Detailed nitrogen and phosphorus flow analysis, nutrient use efficiency and circularity in the agri-food system of a livestock-intensive region

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List of acronyms, abbreviations and definitions

Cap – capita

Diffuse emissions – Losses to the environment originating from point sources

Input – nutrients entering a process or system

Import – nutrient entering a process or system originating from another geographical region

LCA – Life cycle assessment

LSU – livestock unit

N – Nitrogen

NIF – Nitrogen investment factor

Node – sectors, actors or processes that transform flows

Point source emission - losses to the environment originating from point sources

Nr – reactive nitrogen

NUE – Nitrogen use efficiency

P – Phosphorus

PIF – Phosphorus investment factor

Primary stream – A flow of goods that is the intended outcome of a process

PUE – Phosphorus use efficiency

Reused stream – a side stream that is reused in the domestic agri-food chain

SFA – Substance flow analysis

Side stream – Outputs that differ from the desired products

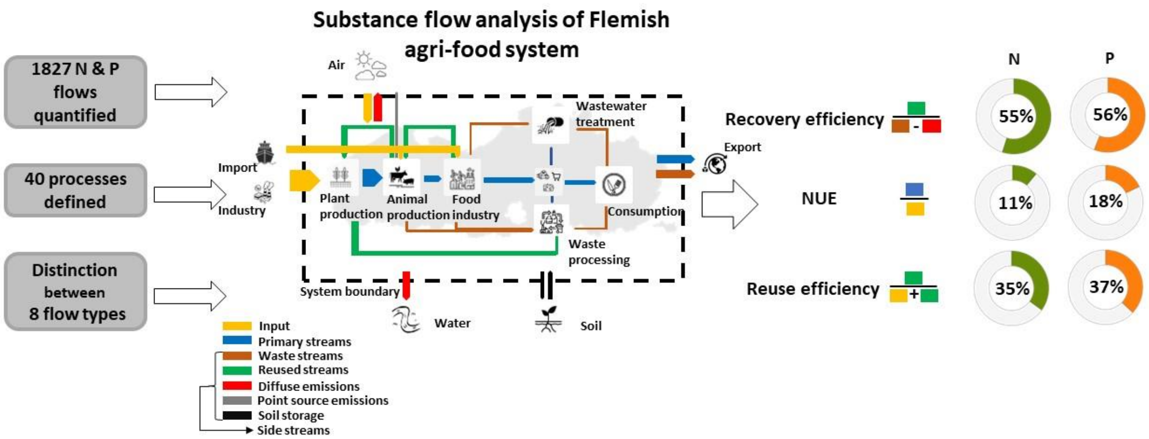
WWTP – Wastewater treatment plant

y – Year

ABSTRACT

The agri-food value chain is a major cause of nitrogen (N) and phosphorus (P) emissions and associated environmental and health impacts. The EU's farm-to-fork strategy (F2F) demands an agri-food value chain approach to reduce nutrient emissions by 50% and fertilizer use by 20%. Substance flow analysis (SFA) is a method that can be applied to study complex systems such as the agri-food chain. A review of 60 SFA studies shows that they often lack detail by not sufficiently distinguishing between nodes, products and types of emissions. The present study aims to assess the added value of detail in SFAs and to illustrate that valuable indicators can be derived from detailed assessments. This aim will be attained by presenting a highly-detailed SFA for the livestock-intensive region of Flanders, Belgium. The SFA distinguishes 40 nodes and 1827 flows that are classified into eight different categories (e.g. by-products, point source emissions) following life cycle methods. Eight novel indicators were calculated, including indicators that assess the N and P recovery potential. Flanders has a low overall nutrient use efficiency (11% N, 18% P). About 55% of the N and 56% of the P embedded in recoverable streams are reused providing 35% and 37% of the total N and P input. Optimized nutrient recycling could replace 45% of N and 48% of P of the external nutrient input, exceeding the target set by the F2F strategy. Detailed accounting for N and P flows and nodes leads to the identification of more recoverable streams and larger N and P flows. More detailed flow accounting is a prerequisite for the quantification of technological intervention options. Future research should focus on including concentration and quality as a parameter in SFAs.

GRAPHICAL ABSTRACT



HIGHLIGHTS

- Detailed substance flow analyses increase the recoverable streams and nutrients
- Detailed flow accounting can reveal the efficacy of technological implementations
- The high share of livestock results in low N & P use efficiencies of 11% and 18%
- Only 55% of N and 56% of P embedded in recoverable streams is currently recovered
- Increased nutrient recycling could replace almost half of the external N & P input

KEYWORDS

Circular economy, green deal, resource recovery, material flow analysis, sustainability indicators

1 INTRODUCTION

Nitrogen (N) and phosphorus (P) are essential elements for food production and food security. Over the last century, global nutrient inputs to agricultural systems have risen sharply. For N an increase of 278-458 times since the patenting of the Haber-Bosch process in 1908 has been reported (Sutton et al., 2013). For P an increase of 88-130 times, since 1900 has been estimated as a result of the mining of this critical raw material (Cordell and White, 2014). Of these massive inputs, only 4-18% of N and 12-50% of P are consumed by humans, the remainder (82-96% of N and 50-88% of P) is emitted to the soil, air and water along the agri-food chain (Erisman et al., 2018, Metson et al., 2016). Agricultural emissions of N and P are the major reason for the exceedance of the planet's carrying capacity (Campbell et al., 2017). In regions dominated by livestock farming, these global problems are exacerbated resulting in severe problems of air pollution, eutrophication, health impacts and economic costs (Gu et al., 2021). More efficient management of N and P throughout the agri-food chain is vital to minimize environmental pollution while ensuring food security. Europe's farm-to-fork (F2F) strategy demands that nutrient management interventions will have to be taken along all agri-food value chain actors aiming for a reduction in nutrient losses by 50% and a reduction in fertilizer use by 20% (European Commission, 2020).

To inform effective interventions across the entire agri-food value chain, an analysis of all activities involved is required. A method to investigate value chains is substance flow analysis (SFA), which details the nodes (i.e. sectors, actors or processes that transform flows), stocks and flows (i.e. exchanges of N and P between nodes) of substances within a defined system. SFAs have been applied to inform decision-making in environmental protection, resource conservation, and waste management (Brunner and Rechberger, 2004). The more detailed an SFA is, the more policy-relevant information can be extracted and the uncertainty of the model itself can be reduced (Klinglmair et al., 2016). In SFAs, detail can be measured by the number of nodes and flows contained in the model. The degree to which sectors (and their associated nodes) are disaggregated and the sectorial 'black box' is opened up is another important measure of detail (van der Wiel et al., 2019). The added value of this can be illustrated between the difference of detailing the node of animal production into stable and grazing emissions rather than aggregating it into a single value; or the nutrient conversion efficiencies of different animal types (pig = 35% vs. cattle = 12% for N, respectively) compared to aggregation in livestock farming. An evaluation of 60 studies concerning the number of nodes and flows used to perform the SFA (Supplementary material (SM) S1), indicates that only a limited number of aggregated nodes (14 ± 25) and flows (67 ± 116) are investigated, which results in a loss of information. A similar conclusion was reached by van der Wiel et al. (2019) who assessed whether studies investigated five major agricultural sub-systems. They showed that 58% of the studies did not include the subsystem food and feed processing industry, thereby omitting insights into emissions and flows generated during food and feed processing. One of the most detailed studies yet comes from Zoboli et al. (2016) who described the Austrian agri-food system by 56 nodes and 122 flows. This dataset was further disaggregated into 194 nodes and 866 flows by Tanzer et al. (2018) for scenario analysis. Another detailed study was published by Leip (2015) who accounted for 504 N containing commodities in an EU-27-wide SFA on livestock products. However, the large geographic scale of this work results in high aggregation of nodes and flows. For the specific case of Belgium and Flanders, Coppens et al. (2016) distinguished 21 nodes and 160 N and P-related flows. This study did however not disaggregate different livestock and crop production sectors and used mass balance equations to estimate aggregated sector input and output flows which makes flow type specification impossible. Papangelou and Mathijs (2021) assessed the circularity of the regional Belgian agri-food chain by using 7 nodes and 98 N and P flows. In their study the waste management sector is represented by one node, reducing the added value for the assessment of recovery measures to increase circularity. Firmansyah et al. (2017) only identified 8 sub-systems and 26 flows to carry out an SFA under limited data availability. Boh and Clark (2020) carrying out an SFA of N for the Ontario region identified 10 nodes and 50 flows, not disaggregating different types of crops and animal production systems again limiting the information value.

To inform the transition to a more sustainable agri-food chain that relies on high efficiencies and reuse of excess nutrients; SFAs should eventually be able to deliver indicators that can provide insight into, amongst others, reuse potentials, recovery ratios and different types of Nutrient Use Efficiencies (NUEs). This is in particular of relevance as a sustainable intensification of the agri-food chain is put forward as a means to meet the increasing food demand while not exceeding planetary boundaries (Cassman and Grassini, 2020). Klement et al. (2021) argue that SFA studies must clearly distinguish between desired products and by-products, such as residual biomass N or P used for fertilization, as this changes the evaluation of the agri-food value chain efficiency of sectors (i.e. a by-product utilized in the agri-food chain can affect NUE as for example soy meal and soy oil). Others have arrived at similar conclusions by classifying different types of flows for each node to calculate the N footprints of beef production (Joensuu et al., 2019). Often the differentiation of flows is inspired by life cycle assessments (LCA) that distinguish between desired product, by-product and waste flow. Beyond that, in SFAs a further distinction into diffuse emissions and point source emissions in a replicable manner will be of added value. The reason for this is that recovery technologies are likely applied to point source emissions, rather than diffuse emissions of N and P (Spiller et al., 2022), and therefore this distinction can enable the assessment of indicators relevant to circular nutrient management. To the knowledge of the authors, there is currently no study that classifies flows of N and P into more detail than by-products.

Detailed SFAs are most needed in agri-food value chains that are highly diverse, as their complexity requires sense-making methods that are offered by the SFAs approach. Regions that combine complexity with high environmental impacts are the most urgent places to apply SFAs. Livestock production intensive regions, characterized by the livestock units per hectare (LSU ha^{-1} - e.g.: Flanders (5.3), the Netherlands (3.8), Lombardi (2.6), Catalunya (2.3), Bretagne (2.7), Müntser (3.8), etc.) meet these criteria as their agri-food systems integrate across arable production, grasslands, livestock production, slaughter, waste processing and feed production/ processing (Eurostat, 2019). These complex agri-food chains, therefore, feature the unique possibility to drastically reduce harmful nutrient losses to the environment while increasing circularity by exploiting the largely untapped recovery potential of side streams (Rothwell et al., 2020). The present study aims to demonstrate the added value of a highly detailed SFA for the livestock-intensive region of Flanders (BE), thereby addressing the two knowledge gaps outlined above, namely:

- SFAs are a promising method for the investigation of agri-food chains, but they often lack detail to inform the implementation of specific (technological) interventions. This study will demonstrate the added value of a higher level of detail by disaggregating the Flemish agri-food chain into 40 nodes and 1827 flows.
- To the knowledge of the authors, there has been no SFA study employing a detailed classification of N and P flows beyond the identification of by-products. This study will present a replicable method to differentiate flows in SFAs, including the accounting for diffuse and point source pollution. As a result, detailed insights into the N and P flows in

Flanders will be generated. This includes the calculation of indicators that are relevant for formulating strategies to reduce environmental impact and integrate circularity in the agri-food chain.

Flanders has been selected as a case example as it is one of the most intensively cultivated regions in Europe. It has one of the highest livestock and population densities in Europe (5.3 LSU ha^{-1} vs EU-average of 0.8 LSU ha^{-1}; 492 inhabitants km^{-2} vs EU-average of 117 inhabitants km^{-2}), has high reactive nitrogen (Nr) emission intensities (51 kg Nr ha^{-1} vs EU-average 28 kg Nr ha^{-1}; data this study and Velthof et al., 2014), is classified as N vulnerable zone and possess one of the largest clusters for food processing. It is further considered that the economy of Flanders is structurally very similar to that of the EU as a whole (Government of Flanders, 2022). Flanders is therefore a good model to draw regional and EU-wide conclusions on how to reorganize the agricultural system.

2 MATERIALS & METHODS

2.1 System boundaries and key assumptions

The system boundaries applied in this study refer to the geographical boundary of the region of Flanders (BE) and the processes within the agri-food chain including the fate of nutrients after consumption. This implies that non-food industry (e.g. Haber-Bosch, mining), transportation and NOx emissions from energy use and N_2O emissions from land-use change are not considered. For the calculation of the systemic nutrient use efficiency, the geographical system boundaries are extended beyond the region of Flanders to account for the N and P utilized across the entire agri-food value chain (see section 2.4 and SM S2). The soil surplus was considered as a stock and derived from the soil N and P balance. The nutrient flows were normalized to the population of Flanders in 2018 (6,571,018) and expressed in kilogram $capita^{-1}$ $year^{-1}$ (kg cap^{-1} y^{-1}).

2.2 Data gathering and preservation of detail

Data collection employed a bottom-up approach with the objective to aggregate data only when necessary. This ambition implied that the detail of available data shapes the definition of nodes and flows. Researchers pursued every feasible route to identify and obtain detailed data. A key enabling factor in this effort was the commitment of government agencies to provide data (e.g. Flemish Environment Agency) (Vingerhoets et al. 2021). In total 54 private and public data sources were used starting from primary data derived from individual actors', economic and environmental statements (farms, industries, treatment facilities, households, etc.) (SM S3). This resulted in a total of 1827 flows and 40 nodes that enable the identification of different goods (e.g. soy meal or wheat) and emissions (e.g. distinction between N_2 and NH_3). This study subdivided conventional sectoral-based nodes into 40 more process-based components (e.g. arable land, grassland and horticulture in the case of crop production - Figure S1). To maintain the detail of the data, a standardized excel spreadsheet was developed and a Python model was created that could read the detailed data, calculate indicators and generate visuals (SM S5). Using this model reduced time for entering data and avoided pre-aggregation of data in excel (as required for example in the software STAN), which persevered the highest possible resolution.

2.3 Uncertainty analysis and data reconciliation

SFAs are based on the principle of conservation of mass. This implies that for every input (i.e. nutrients entering a process), an equal output (i.e. nutrients leaving a process) exists. When using raw data sources from different origins this principle often does not hold, therefore data reconciliation is required; which describes a statistical methodology that resolves contradictions in the data by finding a solution that closes the mass balance within a specific uncertainty interval (Cencic, 2016). To estimate the uncertainty of the flows that make up the model, a life cycle method for determining data quality called the "Pedigree" matrix method was used (Laner et al., 2016). This method involved scoring the 'criteria reliability', 'completeness', 'temporal accuracy', 'geographical specificity' and 'further correlations' on a scale from 1-4, based on which, a confidence interval for each substance flow was estimated (see SM S4 for the methodology and SM S8 for the estimated confidence intervals).

2.4 Indicator definition and technology scenario calculation

Using the reconciled data eight indicators are employed to assess the efficiency, environmental burden, circularity, and potential for increase in nutrient circularity. Table 1 shows the logic behind each indicator (for detailed methodology see SM S2). Calculating these metrics requires the classification of flows into 8 different categories (Figure 1).

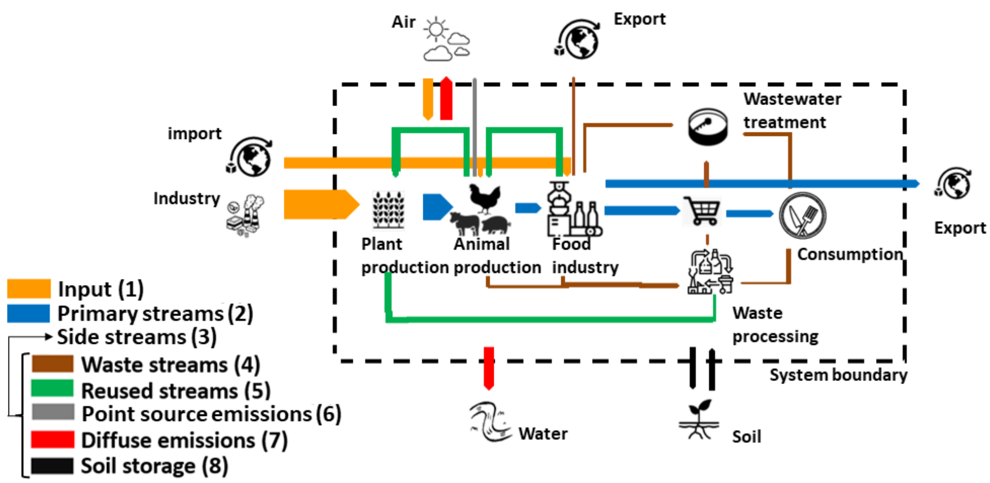


Figure 1*: Visualisation of nodes and life cycle concepts and definitions. (1) Input: nutrients entering the system. (2) Primary streams: Flows of desired products (i.e. goods that are the intended outcome of a process). (3) Side streams: Outputs that differ from the desired products, including flows to waste processing, flows directly reused, exported by-products and emissions. (4) Waste streams: a side stream that is processed and/or exported (5) Reused streams: a side stream that is reused by the domestic agri-food chain. (6) Point source emissions: losses to the environment originating from point sources (e.g. stable). (7) Diffuse emissions: Losses to the environment originating from point sources. (8) Soil storage exchange: The exchange with soil storage is calculated by drawing a mass balance at soil level. There can be net nutrient storage or withdrawal.*

Inspired by LCAs, and more specifically consequential LCA (Schaubroeck et al., 2021), in this research a distinction has been made between *primary and side streams*. A primary stream describes a flow of desired products (i.e. goods that are the intended outcome of a process). Contrary to this, *side streams* comprise all by-products, including flows to waste processing, flows that are directly reused and emissions. A specific case of a side stream is a *reused stream* which is domestically (i.e. excluding export) reused in the agri-food value chain, such as the direct reuse of manure or reuse of processed waste. Side streams that are processed or exported are termed *waste streams* in this study. A novel classification is the distinction between losses to the environment originating from non-point sources or point sources (see SM S8 for how this has been applied). The rationale behind this distinction is that emissions from point sources, such as stables and wastewater treatment plants (WWTPs), can be considered flows from which it is technically feasible to recover N and P. This distinction is novel to SFAs and enables the calculation of indicators related to the systemic efficiency of N and P and future recovery potentials.

Input (Eq. 1) and *emissions* (Eq. 2) provide information on the resource consumption and environmental pressures of the agri-food system. The *overall nitrogen and phosphorus use efficiency* (NUE and PUE) and *nutrient use efficiency per node* are determined (Eq. 3, Ma et al., 2010). Based on Leip et al. (2014), this study employs the *nutrient investment factor* to indicate the virgin nutrient requirement of a food product (Eq. 4). To realize this in a consistent manner, feed imports are replaced in the calculation with the specific fertilizer consumption of the feed product by dividing the values by the derived NUE and PUE of the previous production processes (SM S2). Another novel indicator is the assessment of *recoverable streams*, which quantifies the amount of N and P embedded in side streams of point source origin (Eq. 5); thereby indicating the additional potential for resource recovery in a system. Quantifying the total recoverable streams carries the risk of double counting the same nutrients at different stages of the agri-food chain. This was avoided by accounting only for the side streams produced during the production and consumption stages. The *domestically recovered streams indicator* informs about the quantity of side streams that are reused in the agri-food chain (Eq. 6). Additionally, the *domestic recovery efficiency* is then defined as the ratio of recovered streams to recoverable streams (Eq. 7). Finally, the *reuse efficiency* gives more insights into the current circularity of the agri-food system as it measures the share of recovered streams in relation to total inputs (Eq. 8).

To evaluate the effect of the implementation of recovery technologies for the six largest unexploited recoverable side streams the change of indicators was calculated. A detailed overview of the assumptions and calculations can be found in SM S7.

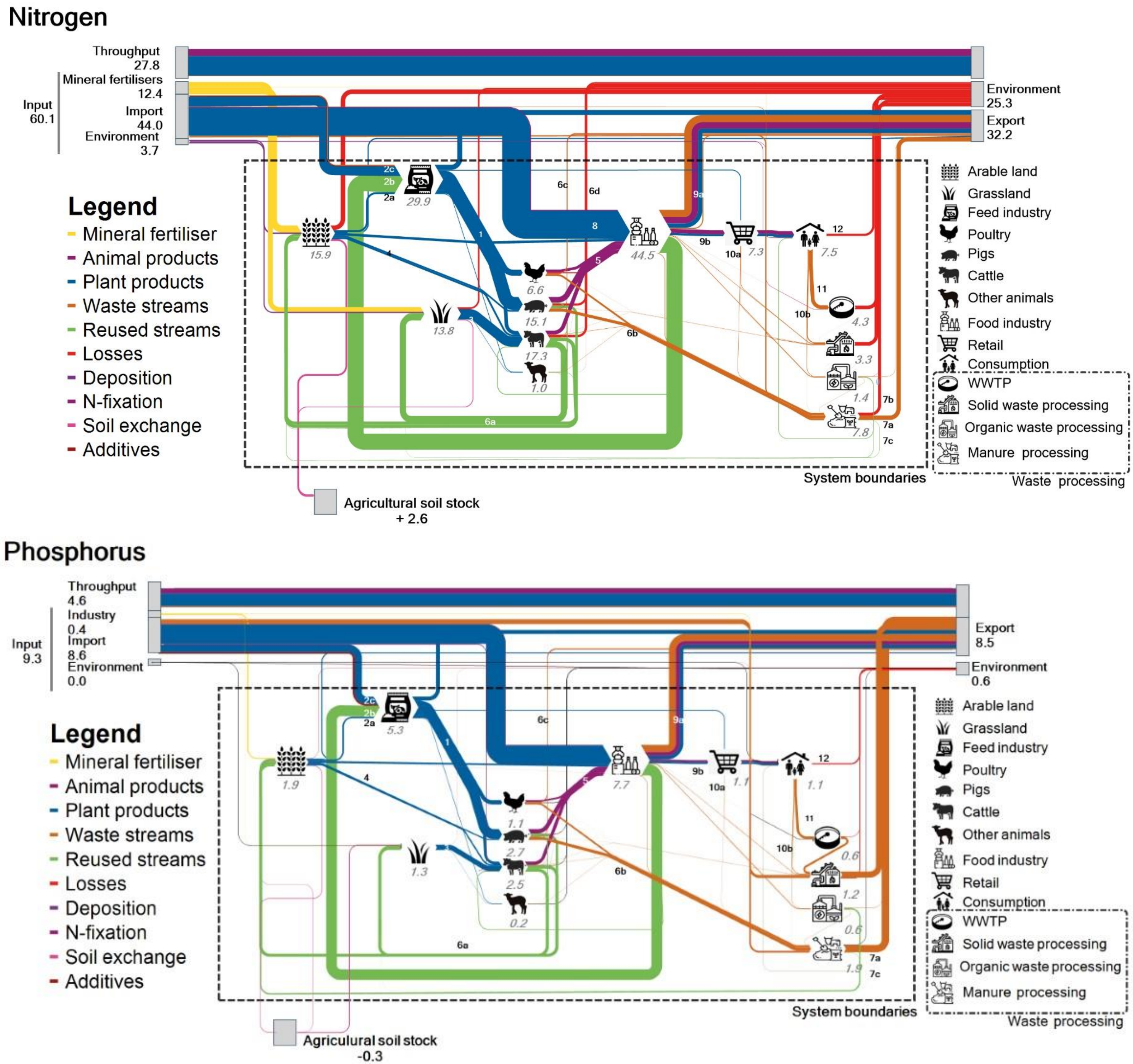
Table 1 Calculation methodology of metrics to assess food system performance. For more detailed calculations see SM S2.

Indicator	Formula	Unit	#	Question answered by indicator
Input	$Total\ input\ \text{-}\ logistic\ transit$	kg N or P cap^{-1} y^{-1}	Eq. 1	What is the absolute nutrient demand of the agri-food chain? What is the intensity of the nutrient metabolism?
Emissions	$Reactive\ N\ or\ P\ flows\ to\ the\ environment$	kg N or P cap^{-1} y^{-1}	Eq. 2	How much N and P is lost to the environment?
Nutrient use efficiency (NUE + PUE)	$\frac{Primary\ stream}{Total\ input}$	%	Eq. 3	How efficient is the agri-food chain? What is the relative nutrient input?
Nutrient investment factor	$\frac{Input - Reused\ stream}{Primary\ stream}$	kg N or P invested//kg N or P product	Eq. 4	What is the relative nutrient consumption per food product? Which food product has the most efficient production chain?
Recoverable streams	$Output - Diffuse\ emissions - Soil\ storage - Primary\ streams$	kg N or P cap^{-1} y^{-1}	Eq. 5	What is the theoretical maximum amount of N or P that can be recovered?
Domestically recovered streams	$Reused\ streams - Imported\ reused\ streams$	kg N or P cap^{-1} y^{-1}	Eq. 6	How circular is the system? How much N and P are reused?
Domestic recovery efficiency	$\frac{Domestically\ recovered\ streams}{Recoverable\ streams}$	%	Eq. 7	How much more N and P could potentially be recycled?
Reuse efficiency	$\frac{Domestically\ recovered\ streams}{Input + Domestically\ recovered\ streams}$	%	Eq. 8	How circular is the system? How (in)dependent is the agri-food chain of external sources?

3 RESULTS

3.1 Overall system mass balance

The N and P balance of the Flemish agri-food system shows a total input of 87.9 ± 2.4 kg N cap^{-1} y^{-1} and 13.9 ± 0.4 kg P cap^{-1} y^{-1}, of which 71.8 ± 2.1 kg N cap^{-1} y^{-1} and 13.2 ± 0.4 kg P cap^{-1} y^{-1} are originating from imports (Figure 2). A share of the imports, namely 27.8 ± 0.8 kg N cap^{-1} y^{-1} and 4.6 ± 0.1 kg P cap^{-1} y^{-1} is directly re-exported without undergoing any processing ("throughput"). The processed input in the Flemish agri-food system equals therefore 60.1 ± 1.6 kg N cap^{-1} y^{-1} and 9.3 ± 0.3 kg P cap^{-1} y^{-1}. Imported plant and animal products to food processing account for more than half of the nutrients input (50% of N, 53% of P), another large share is made up of mineral fertilizers for agriculture (21% of N, 4% of P) and the feed industry (18% of N, 20% of P). The remaining minor faction of the nutrients enter the system as imported side streams to waste management nodes (4% of N, 15% of P), chemical additives to feed industry (1% of N, 5% of P) and flows originating from the environment (6% of N, 3% of P) including nitrogen fixation (0.7% of N). The total output consists of the export of food products (19% of N, 20% of P), composite feeds (8% of N, 11% of P), export of side streams (27% of N, 61% of P) including manure (9% of N, 8% of P), and emissions directly lost to the environment (39% of N, 4% of P). The remainder of the nutrients (7% of N, 4% of P) is assumed to enrich agricultural and non-agricultural soils.



Nitrogen
Throughput 27.8
Input 60.1
Mineral fertilisers 12.4
Import 44.0
Environment 3.7
Environment 25.3
Export 32.2
Legend
Mineral fertiliser
Animal products
Plant products
Waste streams
Reused streams
Losses
Deposition
N-fixation
Soil exchange
Additives
Arable land
Grassland
Feed industry
Poultry
Pigs
Cattle
Other animals
Food industry
Retail
Consumption
WWTP
Solid waste processing
Organic waste processing
Manure processing
System boundaries
Waste processing
Agricultural soil stock + 2.6
Phosphorus
Throughput 4.6
Input 9.3
Industry 0.4
Import 8.6
Environment 0.0
Export 8.5
Environment 0.6
Legend
Mineral fertiliser
Animal products
Plant products
Waste streams
Reused streams
Losses
Deposition
N-fixation
Soil exchange
Additives
Arable land
Grassland
Feed industry
Poultry
Pigs
Cattle
Other animals
Food industry
Retail
Consumption
WWTP
Solid waste processing
Organic waste processing
Manure processing
System boundaries
Waste processing
Agriculural soil stock -0.3

Figure 2 The nitrogen (top) and phosphorus (bottom) balance of the agri-food system in *Flanders with reconciled data in kg N and P cap^{-1} y^{-1} (more detailed information on flows and flow values can be found in SM8). Numbers below the nodes indicate the total N and P processed in the respective node. The colour of the flows represents the product category associated with the flow: mineral fertilizer (yellow), animal product (purple), plant products (blue), side streams (brown), reused streams (green), losses (red), deposition (violet), N-fixation (magenta), soil (pink) and additives (burgundy).*

3.2 Nutrient flows in the agri-food system

3.2.1 Processes contributing to nutrient flows

As the Flemish agri-food system (Figure 2), is characterized by intensive livestock production, feed flows have a dominant position in the nutrient budget (40.0 kg N cap^{-1} y^{-1} and 6.5 kg P cap^{-1} y^{-1}). Composite feeds (Flow 1) from the feed industry (24.0 kg N cap^{-1} y^{-1} and 4.2 kg P cap^{-1} y^{-1}), produce from local crop production (Flow 2a - 2.0 kg N cap^{-1} y^{-1}and 0.4 kg N cap^{-1} y^{-1}), side streams of food-industry (Flow 2b - 16.5 kg N cap^{-1} y^{-1} 2.7 kg P cap^{-1} y^{-1}), and imported products (Flow 2c - 11.5 kg N cap^{-1} y^{-1} 2.3 kg P cap^{-1} y^{-1}) serve as main input to fulfil the nutrient demand of the feed industry. The additional nutrients required to sustain the livestock production originate from grazing (Flow 3 – 10.7 kg N cap^{-1} y^{-1} 1.3 kg P cap^{-1} y^{-1}) and fodder crops from arable farming (Flow 4 – 3.5 kg N cap^{-1} y^{-1} 0.7 kg P cap^{-1} y^{-1}).

Around one-third of the consumed nutrients are assimilated into animal products (Flow 5 – 13.0 kg N cap^{-1} y^{-1} and 2.4 kg P cap^{-1} y^{-1}) and the remainder is excreted by the animal (27.0 kg N cap^{-1} y^{-1} and 4.1 kg P cap^{-1} y^{-1}). The nutrients associated with the manure excreted are either directly reused for crop production (Flow 6a – 53% of N, 61% of P in manure), processed in manure processing facilities (Flow 6b – 20% of N, 32% of P in manure), or exported without processing to surrounding regions (Flow 6c – 6% of N, 7% of P in manure). In stables, 21% of the N excreted is leaving as gaseous emission (52% NH_3, 44% N_2, 4% N_2O) before it reaches the agricultural field or treatment facilities (Flow 6d). The nutrients contained in the processed manure are either exported (Flow 7a - 57% of N and 96% of P), lost to the environment (Flow 7b - 38% of N), or used in crop production (Flow 7c - 5% of N and 4% of P). Nutrients contained in animal excreta are the main input for crop production with 49% of N-input and 78% of P-input.

Input to the food processing sector originates for 34% of N and 36% of P (15.0 kg N cap^{-1} y^{-1} 2.8 kg P cap^{-1} y^{-1}) from within Flanders. Consequently, Flanders relies for the larger share on imports, namely 66% of N and 64% of P (Flow 8 - 29.5 kg N cap^{-1} y^{-1} 4.9 kg P cap^{-1} y^{-1}). Furthermore, 44% of N and 47% of P the processed nutrients in the food industry are heading to processes outside the system boundary (Flow 9a - 19.4 kg N cap^{-1} y^{-1} and 3.6 kg P cap^{-1} y^{-1}). In nearly equal shares this comprises primary products (10.1 kg N cap^{-1} y^{-1} and 1.7 kg P cap^{-1} y^{-1}) and side streams (9.3 kg N cap^{-1} y^{-1} and 1.9 kg P cap^{-1} y^{-1}) mainly made up of oil seed meals. Another 6.5 kg N cap^{-1} y^{-1} and 0.9 kg P cap^{-1} y^{-1} find their way to retail facilities in Flanders (Flow 9b - 15% of N and

12% of P). A share larger than all primary products generated in the food industry, namely 18.6 kg N cap^{-1} y^{-1} and 3.2 kg P cap^{-1} y^{-1} can be found in side streams that are reused or processed within Flanders. Of the food that makes it to retail, 16% of the N and P is not purchased by catering or households (Flows 10a +10b - 1.8 kg N cap^{-1} y^{-1} and 0.2 kg P cap^{-1} y^{-1}) but is wasted and processed in the waste management system. The consumed nutrients end up in the wastewater, of which 86% undergoes sewage treatment (Flow 11), while the remainder is directly or after domestic (septic tank) treatment discharged into the environment (Flow 12 - 14%). Sewage treatment plants remove 80% and 82% N and P load, while the remainder is discharged to the surface water (0.9 kg N cap^{-1} y^{-1} and 0.1 kg P cap^{-1} y^{-1}). Through the nitrification-denitrification process, 66% of N is emitted mainly as N_2 to the atmosphere, and 14% of N is assimilated in the activated sludge. All of the removed P can be found in the sludge. A more detailed description of processes and the complete dataset can be found in SM S6 and SM S8.

3.2.2 Recovery potential

In the Flemish agri-food system, 59.6 ± 2.4 kg N cap^{-1} y^{-1} and 10.0 ± 0.3 kg P cap^{-1} y^{-1} of potentially recoverable side streams are produced, of which currently 32.6 ± 2.2 kg N cap^{-1} y^{-1} (recovery efficiency = 55%, reuse efficiency = 35%) and 5.6 ± 0.3 kg P cap^{-1} y^{-1} (recovery efficiency= 56%, reuse efficiency = 37% for P) are reused or recovered within Flanders (Figure 3). Of the recovered N and P, 96% of N and 93% of P are directly reused without undergoing any processing in the waste management nodes, while only 4% of N and 6% of P are recycled by nutrient recovery processes used in the waste processing industry. Side streams from the food industry reused in the feed industry account for 17.5 kg N cap^{-1} y^{-1} and 2.9 kg P cap^{-1} y^{-1} and consist to the largest share of oilseed meal and slaughterhouse waste. The largest fraction of cattle manure (10.1 kg N cap^{-1} y^{-1} and 1.6 kg P cap^{-1} y^{-1}) and circa half of the pig manure (3.5 kg N cap^{-1} y^{-1} and 0.8 kg P cap^{-1} y^{-1}) is directly applied on agricultural fields.

Waste management treats a total of 16.0 kg N cap^{-1} y^{-1} and 3.8 kg P cap^{-1} y^{-1}. Of this 82% of N and 68% of P or 13.2 kg N cap^{-1} y^{-1} and 2.6 kg P cap^{-1} y^{-1} originates from within the Flemish agri-food system, consisting of domestic and industrial wastewater treated by public and industrial WWTPs (4.2 kg N cap^{-1} y^{-1} and 0.7 kg P cap^{-1} y^{-1}), excess manure destined for manure processing (5.4 kg N cap^{-1} y^{-1} and 1.3 kg P cap^{-1} y^{-1}), solid organic waste originating from food industry, retail, and consumption, including slaughter waste (2.7 kg N cap^{-1} y^{-1} and 0.4 kg P cap^{-1} y^{-1}), cadavers, animal meals destined for incineration (0.6 kg N cap^{-1} y^{-1} and 0.2 kg P cap^{-1} y^{-1}), and pet excreta which are incinerated via municipal solid waste collection (0.3 kg N cap^{-1} y^{-1} and 0.1 kg cap^{-1} y^{-1}). Nutrients embedded in imported waste streams or originating from the environment (e.g. N embedded in groundwater infiltrating sewage) make up the remainder of the input of the waste management system and account for 4.8 kg N cap^{-1} y^{-1} and 1.2 kg P cap^{-1} y^{-1}. Only 1.3 kg N cap^{-1} y^{-1} and 0.2 kg P cap^{-1} y^{-1} (8% of N, 6% P) of the total nutrient input to the waste management nodes is recycled in regionally used products, such as digestate and compost; while 10.1 kg N cap^{-1} y^{-1} and 0.2 kg P cap^{-1} y^{-1} are lost to the environment (63% of N-input and 5% of P-input) and 4.6 kg cap^{-1} y^{-1} and 3.4 kg P cap^{-1} y^{-1} are exported (29% of N-input and 88% of P-input). Furthermore, 9.2 kg N cap^{-1} y^{-1} and 5.4 kg P cap^{-1} y^{-1} of side streams are exported without being processed in the waste management nodes, including oil seed meal, poultry manure and animal by-products. Six major untapped recoverable side streams can be identified (Figure 3) these are: treated municipal wastewater (3.9 kg N cap^{-1} y^{-1} and 0.6 kg P cap^{-1} y^{-1}), dried and exported poultry manure (2.6 kg N cap^{-1} y^{-1} and 0.6 kg P cap^{-1} y^{-1}), activated sludge-treated pig and cattle manure (2.8 kg N cap^{-1} y^{-1} and 0.6 kg P cap^{-1} y^{-1}), point source ammonia (NH_3) emissions (5.8 kg N cap^{-1} y^{-1}), exported oil seed meals (6.1 kg N cap^{-1} y^{-1} and 1.2 kg P cap^{-1} y^{-1}), and incinerated and exported animal by-products (C3) (1.2 kg N cap^{-1} y^{-1} and 0.5 kg P cap^{-1} y^{-1}).

Figure 3: The figure shows the fate of N and P embedded in recoverable streams. The inner circle shows in purple (colour) the total recoverable streams. When there is no colour, this indicates an import. The middle orbit shows the origin of the streams (grey corresponds to import). The outer orbit indicates whether the stream is domestically recovered (i.e. reused). The recovery and reuse efficiencies are shown for N and P.

3.2.3 Efficiency of the agri-food chain

The final efficiency of the entire Flemish agri-food chain is 11% for N and 18% for P. Excluding efficiency losses of the retail and consumption phase, the efficiency is 16% for N and 25% for P.

This efficiency gain is a result of the fact that approximately 30% of N and P embedded in the primary food products are lost in the retail and consumption phase. For individual sectors, the variability in nutrient use efficiency ranges between 23-100% for NUE and 32%-100% for PUE (Figure 4 A).

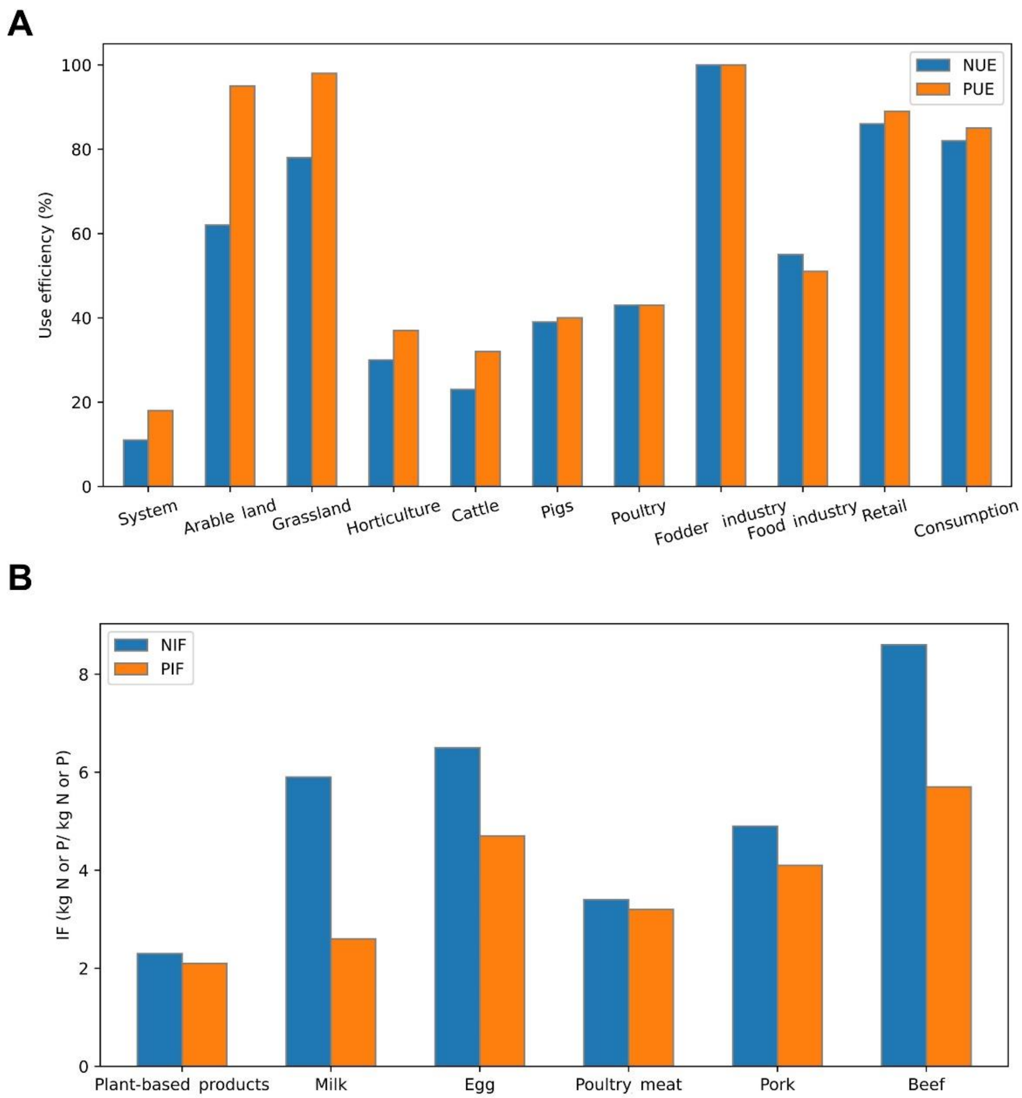


Figure 4: A) Nutrient use efficiencies for N and P (NUE, PUE) for different (sub)processes. B) Nitrogen and phosphorus investment factors (NIF, PIF) for different food categories (kg N or P input kg^{-1} N or P in product).

The N and P investment factors, or the amount of N needed to produce one kg N contained in a product, are lowest for the average of plant-based products with 2.3 for N and 2.1 for P (Figure 4 B). For livestock products, all factors are above 3 for N and 2.5 for P. Large differences were found between the nutrient investment factors of different livestock food categories. Poultry meat had the lowest investment factors of 3.4 for N and 3.2 for P. The investment factors for pig meat were at a lower end of the spectrum for animal food products (3.4-8.6 for N; 2.6-5.7 for P). Beef recorded the highest N and P requirements with 8.6 and 5.7, respectively.

3.2.4 Emissions to air and water

Emissions to air and water account for 39% and 4% of the N and P output (23.5 kg N cap^{-1} y^{-1} and 0.31 kg P cap^{-1} y^{-1}). Almost half of the nitrogen emissions occur in the form of reactive emissions (i.e. excluding N_2 - 10.0 kg N cap^{-1} y^{-1} and 0.31 kg P cap^{-1} y^{-1}). Nr emissions mainly find their origin in agricultural fields (49%), animal production (33%), municipal WWTPs (9%) and untreated domestic wastewater (7%). The most important P emissions originate from municipal WWTPs (33%), crop production (32%), and untreated domestic wastewater (30%) (Figure 5 A).

Around 80% of the N emissions are atmospheric, consisting of 13.6 kg of N_2 and 5.0 kg NH_3-N and 0.7 kg N_2O-N cap^{-1} y^{-1}, 0.1 kg NO_x-N (Figure 5 B). Crop production and animal husbandry are the main sources of reactive atmospheric emissions, contributing to 39% and 56% of the reactive gaseous N emissions, respectively. In crop production, the Nr is mainly released as NH_3 when fertilizers and animal manure are applied (Arable land: 1.1 kg NH_3-N cap^{-1} y^{-1}, grassland: 0.6 kg NH_3-N cap^{-1} y^{-1} and horticulture: 0.1 kg NH_3-N cap^{-1} y^{-1}). The amount of NH_3 emissions generated through fertilization depends upon the product form: mineral N-fertilizers generate 0.4 kg NH_3-N cap^{-1} y^{-1}, while animal manure applications are responsible for 1.4 kg NH_3-N cap^{-1} y^{-1}. NH_3 emissions released by livestock production are mainly a result of NH_3 volatilization in stables and manure storage (Pigs: 1.4 kg NH_3-N cap^{-1} y^{-1}, Poultry: 1.0 kg NH_3-N cap^{-1} y^{-1}, Cattle: 0.5 kg NH_3-N cap^{-1} y^{-1} and other animals: 0.1 kg NH_3-N cap^{-1} y^{-1}). Only 5% of the reactive gaseous N emissions are attributed to waste management (0.14 kg N cap^{-1} y^{-1}), including wastewater and manure processing. A considerable amount of N is lost to the atmosphere as non-reactive N_2 via the activated sludge processes (5.4 kg N_2 cap^{-1} y^{-1}, 41% of total N_2-losses).

The total aquatic nutrient emissions equal 4.1 kg N cap^{-1} y^{-1} and 0.31 kg P cap^{-1} y^{-1} (Figure 5 C). Nutrient fluxes into water bodies are primarily caused by leaching and erosion from crop production (Arable land: 1.7 kg N cap^{-1} y^{-1} and 0.07 kg P cap^{-1} y^{-1}, grassland: 0.65 kg N cap^{-1} y^{-1} and 0.03 kg P cap^{-1} y^{-1} and horticulture 0.15 kg N cap^{-1} y^{-1} and 0.006 kg P cap^{-1} y^{-1}). The remainder of the aquatic nutrient emissions can be attributed to nutrients embedded in discharged wastewater. About, 84% of the produced wastewater is collected by the sewer network and treated by WWTPs. These are responsible for a flow of 0.85 kg N cap^{-1} y^{-1} and 0.1 kg P cap^{-1} y^{-1} to the surface water, by discharging nutrients with treated effluent and untreated wastewater via storm overflows. As 16% of the domestic wastewater is not treated by the municipal WWTPs, their wastewater is discharged without dedicated nutrient removal (e.g. after septic tank treatment) and nearly all nutrients embedded in this untreated wastewater end up in the Flemish surface waters (0.7 kg N cap^{-1} y^{-1} and 0.1 kg P cap^{-1} y^{-1}).

3.3 Technology scenario

Using detailed N and P accounting makes it feasible to identify hotspots, such as nodes with high N losses, that are promising for the implementation of (technological) interventions. The effect of technological improvements can be evaluated by measuring the change in indicators. A detailed overview of the assumptions and calculations can be found in the SM S7. The implementation of recovery technologies and measures for the six largest unexploited recoverable side streams showed that the combined measures could recover 13.5 kg N cap^{-1} y^{-1} and 1.8 kg P cap^{-1} y^{-1}. Thereby, increasing the recovery efficiency by +22.7% for N and +17.6% for P, the reuse efficiency by +14.6% for N and +24.4% for P and the NUE +1.5% for N and +2.6% for P (Table 2).

Table 2: Systemic effects of technology implementation for the six major unexploited recoverable side streams. A detailed overview of the assumptions and calculations can be found in SM S7. (SF= solid fraction, LF=Liquid fraction)

Side stream	Recoverable nutrients (kg cap^{-1} y^{-1})		Current scenario	Proposed technology scenario	New Product	Recovered steams (kg cap^{-1} y^{-1})		Recovery efficiency		Reuse efficiency		NUE	
	N	P				N	P	N	P	N	P	N	P
Pig manure, cattle manure and digestate	2.8	0.6	Raw manure/digestate is separated into SF (exported) and LF which is treated by activated sludge treatment	LF of digestate, pig and cattle manure (i.e. after solid-liquid separation) flowing to the activated sludge process is pre-treated by an NH_3-stripper-scrubber process (57% N recovery efficiency)[a].	Ammonium Sulphate	1.0	0.0	+1.7	0.0	+ 1.1	0.0	+0.1	0.0
Poultry manure	2.6	0.6	Poultry manure is biothermically dried and exported	Poultry manure is treated by Poul-AR technology; Ammoniacal nitrogen of poultry manure is recovered through ammonification followed by stripping-scrubbing (80% of N recovery efficiency), making the substrate useable in a mono-digester whereafter it is dried and exported[b].	Ammonium Sulphate	2.1	0.0	+3.5	0.0	+2.3	0.0	+0.2	0.0
Point source emission	5.8	0	Gaseous emissions from stables are barely recovered	Implementation of stable air-scrubbers (N recovery efficiency 90%) at stables without low emission practices in place.	Ammonium Sulphate	2.5	0.0	+4.2	0.0	+2.7	0.0	+0.2	0.0
Animal by-products (C3)[h]	1.2	0.5	Incinerated or exported	Implementation of sanitation technologies such as pressure sterilization can derive processed proteins from non-ruminant animal by-products (C3) that can be used in the feed industry[d,e].	Feed	1.2	0.5	+2.0	+5.0	1.3	+3.4	+0.2	+0.7
Oilseed meal	6.1	1.2	Exported	Domestic reuse in feed processing can replace imported feed[e].	Feed	6.1	1.2	+10.2	+12.2	+6.6	+8.2	+0.8	+1.8

Municipal wastewater	3.9	0.6	Wastewater is treated by activated sludge whereafter sludge is digested and incinerated.	For all WWTPs equipped with a digester, phosphorus and nitrogen are recovered as struvite from digested sludge (5.3% P recovery efficiency)[f].	Struvite	0.5	0.0	+0.9	+0.4	+0.5	+0.3	+0.0	+0.1
Combined	22.4	3.5				13.5	1.8	+22.5 *77%*	+17.6 *74%*	+14.5 *50%*	+24.4 *62%*	+1.5 *13%*	+2.6 *22%*

[a]N recovery efficiency of stripping-scrubbing as ammonium sulphate from LF of manure found by Brienza et al., (2021)
[b]N recovery efficiency of Poul-AR technology as ammonium sulphate from raw poultry manure found by NUTRIMAN project, (2019)
[c]N recovery efficiency of stable air-scrubbing as ammonium sulphate found by Sigurnjak et al., (2019)
[d]Commission regulation (EU) 142/2011
[e]Efficiency for feed industry found in the present study is assumed
[f]P recovery efficiency of NuReSys® as struvite from wastewater found by Ravi et al., (2022)
[g]The N and P embedded in the recovered product are assumed to have the same fertilization or feeding efficacy as mineral fertilizers or imported feed
[h]Animal by-products are classified according to the level of the health risk they present: C3 is the safest classification and includes animal by-products fit for human and feed consumption.

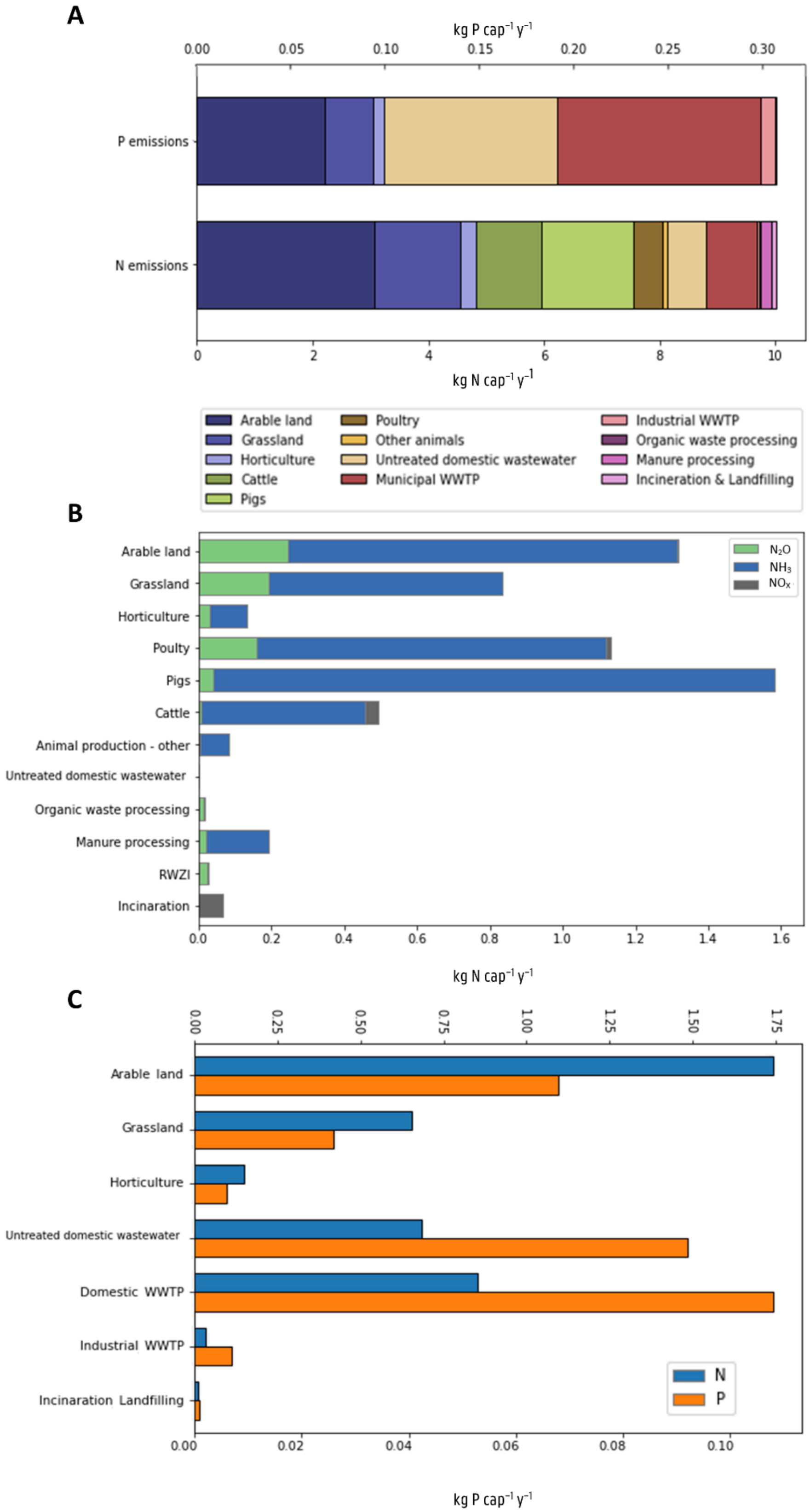

A
kg P cap⁻¹ y⁻¹
0.00
0.05
0.10
0.15
0.20
0.25
0.30
P emissions
N emissions
0
2
4
6
8
10
kg N cap⁻¹ y⁻¹
Arable land
Grassland
Horticulture
Cattle
Pigs
Poultry
Other animals
Untreated domestic wastewater
Municipal WWTP
Industrial WWTP
Organic waste processing
Manure processing
Incineration & Landfilling
B
Arable land
Grassland
Horticulture
Poulty
Pigs
Cattle
Animal production - other
Untreated domestic wastewater
Organic waste processing
Manure processing
RWZI
Incinaration
N_2O
NH_3
NO_x
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
kg N cap⁻¹ y⁻¹
C
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
Arable land
Grassland
Horticulture
Untreated domestic wastewater
Domestic WWTP
Industrial WWTP
Incinaration Landfilling
N
P
0.00
0.02
0.04
0.06
0.08
0.10
kg P cap⁻¹ y⁻¹

Figure 5: A) sum of all anthropogenic reactive N and P emissions to the environment. B) Emissions to air. C) Emissions to water.

4 DISCUSSION

4.1 Opening the SFA black box

A review of more than 60 SFA studies that investigated N and P flows, shows that this study is one of the most detailed yet. At the level of detail applied in this study, the estimation of systemic effects of specific technologies begins to be possible, enabling to gauge the efficacy of each option (section 3.3). At lower levels of detail, technology-specific insights are not possible but remain at the level of generic policy advice that can identify key leveraging points within systems. In the excellent work of Leip et al. (2022), the authors study scenarios for realizing the EU's Farm to Fork strategy ambition to reduce N emissions by 50% through modelling changes in NUEs in three nodes (farming, reduction of food waste and waste treatment, dietary changes). They conclude that in order to realize the EUs ambitions, technical measures and management improvements will be crucial to increase the NUE in crop and animal production. The question they leave unanswered is, which technologies can contribute to this change in NUE? In other words, detailed SFAs can provide opportunities for technology evaluation, while coarser SFAs are more likely to be of value for hot-spot analysis only.

By comparing three available SFAs carried out for Flanders (Table 3) we can demonstrate that the level of detail has an impact on the indicators proposed in this study. Lower detail (measured as fewer flows and nodes) results in the reduced identification of recoverable streams. Coppens et al. (2016) closed the mass balance of the food industry by assuming that all the unaccounted for N and P were exported as a food product which resulted in an underestimation of recoverable side streams produced during food processing, retail and catering. Recoverable streams originating from point emissions were not accounted for due to the lack of information on the emission's origin. Estimates for input and recovered streams were similar as this relied on a few well-documented flows. This resulted in similar reuse efficiencies, but higher recovery efficiencies when compared to the present study (Table 3). Comparison to the study of Papangelou and Mathijs (2021) confirms our observation on the impact of detail. These authors describe the agri-food chain in 98 flows and 8 waste flows. As a result of this simplification, import and export at the food and feed nodes were quasi neglected which resulted in missing N and P imports at these nodes and propagated to previous nodes causing an underestimation of mineral fertilizer inputs. Similarly, values for recoverable and recovered streams were significantly lower as compared to our results. One reason for this is that a higher differentiation in the food and feed nodes enables the identification of nutrient-rich oilseed processing for which by-products are recovered. Consequently, lower resolution at these points reduces the identified amount of recoverable/recovered side streams and hence increases recovery/reuse efficiencies.

The above discussion shows that detail affects the outcome SFAs and their value for decision-making. However, a general definition of the required detail (e.g. in terms of nodes and flows), to evaluate specific technologies will vary between regions. Nonetheless, a number of key features that increase the information value of SFAs can be discerned.

- The nested hierarchy of nodes should be detailed to the level of major production/ treatment systems that permit the estimation of flow properties. Examples are progression from livestock nodes to nodes that detail types of livestock, a breakdown of agriculture into horticulture, grazing and arable agriculture, and different types of waste treatment such as anaerobic digestion and aerobic treatment.
- Flows need to be reclassified in accordance with their destination in the systems. Following the logic of LCA (Joensuu et al., 2019), but also inspired by environmental management that distinguishes between diffuse and point source emissions (European Environmental Agency, 2020). This perspective enables the capturing of the full potential for recovery, as otherwise, SFAs cannot inform the circular economy towards a more efficient reuse of N and P.
- Speciation (the chemical composition) of flows should be detailed as much as possible. For nitrogen especially different speciation (N_2, NOx, N_2O, NH_3, organic and inorganic) needs to be identified to understand environmental impacts, treatment requirements and recovery potentials.
- Concentrations of flows, or other measures of flow quality, should also be captured to understand actual recovery potentials. The reason for this is that many recovery technologies require sufficiently high concentrations to function effectively (Spiller et al. 2022) and hence are relevant for recovery potentials in the circular economy. Concentrations of flows are not assessed in this research, but attempts have been made to

combine SFAs with the assessment of concentrations of flows using relative statistical entropy for nitrogen in agri-food value chains (Sobantka et al., 2014) and for P recovery from wastewater treatment (Lederer and Rechberger, 2010).

Table 3: Number of flows, recoverable streams, recovered streams, input, recovery efficiencies and reuse efficiencies presented in three different SFA for the Flemish region. To make these calculations, the flows were categorized according to the terminology of section 2.4. When the source of emission was not communicated, it was assumed to be diffuse.

Reference	**Number of Flows**	**Recoverable streams (kg cap^{-1} y^{-1})**		**Recovered streams (kg cap^{-1} y^{-1})**		**Input (kg cap^{-1} y^{-1})**		**Recovery efficiency (%)**		**Reuse efficiency (%)**	
		N	P	N	P	N	P	N	P	N	P
Present study[a]	*1827*	*59.6*	*10.0*	*32.6*	*5.6*	*60.1*	*9.3*	*55*	*56*	*35*	*37*
Coppens et al. (2016)	*160*	*41.9*	*8.2*	*30.7*	*5.4*	*58.7*	*7.4*	*73*	*66*	*34*	*42*
Papangelou and Mathijs (2021)	*98*	*32.0*	*6.7*	*23.9*	*4.4*	*28.0*	*4.8*	*73*	*59*	*45*	*44*

4.2 Sustainable intensification and SFA

Recommended annual N and P intakes are 3.3 kg N capita^{-1} y^{-1} and 0.2 kg P capita^{-1} y^{-1} (EFSA, 2015 and Willett et al., 2019). Therefore, Flanders shows overconsumption of N and P with 4.5 kg N cap^{-1} y^{-1} and 0.7 kg P cap^{-1} y^{-1}. Reducing animal product consumption is a crucial mechanism to lower N and P intake as it was shown that they have nutrient investment factors four times higher than plant products (section 3.2.3). Leip et al. (2022) calculated that a shift towards demitarianism (i.e. reduced meat consumption) is essential to meeting environmental targets such as the reduction of N losses by 50% as set by the EU's F2F strategy (European Commission, 2020). The reduced efficacy of animal-based production systems is confirmed for livestock-intensive region Flanders (NUE of 11% and PUE of 18%), while regions with lower LSU (i.e. Wallonia - Papangelou and Mathijs (2021), Austria - Zoboli et al. (2016) and Spain - Álvarez (2018)) have NUE of more than 15 up to 50 and PUE of 19 up to >100.

The shift to demitarianism is unlikely to take place in the short term, hence as suggested by Leip et al. (2022), it needs to be paired with innovations along the agri-food value chain that increase NUE. Sustainable intensification is a shorthand for a set of such innovations, that include amongst others, improvements in feed management and N and P recycling (Willett et al., 2019). One pathway to increase the NUE is a shift towards efficient production systems. For livestock production, it can be expected that monogastric animals raised in stables realize higher feed-to-animal conversion efficiencies than livestock husbandry in cattle and grazing-dominated regions (Hou et al., 2016). This is confirmed for Flanders, where NUE per animal type we are with 23 for cattle, 39 for pigs and 43 for poultry on the higher end of the range of those reported in EU-27 countries (16 ± 3% for cattle, 32 ± 5 for pigs and 34 ± 8% for poultry (Groenestein et al., 2019); by far exceeding the overall livestock-sector efficiency of grazing dominated regions such as Ireland (10% for N and 18% for P vs. 32% for N and 36 for P in Flanders; Hou et al., 2016; Rothwell et al., 2020).

Intensification of production may also contribute to realizing the environmental objectives of the F2F, related to the reduction of fertilizers demand and systemic efficiency. Emissions from stables and manure can be captured and reused in intensive livestock systems as they are point sources of sufficiently large scale to implement recovery technologies (Ramirez-Contreras et al., 2022). Likewise, a comparatively large amount of side streams produced in the industrialized food industry can be utilized in intensive animal production (van Selm et al., 2022). If Flanders, as a livestock-intensive region, would exploit its full potential for reuse of recoverable streams up to 45% of N and 48% of P of the external nutrient input could be avoided. This implies that Flanders could exceed the 20% fertilizer reduction target specified in the F2F strategy (European Commission, 2020). Of course, this is only possible because of dependence on imported nutrients with food and feed of which more than three times N and 18 times more P imported than fertilizer (68% N, 73% P vs. 21% N, 4% P). These calculations emphasise that in particular for livestock-intensive regions detailed SFAs are of added value as they can assist in pinpointing recovery potentials, inform technology choices and the determination of the systemic efficiency gains of future interventions.

4.3 Emissions to the environment

A total of 8.6 kg Nr cap^{-1} y^{-1} and 0.1 kg P cap^{-1} y^{-1} is emitted throughout the agri-food chain processes prior to food retail and consumption, contributing to 78% and 32% of the total agri-food chain Nr and P emissions. This is considerably lower than the EU average (18 kg Nr cap^{-1} y^{-1} and 0.3 kg P cap^{-1} y^{-1}; Leip et al., 2014, Van Dijk et al., 2016). The discrepancy between our results and the EU average can be attributed to high import ratios of food and feed (circa 50% of N and P-input) allocating the N and P footprint of Flanders to other regions. As Leach et al. (2012) found that the Nr creation during the food production associated with the per capita food consumption in the Netherlands equals 20 kg Nr cap^{-1} y^{-1} (including reactive emissions associated with imported products) while only 9.4 kg Nr cap^{-1} y^{-1} is locally emitted (CBS, 2020a, CBS, 2020b), a similar value can be expected for the Flemish food consumption when the allocated N and P emissions of imported products are considered. Furthermore, reduced intensity of the NH_3 emissions produced per kg N fed was found in our study compared to the EU-averages for pork (0.10 vs 0.19 kg N-NH_3 N-fed^{-1}), poultry (0.06 vs 0.14 kg N-NH_3 N-fed^{-1}) and eggs (0.08 vs 0.18 kg N-NH_3 N-fed^{-1}) (Groenestein et al., 2019), which is likely due to the widespread implementation of good manure management practices, such as low-emission stables and air scrubbers that reduce NH_3-emissions from stables and manure storage significantly. Additionally, the focus on monogastric livestock farming in Flanders is also beneficial in terms of NH_3 emissions per amount of meat produced.

The intensive agriculture in Flanders with high mineral fertilizer input and dense livestock sector has a high nutrient input on agricultural fields (296 kg N ha^{-1} and 32 kg P ha^{-1}), which is elevated compared to other regions in Europe (166 kg N ha^{-1} and 17 kg P ha^{-1}). The increased nutrient input with a high share of manure is responsible for the elevated field emissions intensities found in Flanders per hectare (19 kg N-NH_3, 5 kg N-N_2O, 27 kg leached-N, 1 kg leached-P) compared to the European average (10 kg N-NH_3, 1 kg N-N_2O, 17 kg leached-N, 1 0.6 kg leached-P) (van Dijk et al., 2016; Velthof et al., 2014). Additionally, 30 kg N-NH_3 ha^{-1} and 2 kg N-N_2O ha^{-1} is lost in stables and manure storage, which adds up the total agricultural emissions per hectare to 83 kg N and 1 kg P.

Nr and P emissions associated with food consumption are small in European regions, including Flanders, compared to the rest of the world as the sewage treatment with denitrification technology is widespread and converts the major part of the consumed nutrients (4.5 kg Nr cap^{-1} y^{-1} and 0.7

kg P cap^{-1} y^{-1}) embedded in wastewater into N_2 and sludge biomass (P) (Shibata et al., 2017). However, while wastewater treatment has been relatively successful in Flanders, the associated emissions are considerably larger than the ones found in countries like the Netherlands (Smit et al., 2015), Denmark (Hutchings et al., 2014; Klinglmair et al., 2015) and Germany (Theobald et al., 2016) who were able to further reduce their emissions associated with consumption through a higher percentage of collected and treated sewage (Netherlands (99%), Denmark (99%) and Germany (97%)), high treatment efficiency and, investments in separated sewage systems reducing nutrients leached through storm overflows.

5 CONCLUSION

The indicators developed in this research show that Flanders has a relatively low overall nutrient use efficiency with 11% for N and 18% for P. As currently, only 55% and 56% of the 59.6 kg N cap^{-1} y^{-1} and 10.0 kg P cap^{-1} y^{-1} embedded in recoverable streams are recovered providing 35% and 37% of the total N and P-input. The results show however that optimized nutrient recycling could replace 45% of N and 48% of P of the external nutrient input. Therefore, Flanders could exceed the 20% fertilizer reduction target set by the F2F strategy, albeit only through dependence on feed and food imports (European Commission, 2020).

Three general conclusions about the role of detail in SFA studies can be drawn:

- Detailed accounting for N and P flows and nodes enables a higher level of identification of recoverable streams. Conversely, lower levels of detail lead to missing flows that could be recovered. High resolutions SFAs are therefore essential for driving forward the circular economy, especially in livestock-dense regions that offer a higher recovery potential than lower intensity or grazing-based systems.
- More detailed flow accounting allows the identification of the efficacy of specific technological interventions rather than just the identification of generic efficiency gains that are required. Highly detailed studies will aid the calculation of technology change scenarios. An effort that should be pursued to better inform the F2F. Indeed, monitoring requirements that may be stimulated by the F2F will likely stimulate more data gathering (European Commission, 2022), probably leading to the emergence of many more detailed SFAs in the future.

- Future research should focus on including concentration or other measures of flow quality as a parameter in SFAs. This will aid the understanding of actual recovery potentials as these are often dependent on high concentrations or quality (e.g. pathogenic contamination, organic N) of N and P. Detailed specification and speciation of flows can help to define flow concentration and quality with high accuracy in future research.

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