets in the Netherlands are estimated at only 1.7% (CBL 2020).

Data reliability

Data uncertainty was accounted for using the approach of (van der Wiel et al. 2021). An uncertainty level was assigned to each flow based on the type of data source, as most sources did not provide uncertainty estimates. Flows were assigned the uncertainty level of the most uncertain data source used in their calculation, rather than the propagated uncertainty of all variables (van der Wiel et al. 2021). The level of aggregation of source data differed substantially between flows, meaning that uncertainty propagation would disproportionately affect flows based on less aggregated data. Each uncertainty level was associated with a relative uncertainty interval as specified by (van der Wiel et al. 2021) (Table 1). Subsequently, uncertainty ranges were calculated by multiplying each flow by their respective relative uncertainty interval. Flows in the subsystem agriculture were assigned the uncertainty level nearest to the uncertainties reported for each flow by (de Vries et al. 2003) and N losses were assigned the highest uncertainty level as the fate of N in the environment is not well documented. The uncertainty estimates of all flows can be found in the Supplementary Material (Table S1).

Analysis

All flows, balances and indicators were computed for the NN region and for each subregion. Flows were expressed in megagram per year (Mg y^{-1}) and converted to kilogramme per hectare of agricultural land per year ($\text{kg ha}^{-1} \text{y}^{-1}$), using the total area used for agriculture in a (sub)region. Checks were done to

ensure the law of mass conservation was observed. This was done for each subsystem and for the whole food system. The use efficiencies (UE) for N (NUE) and P (PUE) were determined for the whole food system and for each subsystem:

$$\text{UE} = \frac{\text{Output}}{\text{Input}}$$

For NUE and PUE output and input are the N or P flows out of and into the respective (sub)system, excluding losses. An overview of the most important inputs and outputs into the system and subsystems is given in Fig. 2. For example, inputs into subsystem livestock are feed from waste processing, feed from food processing, feed import and feed crops. Outputs of livestock are animal products and excreted manure with losses all resulting from manure storage. A complete overview of all individual flows is given in the Supplementary Material (Fig. S1). All flows with a purpose outside the food system or outside the (sub) region were considered outputs, thus including food exports, manure export (in the case of any excess) and residual flows of food processing, but excluding landfilled food waste which was considered a loss. To assess the effects of the assumption that manure is a useful export product, we also calculated UEs excluding manure export as useful output, as excess manure is of limited value compared to food exports. In this case excess manure was counted as a loss. Furthermore, we estimated the externalized losses from the production of feed imports, by dividing the amount of imported feed by the production efficiency of feed crops in NN. Depletion of N and P in the soil was counted as an input to the system and accumulation as an output.

To assess the recycling of nutrients within the food system, we determined the cycle count indicator (CyCt) for nitrogen (CyCt_N) and phosphorus (CyCt_P) (van

data used in its calculation. In case multiple data sources were used to calculate a flow, the interval associated with the least reliable data source was used

Table 1 Overview of uncertainty intervals of different information sources, by (van der Wiel et al. 2021) (edited). For each source of information an example data source is given. Each flow was assigned an uncertainty level based on the type of

Level	Uncertainty interval	Source of information	Example
1	$\pm 1\%$	Official regional statistics	Population data
2	$\pm 5\%$	Official regional statistics, primary data	Compost
3	$\pm 10\%$	Official national statistics, values from literature	Food consumption data
4	$\pm 20\%$	Educated estimate	Compost to agriculture
5	$\pm 25\%$	Mass conservation modelling	Net feed import

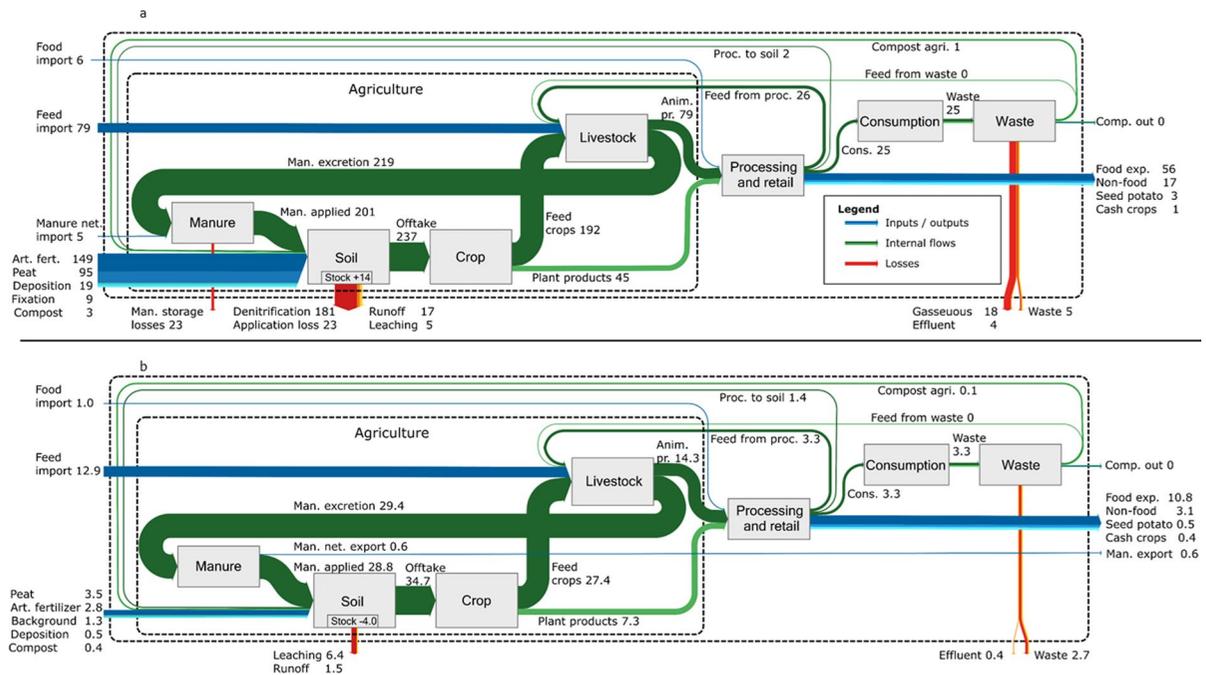


Fig. 2 Nitrogen (panel a.) and phosphorus (panel b.) flows in the North Netherlands food system expressed in kilograms per hectare of agricultural land per year (kg ha⁻¹ y⁻¹). System in- and outputs are shown in blue where inputs enter the system (and each subsystem) from the left, outputs leave from the right. Internal flows are shown in green and losses are shown

as red arrows leaving the (sub)system from the bottom. Values are averages for the period 2015–2019. Note that all (sub)system balances are 0, which may appear differently in this figure due to rounding. The unrounded numbers for each flow are given in the Supplementary Material (Fig. S2)

Loon et al. 2023). The CyCt quantifies the average number of times that inputs are cycled through the food system before being removed from the system as outputs or losses. It is defined as:

$$\text{CyCt} = (1 - A)/A$$

where A is the fraction of inputs that is removed from the food system per cycle and $(1-A)$ indicates the fraction of inputs retained in the system after each cycle.

The flows, UE and CyCt of N and P in the NN region were compared to studies on regional nutrient flows to contextualize our results and thereby provided the baseline for subregional food system flows.

Results

Nutrient flows in North Netherlands food system

In total, 99% of imported N and 96% of imported P went to agriculture and the rest was captured in

imported food (Fig. 2). The largest N inputs were artificial fertilizer (41%), mineralisation of organic peat soils (26%) and imported animal feed (22%). The largest P inputs were imported animal feed (48%), soil stock change due to lowered yearly application limits (15%), mineralisation of organic peat soils (13%) and artificial fertilizer (10%). The main system outputs were the export of food, non-food biomass from processing and the production and export of seed potatoes. About 91% of N losses and 72% of P losses were from agriculture. The NUE and PUE were respectively 0.25 and 0.59 for the food system compared to 0.36 and 0.74 for agriculture (Table 2).

Agriculture

The largest flows in the food system were associated with agriculture (Fig. 2), as NN region is a net production region. Total crop offtake was 237 kg N ha⁻¹ y⁻¹ and 35 kg P ha⁻¹ y⁻¹, of which 81% was in fodder, and 19% in food and feed crops

Table 2 Nitrogen use efficiency (NUE), phosphorus use efficiency (PUE) and Cycle count of N (CyCt_N) and P (CyCt_P) of the food system (System) and NUE and PUE of agriculture in different subregions varying in specialization, soil type and population density^a. Agri.-man indicates the NUE/PUE of

agriculture when not counting exported manure as useful output. Waste processing had an NUE of 0.05 and PUE 0.04 in all subregions, as processing parameters were assumed to be the same for all subregions. The NUE and PUE of food processing were 1, as losses were not identified

	NUE			PUE			CyCt _N	CyCt _P
	System	Agriculture	Agri.-man	System	Agriculture	Agri.-man		
Region NN	0.25	0.36	0.36	0.59	0.74	0.72	0.0069	0.0098
Achtkarspelen	0.47	0.53	0.38	0.80	0.88	0.55	0.0035	0.0034
Assen	0.19	0.51	0.51	0.20	0.74	0.74	0.0148	0.0199
De Fryske Marren	0.22	0.23	0.19	0.63	0.68	0.56	0.0013	0.0021
Veendam—Pekela	0.15	0.47	0.47	0.60	0.90	0.90	0.0198	0.0215

^a The NUE and PUE were calculated as: input/output, where input and output are the N or P flows into and out of the respective (sub)system, excluding losses. The CyCt_N and CyCt_P indicate the average number of times inputs of N or P are cycled through the food system before being removed as outputs or losses. The CyCt_N and CyCt_P were calculated as: (1-A)/A, where A indicates the fraction of N or P leaving the system after each cycle and (1-A) the fraction retained

for processing. The combined production of plant and animal products for processing and human consumption was 124 kg N ha⁻¹ y⁻¹ and 22 kg P ha⁻¹ y⁻¹. Of this, 36% of N and 34% of P were in plant products and 64% of N and 66% of P in animal products. Losses from agriculture were the largest of the food system, with the majority of N losses being lost from the soil via denitrification (72%), fertilizer application losses consisting mainly of NH₃ (9%), runoff (7%) and leaching (2%). The remaining 9% was lost from manure storage, predominantly as NH₃. P was only lost from the soil via leaching (76%) and runoff (24%). In total, 81% of harvested N and 79% of P was directly fed to livestock. Losses were largest in the subsystem soil. Hence, a large proportion of losses from agriculture can be attributed to feed production. Of all livestock feed 26% of N and 30% of P was imported from outside the region. The losses during the production of imported feed were not included in this analysis. Including such losses would increase the N and P losses associated to animal production even further.

Processing and retail

Of the total production of crop- and animal products in the region about 60% of N and P ended up in food products, 23% was returned to agriculture as feed or soil amendment and 14% ended up in products not used in the food system (Fig. 2). A substantial part of the flows leaving the food system was offal, of which

a large part is used in the production of pet feed. Smaller flows leaving the system included seed potatoes, non-food cash crops and non-food/feed products of animal origin (Supplementary Material; Fig. S2). Losses from processing could not be accounted for due to a lack of data. However, 14% of N and P going into processing ended up in non-food products, that left the food system and were essentially lost. For instance, offal from animal carcasses is processed into pet feed and is eventually excreted by pets and generally not recovered. The generation of non-food flows thus indicates an inefficiency in the use of food crops that could (partly) have been used to feed the human population.

Only 25% of N and 18% of P of locally produced food products was consumed within the region, with the rest being exported. This means that 75% of N losses and 82% of P losses from agriculture and food processing could be attributed to the production of food exports, when assuming uniform losses per kg of N and P across crops and animal products. As animal products made up a large share of exports, the percentage of losses associated with export is likely higher.

Consumption and waste

About 24% of N and 30% of P in purchased food was imported from outside the NN food system (Fig. 2). Of purchased food, 91% of N and 93% of P was consumed and ultimately disposed in wastewater. The

remaining 9% of N and 7% of P was food waste, which is in line with the 10% reported by (Yahia and Mourad (2020) for European consumers.

Nitrogen in wastewater was lost as N_2 (64%) or N_2O (1%). About 19% ended up in sewage sludge and 16% was lost to surface water. Phosphorus in wastewater went to sludge (86%) and to surface water (14%). Sludge is usually dried and burned or landfilled, and N and P in sludge was a loss from the system.

Food waste was either burned (35% of N and 40% of P) or composted (30% of N and 27% of P), digested (22% of N and 9% of P), landfilled (3% of N and 3% of P) or used as livestock feed (2% of N and 21% of P). Only compost, digestate and feed from waste were returned to the system, with the rest effectively being lost.

Subregional variation in specialization, soil type and N balances of agriculture

Within NN there is spatial heterogeneity in soil types (Fig. 3; panel a), population density (Fig. 3; panel b) and agricultural specialization, represented by the fraction of produced N in crop products (Fig. 3; panel d). Most areas dominated by sandy soils have a mixture of specialized crop and livestock farms. The eastern part of the region with sandy soils, with some oligotrophic peat residues that were left after peat excavation, is largely specialized in crop production. The fertile clay soils near the coast that were reclaimed from the sea are used by specialized crop farmers (light grey in Fig. 3; panel a), whereas the areas with heavy clay soils further inland (dark grey in Fig. 3; panel a) are dominated by dairy farmers. The south-(western) part of the region that is dominated by peat soils is largely livestock-oriented, specifically toward dairy farming. The spatially segregated specialized crop and livestock production in the northern part of the region is not distinguishable on these maps due to low spatial resolution of the available data, thus showing a ratio of crop to animal production close to 50%. Patterns of specialization largely follow patterns of soil type and groundwater levels. Urban centres are relatively small and population densities are diluted by low population density in the rest of the subregion.

The maps of NUE (Fig. 3; panel e) and losses (Fig. 3; panel f) show a similar pattern as

specialization (Fig. 3; panel c). The highest NUEs and lowest losses were found in the eastern parts, whilst NUE was lower and losses were higher in the southern part of the region. In the cropping regions higher production levels of agricultural products (excl. feed) were achieved (Fig. 3; panels c and d) with lower losses (and less inputs). Most subregions with predominantly animal production had lower NUE and higher losses per hectare. However, there were several outliers to this pattern, which are explained below. The spatial correlation between soil type and NUE and losses was less clear than that between specialization and NUE. The exception was that losses on the south-western peat soils were notably higher than in the rest of the region.

Comparing nutrient flows in contrasting subregions

The N balances of the food system of four selected subregions, contrasting in specialization, soil type and population density are shown in Fig. 4 and NUE and PUE values of their subsystems in Table 2. Additionally, an overview of N flows in the food systems of these subregions is given in the Supplementary Material (Fig. S3). These balances and flows are used to explain the patterns observed for NUE and PUE and specialization and soil type, as well as exceptions to patterns.

De Fryske Marren

De Fryske marren is located on peat soil and is strongly specialized in dairy production (Fig. 4). There was a substantial input from decomposing peat of $335 \text{ kg N ha}^{-1} \text{ y}^{-1}$. Agriculture in *De Fryske Marren* had an NUE of 0.23 and a PUE of 0.68, slightly lower than the average NUE of 0.36 and PUE of 0.74 for the NN region (Table 2). Losses from agriculture were $465 \text{ kg N ha}^{-1} \text{ y}^{-1}$, 86% higher than the regional average of $250 \text{ kg N ha}^{-1} \text{ y}^{-1}$. Production was $96 \text{ kg N ha}^{-1} \text{ y}^{-1}$, 23% lower than the regional average of $124 \text{ kg N ha}^{-1} \text{ y}^{-1}$. The excess N was mostly lost to the air via denitrification. *De Fryske Marren* also had a high feed self-sufficiency, as local feed production met 77% of demand. The losses associated with feed production were thus largely internalized. Of the N in harvested plant material, 99% was in fodder. As the largest part of consumed feed was converted into manure and not into food products, food production was low despite the large inputs and losses.

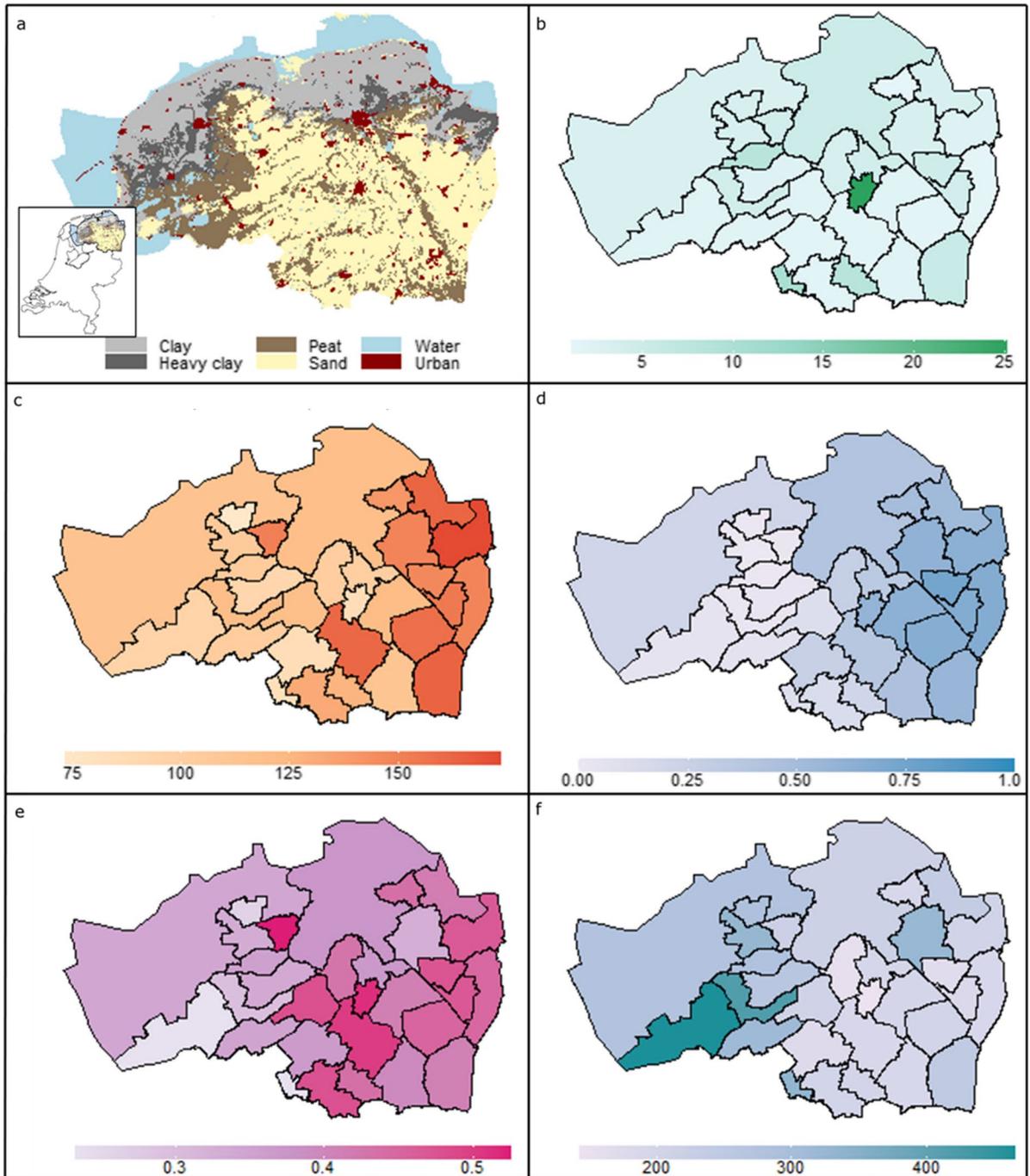
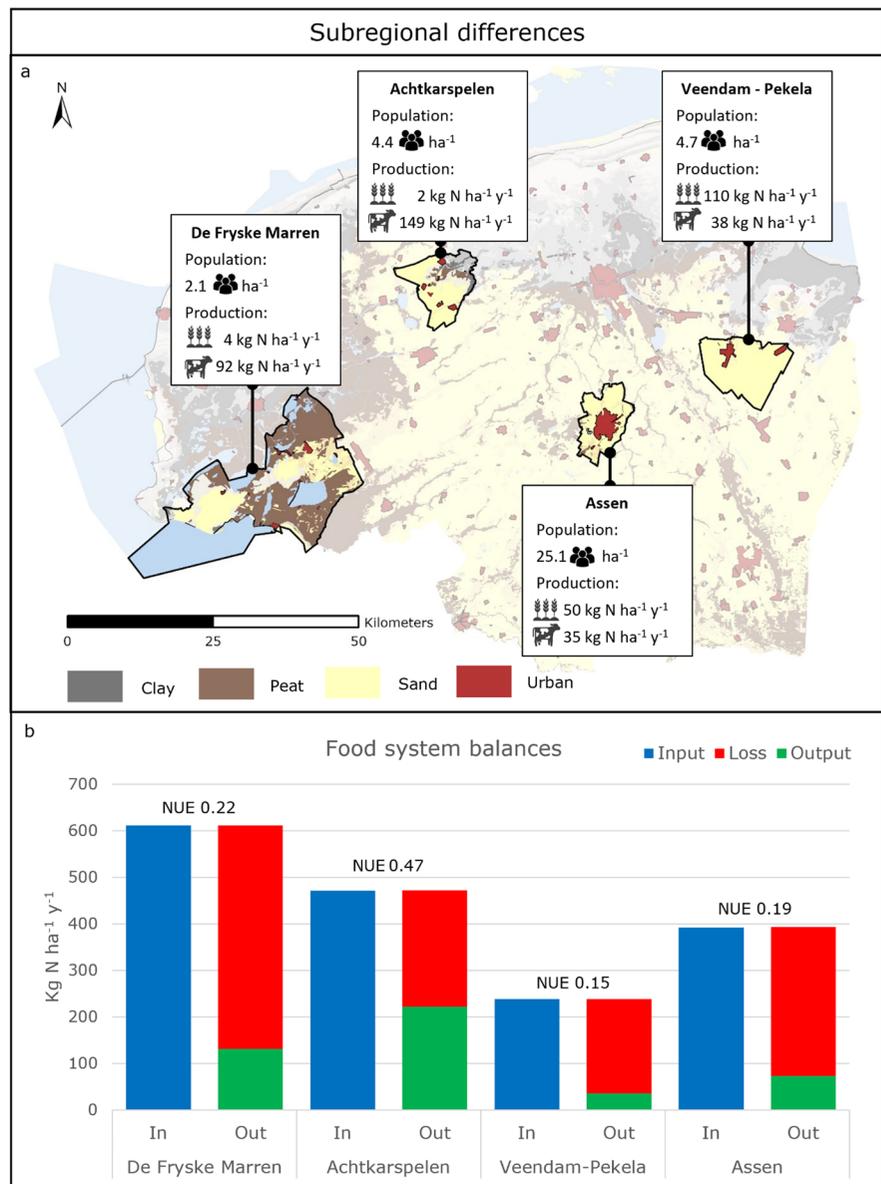


Fig. 3 Maps of soil types and urban areas (a.), population density (b.), total N yield of crop and animal products (c.), proportion of N yield in crop products (d.), nitrogen use efficiency

(NUE) of agriculture (e.) and nitrogen losses from agriculture (f.) per subregion in NN

Fig. 4 Overview of contrasting subregions in north-Netherlands (NN), varying in soil type, specialization, and population density (a.) and their respective food system N balances and nitrogen use efficiencies (NUE) (b.). Food system losses were especially large in areas of dairy farming on peat soils (*Fryske Marren*) and in more urbanized areas where losses were large from both agriculture and consumer waste (*Assen*). Intensive animal production had lower losses inside the region (*Achtkarspelen*), as losses from the production of imported feed and utilization of exported manure took place outside the region. Including such losses would drastically reduce the NUE. Arable farming was associated with higher yields per hectare and smaller losses, but as a large share of nutrients in crop products was processed into livestock feed, the food system NUE and outputs in areas dominated by arable farming were very low (*Veendam-Pekela*)



Achtkarspelen

Achtkarspelen is located on sandy soil (Fig. 4) and had the highest intensity of animal production in the region including landless poultry and pork production, yielding 149 kg N ha⁻¹ y⁻¹ in animal source food products, which was 89% higher than the regional average. The total production including crops was 151 kg N ha⁻¹ y⁻¹, which was 22% above the regional average. At the same time, the NUE of agriculture of 0.53 and PUE of 0.88 were among

the highest of all subregions (Table 2). Losses from agriculture were 219 kg N ha⁻¹ y⁻¹, which was 13% lower than the regional average.

The apparently high efficiency of animal production in this subregion resulted from the externalization of some main sources of losses, i.e. feed production and manure application. *Achtkarspelen* had the largest feed imports and manure exports per hectare of all subregions (Supplementary Material; Fig. S2). About 40% of feed was imported from outside the subregion, thus externalizing a large part of the losses

associated with growing feed crops. Also, manure export made up about a third of system output, but manure is of much lower utility than food products and its utilization causes losses elsewhere. Excluding manure export as system output reduced the NUE of this subregion from 0.53 to 0.38 and the PUE from 0.88 to 0.55 (Table 2). Also including the losses related to the production of imported feed would further reduce the efficiency (to about NUE 0.25).

Veendam-Pekela

Veendam-Pekela is situated on sandy soils with mostly arable farming of especially starch potatoes along with substantial areas of sugar beets and cereals (Fig. 4). The NUE of agriculture in *Veendam-Pekela* was 0.47 and the PUE 0.90, which was higher than the NUE of 0.36 and PUE of 0.74 for the NN region (Table 2). Losses were 169 kg N ha⁻¹ y⁻¹, 32% lower than the regional average. Production was 147 kg N ha⁻¹ y⁻¹, which was 19% higher than the regional average. About 74% of N outputs were in plant products and 26% in animal products. Starch potatoes and sugar beets are processed into starch and sugar products which mostly consist of carbohydrates, whilst most of the nutrients in the raw products end up in non-edible residual flows. Therefore only 27% of total N production ended up in food products; the other part was used for animal feed (58%), soil amendment (9%) or left the food system in non-food products (9%). Therefore, whilst the NUE and PUE of agriculture and productivity were higher than average, food export was lower than in less productive subregions as a large proportion of produce ended up in non-food flows. This resulted in an NUE of only 0.15 and PUE of 0.60 on food system level (Table 2).

Assen

With 25 persons ha⁻¹ *Assen* is the subregion with the highest population density in the NN region (Fig. 4). Consumers purchased 188 kg N ha⁻¹ y⁻¹ in food, of which 87% was imported from outside the subregion. The largest leak of the system was consumer waste processing (178 kg N ha⁻¹ y⁻¹) rather than agriculture (143 kg N ha⁻¹ y⁻¹). The NUE of agriculture was 0.51 compared to 0.05 for waste processing (Table 2). The PUE of agriculture was 0.74, compared to 0.04 for waste

processing. Therefore, subregions with higher population density generally had a lower food system NUE and PUE. However, per kg N in produced food products, 4.0 kg N ha⁻¹ y⁻¹ was lost from agriculture, while of each kg N in purchased food products 0.9 kg N ha⁻¹ y⁻¹ was lost after waste(water) processing. Thus, per kg N in food products losses from agriculture still outweighed losses from consumption. Even if all N lost through consumer waste in this urban subregion were returned to agriculture, it would not be sufficient to replace current inputs to agriculture. Agriculture in turn did not provide sufficient food to feed the local population.

Current circularity in NN and subregions

Nutrient cycling was very low in the food systems of NN and its subregions (Table 2), indicating that hardly any N inputs were recycled through the system. All calculated CyCt values were <0.03, indicating that the vast bulk of N and P inputs did not complete a full cycle through the food system. This resulted from very little re-use of nutrients after consumption and large losses and exports from the system. Subregions with a high production to consumption ratio scored worse on the circularity indicator. Nutrients in exported food were lost from the region and not returned as recycled system inputs and therefore reduced the cycling count.

Discussion

Nutrient flows and efficiencies varied strongly between subsystems and subregions. At system level NUE varied most strongly with agricultural specialization and soil type, whilst PUE varied most strongly with population density. The cycling count was very low for both N and P in all subregions, indicating that the current system heavily depends on external inputs with large losses from the system.

Nutrient dynamics of the food system and its subsystems

Food system performance in this export oriented region was mainly determined by the performance of the subsystem agriculture. The very limited recovery from consumer waste had an insignificant impact on the NN region as these flows were relatively small

(Geertjes et al. 2016; Soethoudt and Timmermans 2013). The NUE of the current food system in the NN region was 0.25, which equals the NUE for the Netherlands (Erismann et al. 2018) and is higher than the reported NUE value (0.18) for Europe (Leip et al. 2022). The relatively high PUE of 0.59 was mostly due to small P surpluses in agriculture when compared to other regions (Einarsson et al. 2020) and partly due to the legacy of historically applied P (Sattari et al. 2012).

The low NUE (0.36) of the agriculture subsystem mainly resulted from the low N conversion efficiency of livestock, the cultivation of feed crops and mineralisation of peat soils. This NUE was lower than the 0.43 reported by CBS for agriculture in the Netherlands (CBS 2022c). The lower NUE found here was mainly the result of counting the additional inputs provided by peat soil, which are usually omitted. In peatlands large nutrient surpluses were found. Strongly reducing application limits for peatlands would improve NUE, reduce N₂O emission and limit P saturation of peatlands without production loss.

The cycle count (CyCt) of the NN food system was only 0.0069 for N and 0.0091 for P. These figures were lower than the CyCt of 0.02 found by van Loon et al. (2023) for the highly linear food system in the Flanders region (Belgium). The lower values for NN can be explained by larger inputs and larger losses per hectare in NN and especially by a larger share of products leaving the region in exports. Of all inputs into the subsystem agriculture only 7% of N was recycled from the NN food system. A similarly strong dependency on nutrient imports has also been reported in other regions with intensive agriculture (Chowdhury et al. 2018; Le Noë et al. 2018; Papangelou and Mathijs 2021). Increasing the CyCt and reducing the dependency on nutrient imports can be achieved by reducing exports and reducing losses, as the CyCt counts the proportion that remains in the system but does not distinguish between losses and useful flows that leave the system.

Differences in nutrient flows between subregions

Variation with soil type: large losses from organic soils

Nutrient flows and losses varied substantially with soil type. Losses from peat soils were higher than

from clay and sandy soils and consequently, UE and CyCt were low in subregions with mainly peat soils (Fig. 3; panels a. and f.). Groundwater tables in areas of peat soils in NL are typically lowered to facilitate intensive agriculture. The resulting aerobic conditions strongly enhance the mineralisation rate of organic matter stored in peat soils, estimated here at 335 kg N ha⁻¹ y⁻¹ and 38 kg P ha⁻¹ y⁻¹ for a subregion dominated by peat soils. Similar rates were found for one test site in the Netherlands (Pijlman et al. 2020), though most estimates for the Netherlands are somewhat lower, i.e. ca. 250 kg ha⁻¹ y⁻¹ (Pijlman et al. 2020; Vellinga and André 1999). Peat soils also receive substantial inputs of N and P from applications of animal manures and artificial fertilizers, resulting in a comparatively large surplus of 465 kg N ha⁻¹ y⁻¹ and 11 kg P ha⁻¹ y⁻¹. Most of the N surplus is eventually lost through denitrification with a substantial amount of N₂O (Velthof et al. 2009). The oxidation of peat soils is also one of the largest sources of GHGs from agriculture worldwide (Leifeld and Menichetti 2018; Lin et al. 2022; Tiemeyer et al. 2016). Peat soils in the Netherlands are frequently P saturated (Schoumans and Chardon 2015), which increases the potential risk of P leaching to water bodies (Lin et al. 2022; Schrier-Uijl et al. 2014). The large differences in NUE and PUE between soil types suggest that prioritizing the use of most suitable soils for agriculture will substantially increase efficiency and reduce losses from agriculture (Muscat et al. 2021; Netherlands Scientific Council for Government Policy 1992).

Nutrient use efficiency of agriculture is strongly associated with specialization

Spatial patterns of NUE, PUE and losses from agriculture largely matched patterns of specialization. In subregions more specialized in crop production the inputs were generally lower, but N and P yields were higher. Losses from animal production were substantial and resulted from losses in the field for feed crop production, manure storage and manure application. The efficiency of e.g., dairy fed mostly with local roughage was low (NUE 0.23). The N and P efficiency of intensive animal husbandry systems fed on imported feeds was much higher, i.e., up to NUEs of 0.53 and PUEs of 0.88. In this case losses during the production of imported feed and application of

exported manure took place outside the subregion's borders and are externalised. Externalizing losses may give a false sense of efficiency of the production systems in question (Quemada et al. 2020; Schröder et al. 2011). When accounting for the external losses that result from manure application elsewhere, the NUE of 0.25 of these subregions was similar to that of subregions with more local feed production, congruent with an NUE of 23% for pig farms (Quemada et al. 2020).

The apparently high NUE and PUE of agriculture in subregions specialised in crop production do not account for the larger losses at food system level. For example *Veendam-Pekela* mainly produces food crops for the processing industry, predominantly starch potato and sugar beet. During processing most nutrients in these crops end up in residual flows that are used as feed and for non-food purposes. Yet, animal food derived from these food crops comes with a substantially larger loss per kg food than food crops: only around 27% of N and 33% of P of nutrients in feed crops is converted into edible food. The rest of the N and P is recycled via manure with associated losses elsewhere. Hence, at system level the UE is much lower. Sectors should therefore be evaluated in a food system context to account for such externalized losses (van Loon et al. 2023).

Low efficiency and large losses from urban areas

Population density was negatively associated with UE and CyCt of the food system, as the UE of waste treatment was lower than that of agriculture and processing. For PUE this effect was stronger than for NUE, as relatively little P was lost from agriculture (PUE 0.74) whilst from waste processing most P was lost (PUE 0.04). The NUE for the subsystem waste processing was 0.05, still much lower than the NUE of 0.36 of the subsystem agriculture. Subregion *Assen* was the only subregion with a net-consumption, i.e., more food was consumed than produced. In this subregion, only 13% of the N that was consumed came from local products. This means recycling of N from consumer waste into agriculture also adds some external N to the farming system. However, about 49% of N going into agriculture is lost in agriculture and another part ends up as non-food product flows after processing. This means that even in a region with net food import, recycling consumer waste can only replace a very limited part

of agricultural N inputs. Recycling P from waste processing to agriculture strongly reduces losses in the system, as the main P losses were from consumer waste whilst P losses from the agriculture subsystem were relatively small. Recycling the nutrients from waste flows requires the adoption of technologies for resource recovery into the waste management system, that until now has been geared toward pollution prevention rather than resource recovery (Coppens et al. 2016; Verger et al. 2018).

Towards circularity in NN

Improving circularity in NN

The circularity of food systems can be improved by avoiding non-essential products and residual flows of essential products, prioritizing biomass use for human consumption, repurposing residual flows and minimizing energy use (Muscat et al. 2021). Applying these principles to the food system of NN could provide benefits to the environment (IFA 2022; Struik and Kuyper 2017) and human health (van Selm et al. 2021), but may also have other consequences. First, nutrient inputs would need to be reduced and internal cycling enhanced by limiting the currently large losses and by re-using residual flows. This could increase the currently low NUE (0.25) and PUE (0.59) of the food system. Reducing losses requires more efficient farming methods and technologies to recover unavoidable urban waste. Food exports should be limited, to maintain a neutral regional nutrient balance. Where possible, nutrients must also be recovered from non-food flows with applications outside the food system such as pet feed or biobased building materials. Second, limiting feed imports would mean that a higher share of the feed that is used in the region must be produced locally, preferably from land unsuitable for food crops and from residual flows from the food system. In NN heavy clay soils that are currently used as grasslands may be unsuited for cropping. Peat soils are not suitable for circular intensive agriculture, including feed production, as oxidation and associated N emissions from peat soils can only be restricted by restoring and maintaining high groundwater tables (Lin et al. 2022; Schrier-Uijl et al. 2014). Safeguarding peat

soils would therefore limit their agricultural use to systems suited to wet conditions (Lin et al. 2022; Offermanns et al. 2023; Schoumans and Char-don 2015). The possible production of additional feed from available recyclable flows that are not yet used is very limited when compared to current feed imports. Therefore, adhering to the principles of circularity would strongly reduce current live-stock production in NN. Third, to meet most of the food demand with food produced in NN requires that rotations are diversified and include more crop types, consequently diversifying current narrow crop rotations. Diversification of crop rotations has additional benefits, including reduced nutrient leaching (Nemecek et al. 2015), increased resilience to biotic and abiotic stress (Degani et al. 2019) and increased productivity (Mudgal et al. 2010). Lastly, a more local food production may lower energy use by reducing the need for transportation. However, there are trade-offs: local production may be less efficient and lead to larger losses (Schulte-Uebbing and De Vries 2021), more energy use and higher GHG emissions in agriculture when more land is needed for cultivation. In subregions with sandy and suitable clay soils for cropping it may be possible to provide a full diet locally, yet in subregions dominated by peat and heavy clay soils only few crops can be grown. In subregions with plenty suitable land but low population density, the exploitation of good soils would be limited by the availability of residual flows as circular inputs. Therefore, closing nutrient loops in NN on the subregional level is probably not feasible.

Consequences of circularity in NN

A more circular food system will have economic consequences for a strongly export-oriented region like NN. Required changes will affect exports (and associated inflow of foreign currency) and the income of farmers, but will at the same time reduce environmental costs that are currently not accounted for. Reducing food export to improve circularity in NN would affect food importing regions, including the nearby Randstad metropolitan area (with larger cities including Amsterdam) with insufficient suitable land. Reduced food production in exporting regions might affect food availability in food importing regions in

the short term (Mayer et al. 2015; van Berkum 2021) when this cannot be compensated elsewhere. However, it can also be argued that maintaining the current system compromises global food security due to the strong food-feed competition of current intensive animal production systems (Mottet et al. 2017; Muscat et al. 2021). Increasing food security with limited environmental impact and reduced land requirements per person requires a shift towards more plant-based diets (Leip et al. 2022). Regardless of dietary composition, some regions may not have the capacity to produce enough food to fulfil local demand in a sustainable way (Schulte-Uebbing and De Vries 2021). For example, there is not much suitable soil for food crops in the Randstad area, located in a region with mostly peat soils unsuitable for most crops. In other areas, crop production may be less efficient than in NN. Shifting production to such an area is likely to lead to large losses with large impacts in those regions, and consequently increase resource use and GHG emissions at national or global level (Leifeld and Menichetti 2018; Tiemeyer et al. 2016). Hence a strict application principles of circularity may thus be detrimental for efficiency at larger scales. A circular food system at the appropriate scale increases the options to produce food where it can be done most efficiently (Billen et al. 2018), where the optimum scale is determined by trade-offs between the efficiency of production and use of recycled biomass flows including associated transport requirements. These environmental and socio-economic trade-offs of circularity on various scales and with varying land use intensities are still poorly understood (Koppelmäki et al. 2021; Muscat et al. 2020). Our study shows that integrating knowledge of the local context and the food system will be key for proper planning of circular systems with limited losses at larger geographical scales, such as the Netherlands including the Randstad metropolitan area.

Quantification of nutrient flows as a prerequisite for circular agriculture

The first step towards circularity is a clear understanding of nutrient flows in the current food system, by using the best available data. Yet, we acknowledge data limitations encountered for the NN region. Nutrient flows are currently poorly monitored, at both the farm and regional scales. Nutrient emissions

from food processing and waste processing facilities were not readily available. Some of the most important flows in the food system, such as livestock feed composition and origin of ingredients, are currently unavailable (Koppelmäki et al. 2021; van der Wiel et al. 2021). We recommend open access of existing data sources and for regular sampling of nutrient contents of farm inputs and produce and of all processing flows including waste. This would also provide key insights in crop nutrient offtakes and hence direct options to improve soil nutrient management and reduce losses in the agricultural system in a local context (Silva et al. 2021; Sylvester-Bradley et al. 2022).

Conclusion

Large differences in flows and efficiencies between subregions with different soil types, specialization, and population density were found. In food system studies not accounting for the local context, such differences are masked. We also found that the efficiency of subsystems in the food system and specialized subregions within the region differ strongly. Food system efficiency strongly depends on how flows are utilized in the system. If flows are not utilized efficiently, food system efficiency will be very low, even though the efficiency of individual subsystems may be high. Hence, to improve efficiency and circularity, a food system lens is required to better tailor the agricultural system to local biophysical conditions and regional food demand. Follow-up research will be needed to address the question what a circular food system would look like in practice, or at what scale such systems should operate.

In the current NN food system the NUE and PUE were low and nutrient recycling was extremely limited with a cycling count close to zero. The system depends heavily on feed and fertilizer imports. A large proportion of the losses can be attributed to production for export. There is little scope to improve nutrient cycling by utilizing unused residues as these residual flows are small compared to the losses from the system. We conclude that reducing losses would therefore require substantial changes to the current food system, especially to the subsystem agriculture. Important steps towards circularity in production-oriented regions such as NN include: matching livestock production with the potential feed supply from

residual flows and lands unsuitable for food crops, diversification of crop production to better match local demand and the adoption of technologies to facilitate recovery of nutrients from (consumer) waste. In more urbanized regions where consumption exceeds production, dietary change and the adoption of technologies for nutrient recovery from waste will be most important.

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Declarations

Competing interests The authors declare no competing interests.

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