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Restoring nutrient circularity in a nutrient-saturated area in Germany requires systemic change

Bernou Zoë van der Wiel (ID) · **Jan Weijma · Corina Everarda van Middelaar ·**
Matthias Kleinke · Cees Jan Nico Buisman · Florian Wichern

Abstract Regions with intensive agriculture often encounter environmental problems caused by nutrient excess of agro-food-waste systems that have become increasingly linear over previous decades. In this study, nitrogen (N), phosphorus (P), potassium (K) and carbon (C) flows in the whole agro-food-waste system of district Cleves in Germany were quantified simultaneously using substance flow analysis. Moreover, nutrient use inefficiency hotspots were identified to establish options to improve nutrient self-sufficiency as a first step towards nutrient circularity.

B. Z. van der Wiel (✉) · M. Kleinke · F. Wichern (✉)
Soil Science and Plant Nutrition, Institute of Biogenic Resources in Sustainable Food Systems-From Farm to Function, Rhine-Waal University of Applied Sciences, Marie-Curie-Str. 1, 47533 Kleve, Germany
e-mail: bernouzoe.vanderwiel@hochschule-rhein-waal.de

F. Wichern
e-mail: florian.wichern@hochschule-rhein-waal.de

B. Z. van der Wiel · J. Weijma · C. J. N. Buisman
Department of Environmental Technology, Wageningen University & Research, P.O. Box 17, 6700 AA Wageningen, The Netherlands

C. E. van Middelaar
Animal Production Systems Group, Wageningen University & Research, P.O. Box 338, 6700 AH Wageningen, The Netherlands

Data on mass flows and nutrient contents was acquired for the year 2016 from stakeholders, statistical databases, literature and modelling. Organic C was included for flows with potential as organic fertilizer. Results show that animal production drives the nutrient flows in the export-oriented district, with feed import, manure application and losses from housing and manure storage accounting for 40, 45 and 60% of all N, P and K flows, respectively. In particular agriculture is responsible for N losses, with 150 kg N lost ha^{-1} agricultural land. Crop production surplus and with that soil accumulation of P and K are 515 t and 4100 t respectively. Stoichiometry of N:P:K:C in the different organic materials does not allow direct application and meeting crop requirements without exceeding demand of especially P. Processing of biomass is therefore required. Based on mass, especially manure holds potential for processing into bio-based fertilizers. To improve nutrient cycling and soil C conservation, being an important element for a sustainable agricultural sector, local balances between crop and animal production need to be considered.

Keywords Agro-food-waste system · Circularity · Substance flow analysis (SFA) · Local · Nutrients · Carbon

Introduction

Currently, food production in Europe and other areas of intensive agriculture depends heavily on external inputs of inorganic nitrogen (N), phosphorus (P) and also potassium (K) fertilizers (Bellarby et al. 2018; Kuokkanen et al. 2017). Furthermore, due to specialization of agriculture, spatial separation of production and consumption of feed crops, and globalization of agricultural trade beginning towards the end of the nineteenth century, local nutrient cycles between animal and crop production became decoupled (Le Noë et al. 2018; Theobald et al. 2016). Despite the abundant availability of N_2 in the atmosphere, it is not bioavailable for most crops and needs to be transformed into reactive N forms. The synthesis of N fertilizer from N_2, however, is energy intensive, requiring high inputs of fossil fuel (Maurer et al. 2002). P, on the other hand, is a finite resource and phosphate rock reserves are mainly concentrated in a small number of countries (Cordell and White 2015). In combination with the rising value due to high demand from a growing global human population, this may cause geopolitical tension (Cordell and White 2015). Furthermore, some areas in the world are dependent on diminishing reserves of K (Bellarby et al. 2018; Santos et al. 2017; Sipert et al. 2020) and in light of climatic extremes, K´s role in plant and soil functions, such as for the soil's water holding capacity and plant drought stress alleviation, might become more important. Other regions of the world have insufficient access to inorganic fertilizers, which limits production of crops and impairs food security (Van Ittersum et al. 2016).

In current agro-food-waste systems nutrient losses occur throughout the chain, from losses due to overfertilization, to losses of nutrients through discharge of sewage effluent (Treadwell et al. 2018; Wendland et al. 2020). In Germany over the last years on average 227 kg N ha^{-1} were applied in primary production, with an annual crop removal of 149 kg N ha^{-1} this resulted in an average budget surplus of 77 kg N ha^{-1} (Häußermann et al. 2020). Some of this excess N is lost and causes multiple environmental issues such as eutrophication of terrestrial and aquatic ecosystems, which in turn can lead to a loss of biodiversity (De Vries et al. 2013; Van Grinsven et al. 2010). Above mentioned issues show the need to improve nutrient cycling, to become less dependent on fossil resources and to contribute to reduced emissions. Excess application of one plant nutrient, for example, can result in imbalanced nutrient availability, reducing the nutrient use efficiency because of a defined stoichiometric essential nutrient demand of plants, with the lowest nutrient defining the production level, leaving nutrients applied in excess unused. However, as crops vary in their nutrient demand for the essential macro nutrients N, P and K, the elemental stoichiometry of fertilizers varies. Consequently, local nutrient recycling requires to link the N:P:K stoichiometry in biomasses that are locally available as nutrient sources with the demand of crops based on their stoichiometry. As a first step towards improvement, therefore, N, P and K flows and demands need to be assessed simultaneously.

Besides the essential plant macronutrients N, P and K, also organic carbon (C) is vital for crop cultivation, as it contributes to formation of soil organic matter (SOM) (Kallenbach et al. 2016). SOM plays a crucial role in maintaining key soil functions that serve soil fertility, as it enhances water holding capacity, water infiltration, nutrient retention and nutrient provision to plants roots (Lal 2004; Paul 2016). However, intensive agricultural activities, in particular frequent soil disturbance like tillage, increases the conversion of SOM by soil microorganisms to carbon dioxide (CO_2) (Kallenbach et al. 2016; Miltner et al. 2012; Steinmann et al. 2016). Increased organic matter input and reduced soil disturbance along with optimal nutrient availability for plants and soil facilitates sequestration of C in the soil after uptake by plants. In contrast, an unbalanced nutrient stoichiometry, e.g. from excess N application, results in less efficient organic C use by plants as well as larger organic C losses caused by lower microbial C use efficiency (Joergensen and Wichern 2018; Verger et al. 2018). This paper includes C as it is present in waste streams (e.g. manure) and relevant for both plant growth as well as SOM formation and thus crucial in climate change mitigation and adaptation. In addition to quantifying the specific ratios of N, P and K in biomass, and the crop specific demand for these nutrients simultaneously, organic C needs to be included for the relevant biomasses to avoid disregarding organic matter provision when processing biomass into bio-based fertilizers and assessing the full potential of recycling biomasses (Moinard et al. 2021).

An indispensable first step to improve nutrient cycling in a geographic area is to assess the current nutrient flows on system level (Chowdhury et al. 2014; Mehta et al. 2016; van der Wiel et al. 2020). Substance Flow Analyses (SFA) quantify the stocks and flows of substances of choice throughout a system predefined in space and time. It can thereby identify hotspots of inefficient nutrient use where interventions may have a high impact (Brunner and Rechberger 2016). SFA´s for the nutrients N, P and K have been conducted on various scales from global (Van Vuuren et al. 2010) to field level (Bučiene et al. 2003). A wide geographic scale, such as for a country, fails to capture local nuances of nutrient surplus within a study area and therefore the potential for optimizing redistribution locally (Klinglmair et al. 2015; Senthilkumar et al. 2012). A narrow scale, like the farm or field scale, does not include all supply and demand as not all subsystems which are part of the agro-food-waste system are included. When striving for closing nutrient cycles a local scale, to keep transport of biomass to a minimum, is therefore vital to capture local circumstances and thereafter adjust nutrient management accordingly (van der Wiel et al. 2020). Various SFA studies on local scales of areas with differing levels of nutrient surplus, have been performed (Chowdhury et al. 2018; Coppens et al. 2016; Theobald et al. 2016). However, currently no study captures the flows of the main macronutrients for crop growth or considers the stoichiometric balance between N, P, K and C while simultaneously covering the whole agro-food-waste system (van der Wiel et al. 2020).

The objective of the present study was to quantify the N, P and K flows throughout the agro-food-waste system of a nutrient-saturated area. This paper hypothesized that a nutrient-saturated area requires systemic change to restore nutrient circularity and identifies options to improve the nutrient self-sufficiency of the system as a first step towards nutrient circularity within the district. Nutrient self-sufficiency, the extent to which a system provides its own input, contributes to circularity as it reduces resource import and nutrient losses, in particular in nutrient surplus areas (Jurgilevich et al. 2016). For flows of biomass potentially available as fertilizers or soil amendments, the analysis was extended to include C, which is relevant for SOM maintenance.

Materials and methods

Description of study area

The district Cleves in the German state of North Rhine-Westphalia is characterized by intensive agriculture with high nutrient inputs and lies close to several urban centres. These characteristics and the location, bordering other areas with intensive agriculture and high nutrient input, makes it a suitable model area for this study. District Cleves (German: Kreis Kleve) covers 1233 km^2 based on the administrative border, and is located in the Lower Rhine region of the federal state North Rhine-Westphalia (NRW), Germany. In the west and north, Cleves is neighbouring the Netherlands and in the east and south it is bordered by three other German districts. With an average annual population growth since 2007 of 156 inhabitants (0.5%), the population of the district was 310,329 in the investigation year 2016. The total farmland area in the same year covered 708 km^2. This corresponds to 57% of the total area in the district, placing it amongst the one-third most rural districts in the state (NRW, 2018; Regionalstatistik, 2021). Of the farmland 49,585 ha was arable land and 21,254 ha was grassland in 2016 (NRW 2018). In the reference year (2016) 5% of the working population was employed in agriculture.

Cleves is, as are the surrounding districts, largely rural. It contains small ($\leq$ 29,999 inhabitants) urban centres and is in the vicinity (circa 100 km) of several larger urban areas ($\geq$ 100,000 inhabitants), such as the Ruhr region, the Rhineland (Aachen, Cologne, Düsseldorf), and the Arnhem/Nijmegen and Randstad regions in the Netherlands. The district is characterized by intensive animal production (in particular cattle (101,713 large livestock units (LLU)), pigs (41,141 LLU) and poultry (6,681 LLU)) and production of cash crops (i.e. potatoes, sugar beet, cereals and corn), vegetables and ornamentals (NRW 2018). These activities are associated with large inputs of feed and fertilizer into the animal and crop production subsystems. Livestock density (expressed in large livestock units (LLU)) per ha agricultural area is 2.2, well above the average animal density in NRW of 1.6 (NRW 2018). As a result of prolonged surplus N fertilization, some groundwater bodies in the Cleves district exceed the threshold of 50 mg nitrate litre^{-1} as

set in the European Water Framework Directive 2000/60/EC (Wendland et al. 2020).

Moreover, the vicinity to the Netherlands makes Cleves an export destination for organic fertilizers (e.g. mushroom substrate and manure) from that country. Cleves´ nutrient flows are therefore strongly related to those of the Netherlands, as in 2014 it supplied 58% of the imported organic fertilizers, while the rest came from other districts in NRW and from one other federal state (Lower Saxony) (NRW, 2014).

The district of Cleves harbours several food and feed processing industries (e.g. ForFarmers (feed processing), Katjes (candy manufacturing), Pfeiffer & Langen (sugar production), etc.). These processing industries utilize raw materials from outside the district and locally produced vegetal and animal products. Besides part of their products, also nutrient rich by-products generated during processing remain in the region which add to the nutrient flows in the district.

Substance flow analysis model description

A SFA model was developed for the flows of N, P, K and C in the agro-food-waste system of the Cleves district, based on the conceptual design by van der Wiel et al. (2020) using STAN 2.6 modelling software (Cencic and Rechberger 2008). The geographic boundary was defined by the administrative border. For the quantification of flows the year 2016 was chosen as reference, as it was the most recent year with the highest data availability. In the model, the agro-food-waste system was divided into 5 subsystems: (1) crop production, (2) animal production, (3) food and feed processing industry, (4) consumption and (5) waste management (Fig. 1). A detailed description of each subsystem can be found in Supplementary Material A.

Computation of nutrient flows

The flows of nutrients imported into the region, the nutrient flows between the subsystems in the district, and the flows of nutrients exported out of the district were identified through stakeholder and literature consultation. To compute the nutrient flows, firstly information on the biomass flows was acquired, thereafter the nutrient concentrations of the biomasses was compiled (Brunner and Rechberger 2016). In

some cases, especially for the flows related to agriculture, the flows were directly acquired as nutrient flows. Face-to-face interviews and e-mail correspondences were undertaken initially to consult different stakeholders and experts within the system. Data was thereafter acquired from statistical databases freely accessible at statistical websites (e.g. Destatis), personal consultation, literature and modelling. For flows where no data was available for 2016, data from the next previous or following year was used and extrapolated to 2016. For the crop production subsystem also the nutrient stock change (e.g. accumulation in soil) over the reference year was quantified (see below). For the other subsystems it was assumed that no stock changes occurred (Figs. 1, 2 and 3).

For the computation of nutrient flows the following first equation was applied:

$$\text{Nutrient flow } (\text{kg}_{\text{NPKC}}/\text{year})$$
$$= \text{mass of biomass flow } (\text{kg}_{\text{biomass}}/\text{year})$$
$$\quad * \text{ nutrient concentration of the biomass}$$
$$(\text{kg}_{\text{NPKC}}/\text{kg}_{\text{biomass}})$$

Biomass flows were expressed in metric ton (t) fresh mass or in t dry matter, based on data availability. The corresponding nutrient content was selected accordingly. Where no corresponding nutrient content was available, the mass flow was converted based on the dry matter content of the biomass.

The N losses occurring during the cultivation of crops through nitrate (NO_3^-) leaching and ammonia (NH_3), nitrous oxide (N_2O) and dinitrogen (N_2) gaseous emissions, were lumped and modelled by assuming the principle of mass conservation (all inputs—all outputs). The inputs covered inorganic fertilizers and different organic fertilizers, and the output were harvested crops. This principle was used as N does not accumulate in soils in the district (Steinmann et al. 2016). In contrast to N, for P and K losses and soil accumulation were assumed based on literature (Kayser et al., 2012; Schoumans 2015). These losses are assumed as the local intensive agricultural activities over time, after soil P and K accumulation and saturation, can lead to leaching to groundwater (Eder 2001; Fischer et al. 2017; Kayser and Isselstein 2005).

To compute P and K soil stock changes in case of crop production, this second equation was applied:
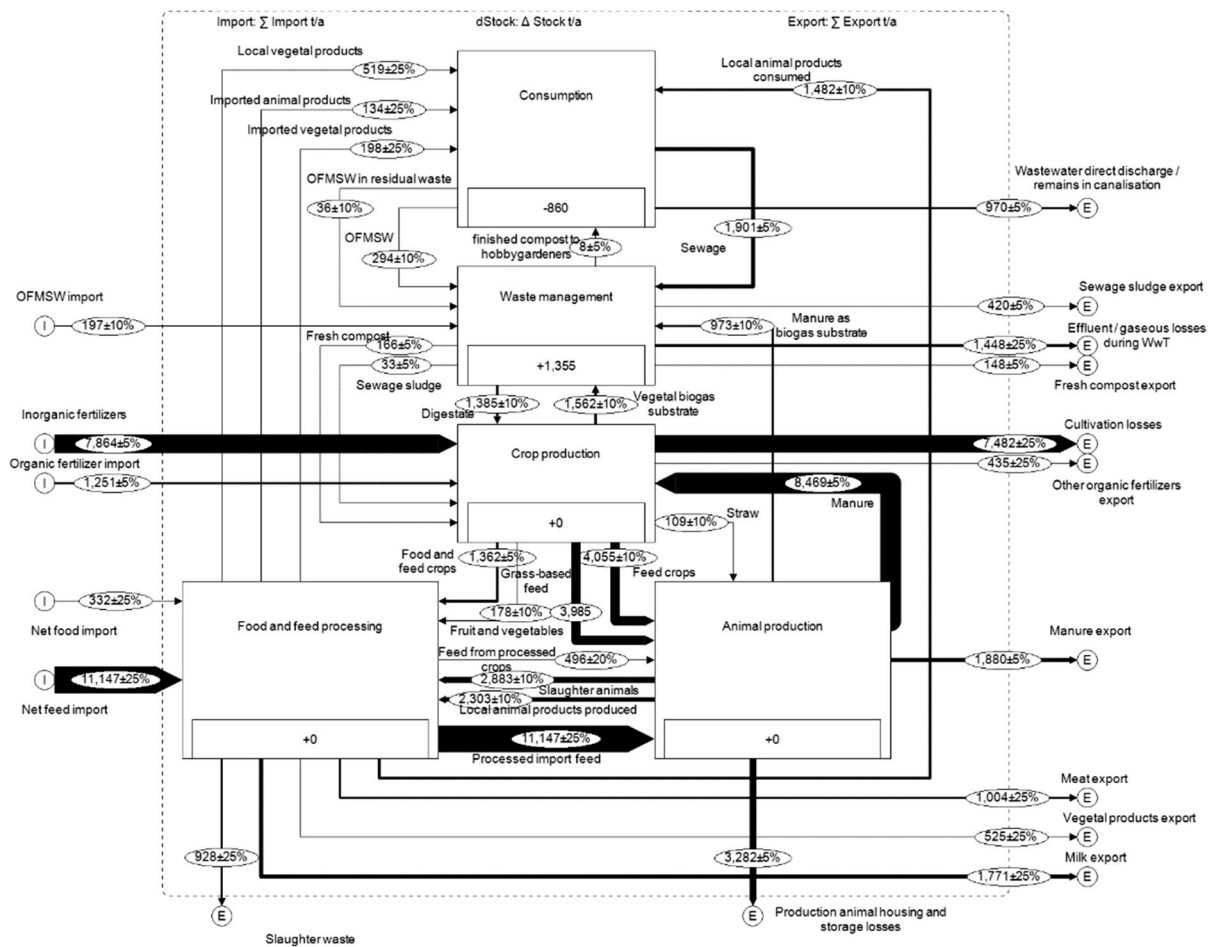
Fig. 1 Nitrogen SFA with flows in ton year^{-1}. I = import E = export. WwT = wastewater treatment

Total inputs − total outputs

- − leaching rate ha^{-1}agricultural land
- ∗ agricultural land = annual stock change

(all in kg$_{NPKC}$/ year)

When no data for a flow was available, neither through expert consultation, databases, nor from literature, the flow was computed based on the principle of mass conservation (Brunner and Rechberger 2016).

A range of flows such as minor animal products (e.g. wool) and crop seeds were regarded as negligible based on literature and were therefore excluded (Häußermann et al. 2020; Wironen et al. 2018). Moreover, atmospheric deposition of N, P and K was excluded due to the difficulty in attaining district specific data as it spatially varies depending on local management practices (Wendland et al. 2020). However, atmospheric N deposition in Germany, which was on average 14 kg N ha^{-1} a^{-1} (Häußermann et al. 2020) but in the state North Rhine-Westphalia as high as 30 kg N ha^{-1} a^{-1} (Wendland et al. 2020), needs to be considered when assessing means of reducing N loads to ecosystems. Data acquisition from the private sector (food—and feed processing industry) was severely restricted due to confidentiality issues, in agreement with findings of other SFA analyses (Theobald et al. 2016).

Main aspects of the data acquisition for the different subsystems and the complete methodology underlying the computation of each flow including the data sources, assumptions made and references supporting these assumptions are presented in Supplementary Material B.
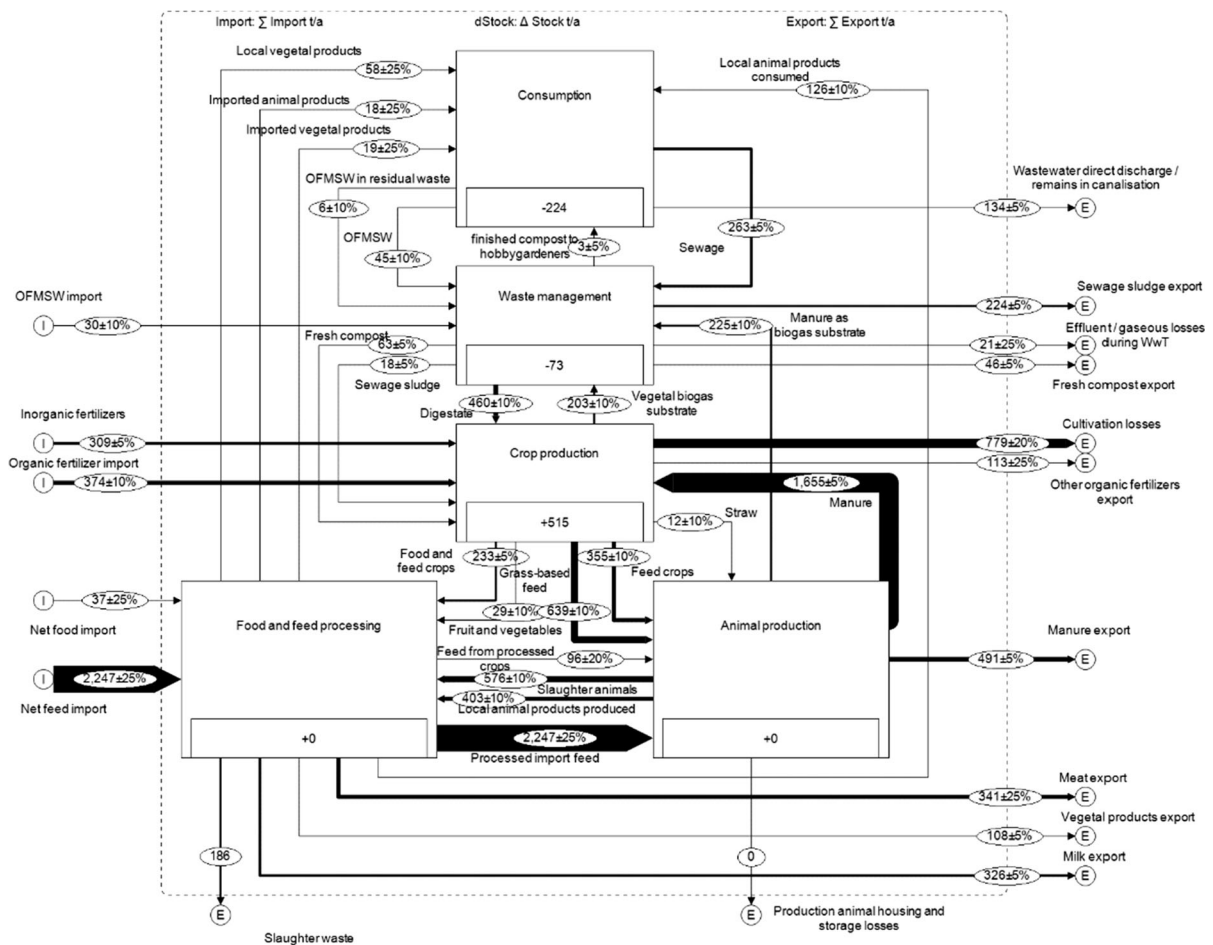
Fig. 2 Phosphorus SFA with flows in ton year^{-1}. I = import E = export. WwT = wastewater treatment

The net import–export dilemma

It was assumed that the subsystem consumption was firstly supplied with vegetal and animal-sourced food products produced in the district and thereafter supplemented with input from agriculture elsewhere. However, it was taken into account that products not grown in the district, such as citrus fruits, must be imported. This computation was moreover utilized for feed provision, firstly supplying animals with locally sourced feed.

This net import—export approach was undertaken because of lack of data on the origin of food and feed consumed in the district, and lack of data on import and export of products. This is a general limitation of nutrient studies on a regional scale (Harder et al. 2021). Estimation of product import and export were based on the amount of locally consumed and

produced feed and food instead. On one hand, this method of flow computation results in maximized local self-sufficiency with regard to food and feed provision. On the other hand, it minimizes the amount of exported products. The relevance of this approach for each subsystem is described under the separate sections (Supplementary material B), while the relevance for the results is evaluated there.

Carbon supply and demand

For the flows (Table 2) with potential as soil amendment and to supply organic C to soil, first their humus equivalents (HE t^{-1} biomass) were attained from NRW (2015) (Supplementary material C). In brief, the HE describes the potential level of SOM that can accumulate over time from an organic amendment or from a crop. One HE corresponds to 1 kg SOM-C. The
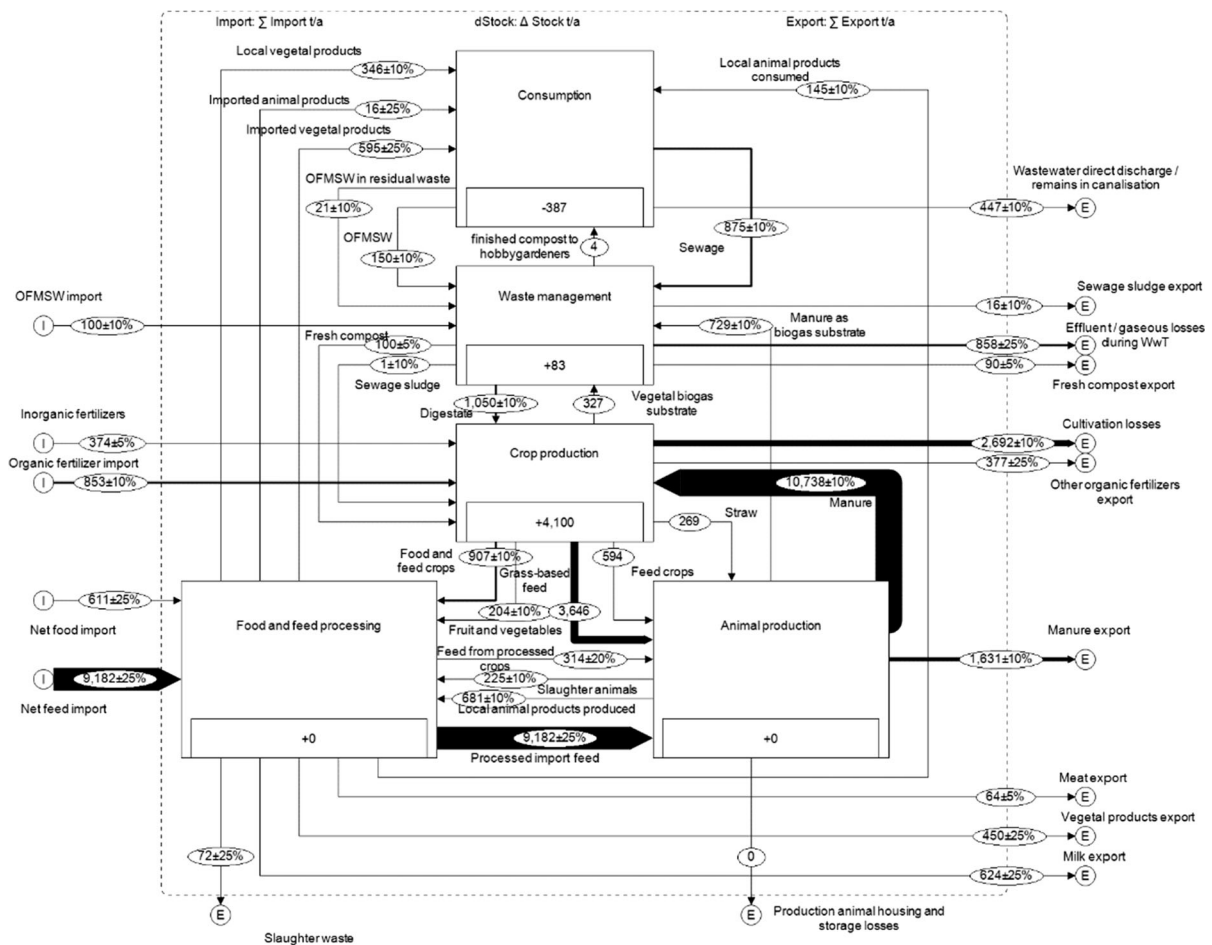
Fig. 3 Potassium SFA with flows in ton year^{-1}. I = import E = export. WwT = wastewater treatment

HE can also be negative, e.g., when crop management results in an overall reduction of SOM, like for potatoes (NRW 2015). After calculating the HE per crop, the balance between HE supply (i.e. crop residues not harvested from the land and biomass available as soil amendment or fertilizer such as compost) and demand (NRW 2015) (i.e. HE requirements due to harvested crops) was calculated for the entire district. Biomasses considered for soil amendment were: manure currently recycled to crop production in the district and exported manure, digestate from biogas plants, imported and exported organic fertilizer, currently recycled and exported sewage sludge, currently recycled and exported fresh compost and finished compost.

Data reliability

Data used in this study was derived from various types of sources of varying quality. Uncertainty intervals for each flow are presented in Table 1 to provide an indication of the reliability of the sources of information. Uncertainties were defined according to the data uncertainty method presented by Antikainen et al. (2005). Each factor (e.g. nutrient concentrations, mass flows) was assigned an uncertainty level (1–5), based on the source of the information, and a corresponding uncertainty interval (1, 5, 10, 20 and 25%) (Table 1). In this study each nutrient flow was assigned an uncertainty level based on the least certain factor contributing to its calculation. The uncertainty intervals are depicted as standard deviations in Figs. 1, 2 and 3.

Table 1 The five uncertainty intervals for various sources of information as used in this study with examples regarding their application to certain data (after Antikainen et al. (2008))

Level	Uncertainty interval	Source of information	Examples
1	± 1%	Official regional statistics	Population data
2	± 5%	Official regional official statistics, primary data	Compost and manure data
3	± 10%	Official national statistics, values from literature	Food consumption data
4	± 20%	Educated estimate	Food processing by-products data
5	± 25%	Mass conservation modelling	Net feed import data

Results

Overall system NPK imports and exports

For the agro-food-waste system in the district of Cleves the imports, exports, soil stock changes in crop production and flows between the subsystems (1) crop production, (2) animal production, (3) food and feed processing industry, (4) consumption and (5) waste management were computed in tons nutrient (N, P and K) year^{-1} (Figs. 1, 2 and 3). The entire model of the agro-food-waste system includes 40 flows. The 21 largest flows cover at least 90% of the sum of all studied nutrient flows (Table 2). To improve clarity without losing substantially on accuracy, the remaining smallest 19 flows were included in the analysis and figures but not in Table 2. A table with all the flows of the analysis is shown in Supplementary Material D.

The Cleves district imported a total of 20,791 t N, 2,997 t P and 11,120 t K while 20,293 t N (98%), 2,000 t P (67%) and 4,629 t K (42%), left the system in agricultural products, organic fertilizers and through losses. Considering only agricultural food products, including exported products and consumption within the district as intended output, results in N, P and K production efficiencies of 25, 32 and 15%, respectively. The system's current nutrient self-sufficiency, calculated as the percentage of all input flows stemming from local sources was, 50, 54 and 61%, respectively for N, P and K (all nutrients supplied to crop production, animal production and local consumption are considered in this calculation). This percentage, therefore, represents the food, feed and fertilizer self-sufficiency. The system needed to import 50%, 46% and 39% of its required N, P and K.

The largest nutrient import was represented by (net) feed import (54% of total N import; 75% of total P import; 83% of total K import). Inorganic fertilizer was the second largest import for N, while for P and K it was manure and other organic fertilizers. Cultivation losses (7482 t N) and housing and storage losses from animal production (3,282 t N) accounted for the largest removal of N from the system. Agricultural food products (i.e. all export flows combined), constituted another 3,300 t N (16%), 775 t P (39%) and 1,138 t K (25%). The next largest export flow for N and P was manure (1880 t N and 491 t P), while for K (1631 t) manure represented the largest export flow.

The nutrient ratio in Table 2 shows the NPK stoichiometry of the individual flows. In some flows N and K are present at equal amounts, while some are richer in N. The stoichiometry of the inorganic fertilizer import is skewed as single N fertilizers are imported in larger quantities as compared to inorganic K and P.

Crop production

N, P and K entered the crop production subsystem mostly in the form of manure (8469 t N, 1655 t P and 10,738 t K). This corresponded to 44%, 57% and 82%, respectively, of the total input into crop production. The second largest input for N was inorganic fertilizer (41%), while for both P (13%) and K (7%) it was imported organic fertilizers (Fig. 4a-c). The largest output of the crop production subsystem for N were cultivation losses (representing 39% of all N output) being almost as high as the inorganic N import. In contrast, for both P and K grass-based feed was the largest output, constituting 40 and 58% respectively. Based on the calculated balance and leaching rates in literature, this could indicate an accumulation of 515 t P and 4100 t K in agricultural soils in the reference year, which corresponds to an average of 7 kg P ha^{-1}

Table 2 List of the 21 largest nutrient flows of the agro-food-waste system of Cleves district in 2016. Besides the source and destination of each flow, the mass of N, P, K and C (for biomass with potential to use as (source of) bio-based fertilizers) are indicated

Flow name	Source	Destination	N (ton)	P (ton)	K (ton)	C (ton)	N:P:K (weight based)
Net feed import	IMPORT	Food and feed processing industry	11,147	2247	9181		5:1:4
Processed import feed	Food and feed processing industry	Animal production	11,147	2247	9181		5:1:4
Manure*	Animal production	Crop production	8469	1655	10,738	75,678	5:1:6
Inorganic fertilizers	IMPORT	Crop production	7864	309	374		25:1:1
Cultivation losses	Crop production	EXPORT	7482	779	2692		10:1:3
Feed crops	Crop production	Animal production	4055	355	594		11:1:2
Grass-based feed	Crop production	Animal production	3985	639	3646		6:1:6
Production animal housing and storage losses	Animal production	EXPORT	3282	0	0		
Slaughter animals	Animal production	Food and feed processing industry	2883	576	225		5:1:0.4
Local animal products produced (dairy and eggs)	Animal production	Food and feed processing industry	2303	403	681		6:1:2
Sewage	Consumption	Waste management	1901	263	875		7:1:3
Manure export*	Animal production	EXPORT	1880	491	1,631	12,607	4:1:3
Milk export	Animal production	EXPORT	1771	326	624		5:1:2
Vegetal biogas substrate	Crop production	Waste management	1562	203	327		8:1:2
Local animal products consumed (dairy, eggs and meat)	Food and feed processing industry	Consumption	1482	126	145		12:1:1
Effluent / gaseous losses WWTP	Waste management	EXPORT	1448	21	858		69:1:41
Digestate*	Waste management	Crop production	1385	460	1050	7064	3:1:2
Crops	Crop production	Food and feed processing industry	1362	233	907		6:1:4
Organic fertilizer import*	IMPORT	Crop production	1251	374	853	13,264	3:1:2
Meat export	Food and feed processing industry	EXPORT	1004	341	64		3:1:0.2
Manure as biogas substrate	Animal production	Waste management	973	225	729		4:1:3

*A biomass with the potential to recover nutrients for bio-based fertilizers

and 58 kg K ha^{-1}. The nutrient use efficiency (NUE) of crop production was 61, 55 and 48% for N, P and K, respectively. For N this was close to the German average over the period 2010 to 2014 (Eurostat, 2018). For P, however, it is below the average between the years 2009 to 2014 (Eurostat, 2017). The K NUE of the dominant crop in the district, maize, shows a higher K efficiency in the district compared to literature (Tomaz et al., 2018).
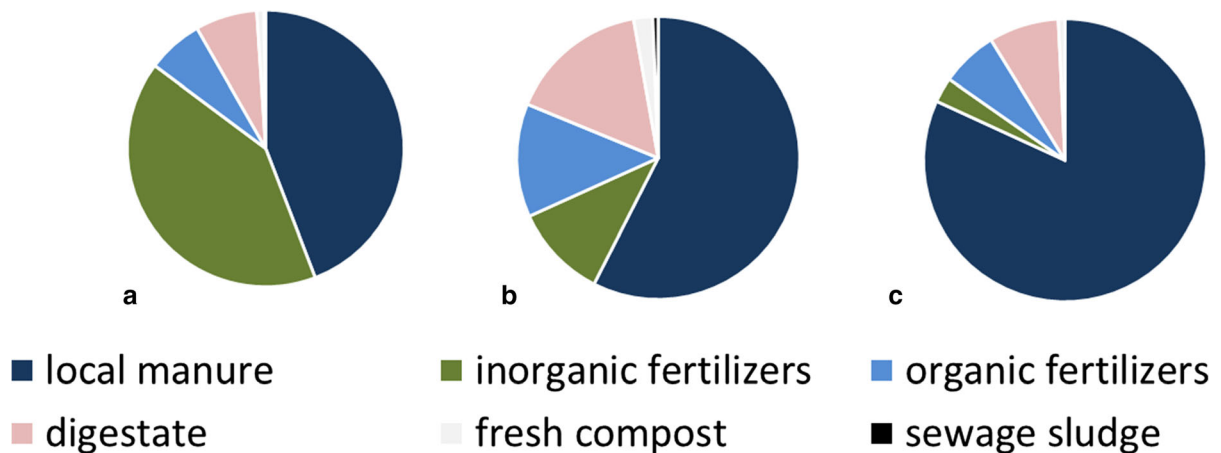
■ local manure   ■ inorganic fertilizers   ■ organic fertilizers

■ digestate   ■ fresh compost   ■ sewage sludge

Fig. 4 Nitrogen **a**, phosphorus **b** and potassium **c** input composition into crop production

Animal production

The relative contribution of imported feed to the total input of feed into animal production was 56% for N, 67% for P and 66% for K. This exemplifies the big dependence of animal production on imported feed, even more so when it is considered that these are minimum values, as the model assumed that all locally produced grass-based feed and locally produced feed crops are fed to livestock in the district. Nevertheless, the presented values are expected to be reasonably representative, as grass-based feed and feed crops are usually not transported over larger distances (Billen et al. 2012).

The overall output of animal products (not including manure) of this subsystem were 5186 t N, 979 t P and 906 t K. The NUE of the animal production subsystem, considering all animal products (including the whole live animal, except for manure), were 26%, 29% and 6%, for N, P and K, respectively.

Food and feed processing industry

As assumed there were no losses or by-products during processing of imported feed, the import of feed into the food and feed processing industry subsystem equalled the amount of processed feed imported into the animal production subsystem. This same principle applies to food import, adding up to the flows "imported animal products" and "imported vegetal products" representing inputs to consumption. However, in reality, processing of food also generates by-

products that are not used as food and emissions and potentially losses can be expected (Wironen et al. 2018).

Consumption

Based on consumers´ diet, the consumption subsystem could have been supplied with a maximum of 2002 t N, 185 t P and 492 t K originating from locally produced food. For N and P, this maximum local supply mainly originates from local animal production (74% of N, 69% of P and 30% of K), while for K this is from local crop production (26% of N, 31% of P and 70% of K). Results show that the consumption subsystem can be supplied with food from local agriculture to the levels of 86% (N), 83% (P) and 83% (K) of the total consumption. This scenario represents the highest possible local consumption under current production and consumption volumes; certain products (e.g. coffee, fish) that are currently not produced in the district are still to be imported. These values, therefore, represent the maximum level of food self-sufficiency of the district that is possible with current consumption patterns. The minimized export of locally produced food, representing 3300 t N, 775 t P and 1138 t K, consisted of dairy products, meat and vegetal products. However, besides the import of animal products in the form of fish, also additional eggs had to be imported as local production was insufficient. Based on the production and consumption levels the system has an N, P and K self-sufficiency capacity of 236%, 471% and 160%, respectively.

Comparing the N food self-sufficiency capacity with that of a peri-urban area (with an N food self-sufficiency ≤ 170), exemplifies the exporting nature of the district under study (Tedesco et al. 2017).

Waste management

The waste management subsystem in the district received organic fractions of municipal solid waste (OFMSW) (separately collected from households) and green garden waste from local sources in the Cleves district (including households) (294 t N, 45 t P and 150 t K) as well as from surrounding districts (197 t N, 30 t P and 100 t K). The OFMSW and green garden waste were composted at one single site. The compost was used as soil amendment within the district (166 t N, 63 t P and 100 t K) or exported (46% of N, P and K in compost). A part of the OFMSW was not collected separately but ends up in the residual waste and is concurrently not composted but predominantly incinerated (36 t N, 6 t P and 19 t K).

Nutrients in sewage amounted to 1,901 t N, 263 t P and 875 t K, of which 24, 92 and 2% respectively, were retained in the sewage sludge generated by wastewater treatment plants (WwTP). Sewage sludge was in part supplied to agricultural land in the district in 2016 (33 t N, 18 t P and 1 t K) (Fig. 5). However, the largest majority of nutrients in sewage sludge left the agro-food-waste system in Cleves as sludge which was either incinerated after which the ashes were landfilled or used elsewhere (420 t N, 224 t P and 16 t K) (Fig. 5). These applications represent losses as the nutrients are left unavailable for the agro-food-waste system. The lumped flows nutrient load in WwTP effluent and (for N) nutrient elements emitted to the atmosphere, mainly as N_2 during nitrification, were deduced through mass conservation, subtracting the nutrients

in the sewage sludge from the nutrients in the sewage (1448 t N, 21 t P and 858 t K). These flows were lumped as both represent losses. Also the modelled waste management subsystem N stock change (1355 t) can be considered as losses, arising during waste treatment (e.g. gaseous N losses during composting).

One further output flow of the waste management subsystem was digestate from anaerobic digestion of crop- and animal-sourced biomass (1385 t N, 460 t P and 1050 t K). Based on the average substrate use in North Rhine-Westphalia, the substrate supplied to biogas plants in the district was a combination of biomass from animal production (manure) (38% of N, 53% of P and 69% of K) and from crop production (crops and by-products) (62% of N, 47% of P and 31% of K).

As this study only focussed on flows related to the food production system, P originating from detergent inputs into households was excluded. However, earlier studies determined the substantial contribution of detergents to the P inputs into households (Theobald et al. 2016). Thus, while P from detergents is not an input, through the household wastewater and ultimately the sewage, it still emerges as an output, resulting in a higher overall P output than input into consumption (Supplementary Material B). Furthermore, not all the food waste originated from food that was purchased by households, because a part was food waste from commercial sources for which the input was not included in the input to the consumption subsystem. Imbalances were also computed in the waste management subsystem, likely reflecting losses of N and K during waste processing, while a negative balance for P indicates a declining stock of waste.

Carbon supply and demand

The agricultural land in the district (arable and grassland) was supplied with 222 humus equivalents (HE) of C ha^{-1} agricultural land through the application of locally produced manure, digestate, imported organic fertilizer, compost and sewage sludge. However, grasslands are usually fertilized with organic fertilizer to provide N, P and K rather than with organic amendments. The main reason for this is that grasslands are C sinks due to their permanent vegetation cover and limited soil disturbance and therefore do not demand external C input through, e.g. organic amendments (Jones et al. 2005). The C supply to the
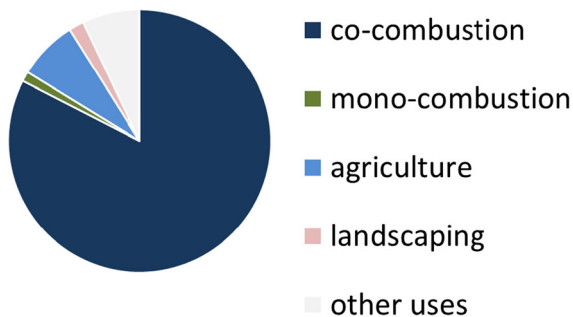

Fig. 5 Fate of sewage sludge in Cleves in 2016

- co-combustion
- mono-combustion
- agriculture
- landscaping
- other uses

more C demanding arable land, is thus limited by the use of organic fertilizer on grassland. Manure produced in the district (75,678 t C) contributed the majority of the C (Table 2). Digestate was substantially lower and compost and sewage sludge negligible. Imported and exported organic fertilizer are almost at balance in terms of C. The demand for HE was calculated to be 257 per ha arable land based on the crops harvested resulting in a C surplus of 60 HE ha^{-1} in the district if all organic fertilizers were applied to arable land only (317 HE) (Supplementary Material C). However, as explained above, organic fertilizers are also applied as nutrient source to grassland in the region, where the added C is not required but may contribute to C accumulation in those C rich soils (Fornara et al. 2016). This highlights the relevance of a stoichiometric perspective including C in the regional evaluation of nutrient flows.

Discussion

High livestock density and feed import create a nutrient legacy

The district of Cleves is characterized by a high livestock density (2.2 LLU ha^{-1} agricultural land), which strongly influences the nutrient balance of the entire agro-food-waste system. On one hand, feed import results in high quantities of N, P and K entering the system, while only a minor part of these nutrients are exported as animal-sourced food products (25% of N, 30% of P and 7% of K) and as manure (17% of N, 22% of P and 18% of K). On the other hand, animal production is export-oriented and only 35%, 16% and 18% of N, P and K present in food products, respectively, are consumed by the local human population. This imbalance between input and output results in a large surplus of nutrients, of which a part is lost (in particular N) as a result of agricultural and waste management emissions and discharge, and a part is accumulating (in particular P and K) in agricultural soils. For N, for example, 13,182 t N (63% of the total N import) is lost from the system. Losses from agricultural production only (crop production and animal production), correspond to 150 kg N ha^{-1} agricultural land. For every kg of product-N there are about three kg N livestock related losses, including losses during animal housing,

manure storage and manure application. The nutrient quantities in manure produced by the livestock sector are, furthermore, far in excess of crop demand (Bateman et al. 2011; Schipanski and Bennett 2012). Moreover, additional N deposition in the district being somewhere between 11 and 30 kg N ha^{-1} yr^{-1} (Wendland et al. 2020) was not included in the analysis, and needs to be considered to cover all inputs and losses. Together, the total sum of inputs have an important impact on nutrient saturation of soils (Senthilkumar et al. 2012) and liquid and gaseous losses of N causing environmental effects in groundwater, aquatic and terrestrial ecosystems also beyond the district. Utilizing average leaching rates (11 kg P ha^{-1} yr^{-1}) (Schoumans 2015) for Dutch agricultural soils, with a high degree of P saturation, resulted in 779 t P losses in Cleves in 2016. Utilizing K leaching losses for the most common crop (maize silage) (38 kg ha^{-1} yr^{-1}) as presented by Kayser et al. (2012), results in 4,100 t of K accumulating in Cleves´ agricultural soils and 2692 t K lost, again showing the large nutrient use inefficiency of the animal production subsystem, leaving a nutrient legacy in soil and the environment.

Local improvement options

Organic fertilizers do not have the same quality as inorganic fertilizers as the latter can precisely fulfil the specific stoichiometric nutrient demand of crops which results in a higher nutrient use efficiency (Cardenas et al. 2019; Sharif et al. 2004). This is in particular the case for high value and high nutrient demanding crops, such as vegetables and some cash crops. Inorganic fertilizers are therefore preferred by farmers for certain crops. Nonetheless, solely on a mass basis locally recycled manure covers 72, 104 and 170% of the required N, P and K in total crop production. However, for the most common crops in the district, being maize (33% of arable land), winter wheat (21% of arable land) and potato (12% of arable land), nutrient demand cannot be matched with manure, the biggest mass flow, because of nutrient stoichiometry. This analysis does not consider grassland as inorganic fertilizers are generally not applied to grassland and therefore substitution by organic fertilizers does not have to be considered (NRW 2018). The NPK ratio of manure is 5:1:6, whereas the nutrient ratio requirements of maize, winter wheat and

potato are 7:1:5, 6:1:3 and 6:1:8, respectively (supplementary material D), while in practice even more N is needed due to limited N availability from the manure. Direct application according to N crop requirements would result in exceeding EU nutrient application limits for Germany (six-year average of 20 kg P_2O_5 ha^{-1} yr^{-1}) and in particular causing P application in excess and accumulation over time (Bittman et al. 2017; Jakobsen 1993; Kuhn et al. 2018; Little et al. 2015). In addition to manure, also wastes produced by humans (e.g. sewage, OFMSW) hold potential as source of plant nutrients. Despite the relatively low contribution of waste management flows to total nutrient flows (10%), as compared to those related to agriculture in the district of Cleves their significance for nutrient self-sufficiency of the whole system will be higher in urban areas, with increasing urbanization (Neset et al. 2010) and with increasing circularity in agriculture. Considering the NPK ratio of sewage sludge, of 2:1:0.1, the same issue arises with direct application as with manure, causing P excess and K limitation. However, considering a local SOM decline as reported in literature (Steinmann et al. 2016), recycling of all organic C contained in the biomass is desired and could contribute to SOM maintenance in the arable soils in the district of Cleves (Steinmann et al. 2016). Overall, to improve nutrient self-sufficiency for N, P, K and C, the system needs to be either adapted to produce less biomass with an N:P:K:C ratio which, however, will not fit the crop specific demand for those nutrients (e.g. manure) leaving some nutrient unused, or biomass needs to be processed to allow precision fertilization of single nutrients. The latter case would also allow the export of any excess nutrients.

Identifying technological intervention with high potential to improve circularity

The agro-food-waste system of district Cleves exported 2883 t N, 884 t P and 2114 t K in biomasses that could potentially be used as fertilizers. These exported biomasses had, on a mass basis, the potential to replace 37%, 286% and 565%, respectively of the N, P and K imported as inorganic fertilizers. Recycling of manure requires safe and economically viable technologies recovering single nutrients for local application, while excess nutrients are recovered in a form which can be exported economically. A range of mechanical separation technological options allows for isolating nutrients from manure which can replace inorganic fertilizers while also conserving organic C (Sigurnjak et al. 2017; Vaneeckhaute et al. 2013). Struvite precipitation for example can provide a phosphorus source from manure as well as sewage (Ackerman et al. 2013; Le Corre et al. 2009). However, there is a deficiency of C when biomass is also directly applied to grassland. The multi-nutrient perspective combined with C for biomasses with potential to process into bio-based fertilizers indicates that in order to provide arable soil with sufficient C, biomass will have to be processed. Recovering nutrients would allow for nutrients to be supplied to arable soils and grassland, while the C demand of cultivated crops can be met to conserve C soil stocks and with that soil fertility.

Human waste management currently focuses on nutrient removal rather than on recycling (Coppens et al. 2016; Theobald et al. 2016; Verger et al. 2018). Legislation in Germany obliges WwTP as of 2032 to recover all P and recycle this to agriculture (Heidecke 2018). This contributes to planned changes in district Cleves to recover nutrients in local WwTP´s. However, direct application of sewage sludge is therewith no longer allowed which hinders the recycling of other nutrients. Technologies which recover N, P and K, such as membrane and ultrafiltration, are preferred, as they allow for creation of tailor made fertilizers, fulfilling the stoichiometric nutrient demand of arable crops and vegetables (Zhang et al. 2014).

To implement technological measures, a shift in farm practices is required to allow the replacement of inorganic NPK fertilizers (Hanserud et al. 2016; Verger et al. 2018). However, in the future increasing extraction costs for phosphate rock might give incentives to replace it with bio-based fertilizers (Cordell et al. 2009). Moreover, possibilities of processing nutrient-rich biomasses, such as manure, to bio-based fertilizer in order to recycle N, P, K and organic C in the district need to be more thoroughly evaluated considering their applicability as well as their ecological, economic and social impact. In this context, the stoichiometry of crop nutrient demand as well as the stoichiometry of SOM need to be considered to allow for a truly sustainable nutrient recovery and soil fertility management including the C component.

Ultimately, excess nutrients will have to be exported to areas with nutrient demand when

agricultural production, in particular animal production, in the district of Cleves, remains dependent on feed import. However, given the manure export from Cleves´ neighbouring districts, distribution beyond the district might result in an area-wide nutrient surplus beyond feasible transport distances (NRW 2018). Facilitating biomass transport from areas with supply to those with nutrient demand, both inside the district as well as to neighbouring districts, could improve nutrient cycling. However, analyses of nutrient flows at multi-local and sub-local perspectives are needed to identify demand and supply (Cooper and Carliell-Marquet 2013; Wendland et al. 2020), therefore shaping the perspective of nutrient circularity in food systems.

Identifying systemic changes with high potential to improve circularity

Beyond technological measures, systemic changes are ultimately required to address the imbalance in nutrient supply and demand due to specialization in agricultural production with animal production relying on feed import. Thus, in a circular system, nutrients from surplus areas must be returned to areas of feed crop cultivation. The net input–output approach taken in this study assumes maximum local feed self-sufficiency under current crop and animal production practices. However, even under this assumption import of feed is required to feed the livestock in the district which produce large quantities of products for export. Uwizeye et al. (2020) found that reducing imports of feed for livestock, can contribute to a reduced surplus of N, P and K in the system. In a circular agricultural system, a role of animals is especially to utilize and upgrade biomass unsuitable or undesired for human consumption, such as by-products from food processing, and change them into highly nutritious food (Röös et al. 2016; Van Zanten et al. 2014). The utilization of land only suitable as grassland is moreover a valuable role of animals in a circular system (Van Zanten et al. 2018). In the case of grassland it needs to be considered whether land is not rather used for crop production as utilizing land for crop production for human consumption is more efficient (Mottet et al. 2017). However, grassland contributes to C sequestration and biodiversity conservation, while the conversion to arable land causes soil C and biodiversity loss

(Bretagnolle et al. 2011; Lal 2004; Van Zanten et al. 2018). This means that the size of the livestock population in a system depends on the available feed in that system. Applying this to Cleves would ultimately imply a decrease of the livestock density in the district (Granstedt et al. 2008; Senthilkumar et al. 2012; Van Zanten et al. 2014; Wironen et al. 2018). The system´s feed self-sufficiency of 44% for N, 33% for P and 34% for K implies that a maximum of 33% of the 156,098 LLU that were present in 2016 could have been fed with locally produced feed (grass-based feed, feed crops and feed from processed crops). Considering this reduction in livestock numbers, the resulting decline in available manure, and the extent to which local biomass can cover the cultivated crops´ demand for C under the current situation, it becomes apparent that other biomass flows are required to be used efficiently to fulfil N, P, K and C demand. To estimate the potential of feeding with locally produced feed, more data on food processing by-products is required and could be collected through participatory research (Metson et al. 2012). Optimising recycling of biomass and adjusting the local livestock number to available feed, would reduce the production of animal-sourced food. As a consequence of reduced livestock numbers, the export of animal-sourced food will be reduced, creating demand for food production elsewhere. Circular agriculture, therefore, inherently means a reduction in the consumption of animal products, or the problems related to high livestock numbers is likely to shift to another, potentially less favourable, area. However, sourcing feed locally can provide additional revenues to industry providing by-products and supporting local nutrient circularity and lower emissions of nutrients (Seddighi and Thomas 2011). Moreover, farmers would not depend on fluctuating feed prices and improve their economic independency. Feed exporting areas in turn would not remove N, P, K and organic matter from the soils by exporting the feed and not recovering the resulting nutrients contained in the manure (Craswell et al. 2004; Jones et al. 2013).

Outlook

The net input–output approach taken in this study allows nutrient flow analyses to be done despite lack of data on import and export of food and feed products of a certain area. It gives moreover an insight into the potential nutrient self-sufficiency of an area. However,

it does not represent necessarily the actual situation as the district, for example, exports part of its harvested grass. Moreover, the spatial variation with regard to nutrient surplus within the studied area (Wendland et al. 2020) was not addressed in this study, but would be required for local implementation of means to reduce nutrient surplus and restore nutrient cycles. The results indicate that especially for the subsystem food- and feed processing industry more data is required in order to determine the district´s self-sufficiency more accurately. The present analysis, therefore, illustrates a starting point to analyse quantitative effects of promising changes, e.g. through scenario studies, towards nutrient self-sufficiency and improved nutrient circularity. This study, furthermore, may serve as a methodical blueprint for others who aim to analyse local nutrient flows in agro-food-waste systems.

Conclusions

This multi-nutrient flow analysis with a local perspective indicates that the primary flows in the agro-food-waste system in district Cleves are related to agriculture, especially to animal production. The large imports of feed and inorganic fertilizers and the low levels of nutrients exported in food, illustrate the linear nature of the agro-food-waste system in the district and explains the nutrient surplus. Currently, animal husbandry is highly dependent on feed import, with 56% of N, 67% of P and 66% of K in annual feed uptake being imported. Consequently, the application of locally generated manure contributes to large losses to the environment (7482 t N, 779 t P and 2692 t K). This study denotes that system change with regard to animal production, namely reducing livestock numbers based on local feed supply, using grasslands and by-products from food processing, and linking it to local crop demand could support a more circular agro-food-waste system. Through the implementation of technologies for the production of bio-based fertilizers, biomass can replace inorganic fertilizers. On a mass basis, currently exported biomass has the potential to replace 37, 286 and 565%, respectively of the N, P and K imported as inorganic fertilizers. While, local recycling is desired to reach a self-sufficient local system and conserve organic C, direct application of biomass results in oversupply of especially P due to imbalanced nutrient stoichiometry of supply and demand. Therefore, future research should aim at balancing crop—and animal production and evaluating the potential of technologies for creating bio-based fertilizers to facilitate a more circular agro-food-waste system.

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