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# Participatory modelling of scenarios to restore nitrogen cycles in a nutrient-saturated area

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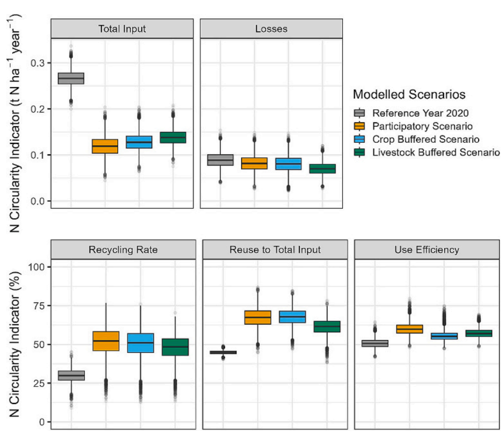
## HIGHLIGHTS

- New insights can improve stakeholders' quantitative input to model circular scenarios.
- Halving livestock numbers is not enough to reduce N losses substantially.
- Stakeholders do not envision livestock numbers to match locally available feed.
- NUE improvement of 6 % can be reached when crop and animal production are recoupled.
- Reduced livestock numbers must be combined with improved N efficiency and consumption.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

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## ABSTRACT

This paper aims to find socially acceptable solutions of circularity as measure to reduce nitrogen (N) losses and prevent environmental damage by combining participatory modelling and scenario Substance Flow Analyses (SFA). A local perspective was taken on the agro-food-waste system in the animal production-dominated German district Cleves. Three scenarios were programmed as Monte Carlo simulation of SFA with stakeholder input regarding crop allocation, livestock composition, livestock reduction, and manure allocation following the elimination of feed imports. The three scenarios either utilized the unaltered stakeholder input (PS), altered crop allocation to satisfy the demand for feed (CBS), or adjusted the livestock numbers to match the locally available feed (LBS). In the reference year (2020) agricultural losses amounted to 68 kg N year$^{-1}$ ha$^{-1}$ agricultural land and 116 kg N in feed was imported year$^{-1}$ ha$^{-1}$ agricultural land. In the PS feed import elimination led to deficits in feed availability. The LBS showed the biggest reduction of agricultural N losses and improved N use efficiency (+6 %), however agricultural losses were still high (50 kg N year$^{-1}$ ha$^{-1}$ agricultural land). The results show a

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limited effect of feed import elimination on N losses if no further measures are taken, such as reduced consumption of animal-based products. Further, the study shows that it is important to improve stakeholders' knowledge about approaches to circular agro-food-waste systems. The discrepancy between stakeholder visions and N circularity provide policy makers with the recommendation to improve stakeholders' visions of a circular agro-food-waste system.

## 1. Introduction

Traditional processes of recycling animal waste for crop production have become inefficient due to the introduction of relatively cheap fossil-based fertilizers (Theobald et al., 2016; Wang et al., 2021). This allowed specialization and intensification of farm production, leading to spatial disruption of nutrient cycles (Le Noë et al., 2018). This disruption of regional nutrient cycles has a spatially heterogeneous effect (De Vries et al., 2013). Areas with specialization in animal production can experience local nutrient oversaturation (Coppens et al., 2016; van der Wiel et al., 2021; Wironen et al., 2018). In such areas nutrients accumulate as the export of animal-sourced food does not compensate for the import of feed. Areas that produce the feed on the other hand experience soil degradation and rely heavily on inorganic fertilizers (Theobald et al., 2016). Overall, the current agro-food-waste system (AFWS) depends on continuous input of non-renewable resources, while nutrients brought into the system are lost to the environment (Kuokkanen et al., 2017; Steffen et al., 2015; Valve et al., 2020). Losses, in turn, can cause environmental problems such as the eutrophication of water bodies, which can have detrimental effects on local biodiversity and human health (De Vries et al., 2013; Van Grinsven et al., 2010).

Restoring circularity of the AFWS is recognized in research to reduce environmental impact (Frehner et al., 2022; Harder et al., 2021a; Velasco-Muñoz et al., 2021). Restoring nutrient circularity means that in animal-dominated areas the capacity to produce feed locally determines the number of livestock that can be kept locally (Frehner et al., 2022; Röös et al., 2016; Ryschawy et al., 2017). Currently this potential is not fully utilized as intensive crop and animal production often occur geographically separate (Bijon et al., 2022). However, such a systemic change of nutrient management in the AFWS is required to reduce environmental nutrient losses effectively (de Boer and van Ittersum, 2018; Vanhamäki et al., 2020). In this study, systemic change was defined as the emergence of a new pattern of organization or system structure aimed to solve the current challenges (Clarke and Crane, 2018).

Substance Flow Analysis (SFA) is an effective tool for analyzing nutrient flows, and could provide useful information on the expected impact of any systemic change in AFWS on nutrient flows and losses. Although providing important information, it is also acknowledged that any attempt to capture the complexity of the AFWS with a model comes with limitations. Important limitations include those related to the socio-economic and cultural aspects underlying everyday choices that farmers have to make. Stakeholder participation in scenario SFAs has potential efficacy to overcome a major challenge of nutrient flow analyses, i.e. access to nutrient flow and stock data (Zhang et al., 2020). Participatory modelling is a method which employs stakeholders' practical and administrative knowledge from the field in the process of decision making, besides scientific knowledge (Sattler et al., 2022). Incorporating a participatory approach with SFAs through a bottom-up approach has been shown to allow access to otherwise tacit knowledge and data (Martin-Ortega et al., 2022; Nanda et al., 2020). Moreover, cooperation with stakeholders facilitates the implementation of system changes (Metson et al., 2012; Whitney et al., 2018). Vanhamäki et al. (2020) illustrated specifically that a regional approach, in which the area is defined by common characteristics, such as data collection and level of regulations, could facilitate the transition towards circularity. Involving different stakeholders, like farmers and waste managers, considers a wider range of visions and gives stakeholders a sense of legitimacy (van der Wiel et al., 2023).

Till now no research has presented a participative approach to modelling scenarios attempting to restore N circularity in an animal-dominated, nutrient-saturated region. This paper aims to develop socially acceptable solutions to reduce N losses and prevent local environmental damage by incorporating stakeholder visions in scenario SFAs through participatory modelling. The study uses nutrient flow scenarios to assess the impact of systemic changes aimed at restoring local nutrient circularity in a complex AFWS. The stakeholders provided information about the, in their vision, likely changes in crop allocation, livestock composition, livestock reduction and manure allocation, following elimination of feed import from outside the study area. The hypothesis that feed import elimination can reduce environmental impacts, is rooted in the observation that feed import is the main driver of nutrient linearity in the district studied contributing largely to nutrient losses (van der Wiel et al., 2021).

## 2. Materials and methods

### 2.1. The agro-food-waste system of Cleves district

This study focused on the AFWS of Cleves district in the Federal State of North Rhine-Westphalia, Germany. Cleves was selected as it experiences environmental issues associated with nutrient losses from agricultural activities. Groundwater and surface water bodies in Cleves exceed the threshold of 50 mg nitrate $L^{-1}$ as set in the Nitrates Directive (Directive 2000/60/EC) (NRW, 2014). The system studied encompassed the subsystems crop production, animal production, food and feed processing industry, consumption and waste management (van der Wiel et al., 2020). The waste management subsystem comprises municipal solid organic waste, wastewater and biogas production.

The 1233 $km^2$ district lies along the river Rhine. In the reference year of 2020, the population was just over 300,000 (Statistische Ämter des Bundes und der Länder, 2021). The population density was 254 inhabitants per $km^2$. Local diets contain around 70 % animal-sourced and 30 % plant-based protein (Fig. 1). Cleves borders the Netherlands to the west and the German districts of Borken, Wesel and Viersen to the north, east and south respectively. The bordering districts in Germany, as well as the Netherlands, are net importers of nutrients and have their own nutrient surplus. An economically important sector in the area is the food and feed processing industry. Multiple larger companies are located in the district (e.g. ForFarmers (feed processing), Katjes (candy manufacturing), Pfeiffer & Langen (sugar production)). The human population in the district is for 92 % connected to centralized municipal wastewater treatment plants, providing potential for recovery of nutrients from wastewater (Statistische Ämter des Bundes und der Länder, 2022), as currently nutrients are not recovered to a larger extent. In the reference year 2020, 45 % of the biogas substrate (in fresh mass) was maize silage, 12 % consisted of different types of manure and the rest were other vegetal sources (Landwirtschaftskammer Nordrhein-Westfalen, 2012; Settnik, 2019).

With 57 % of the total area covered by farmland (73,014 ha) and 13 % with urban activities, the area is mostly rural. The agricultural land is divided in 70 % cropland and 30 % grassland. However several large urban centers, such as the Ruhr region, are in the vicinity. Agriculture is dominated by animal production (138,137 large livestock units (LLU)). Cattle made up the largest proportion of the livestock (63 %), followed by pigs (28 %), poultry (4 %) and other animals (4 %). In 2020 livestock density was on average 2 LLU ha $^{-1}$ agricultural land. To feed these animals in the reference year 2020, 66 % of the N in feed was imported into the study area (8490 metric tonne N year$^{-1}$), while 34 % was produced locally. The locally available feed consisted of 45 % grass-based feed. Crop production is characterized by cash crop production (i.e. potato with 13 % of arable land) and feed production (i.e. maize silage with 36 % of arable land).

### 2.2. Stakeholder involvement

Actors stemming from all the subsystems of the AFWS (crop production, animal production, food processing, consumption and waste management) in district Cleves were identified and selected representatives were invited to provide input to the participatory modelling. Stakeholders invited included those that provided data for the base study (van der Wiel et al., 2021) and additionally, farmers from the district were invited. Furthermore, scientists and environmental non-governmental organisations were involved. Stakeholder input was gathered during the summer of 2022. In total nine stakeholders stemming from five stakeholder groups representing the AFWS evenly contributed to the participatory modelling. The stakeholder groups were farming ($n = 2$), food processing ($n = 1$), nature conservation (n = 2), research (n = 2) and waste management (n = 2). The input from the stakeholders was gathered using a questionnaire (Supplementary Material) and one-on-one interviews thereafter.

Stakeholders were asked for their vision on expected changes to four critical aspects, namely crop allocation, livestock composition, livestock reduction and manure allocation, resulting from the eliminating the import of livestock feed into the region. Crop allocation and manure allocation were expressed in % of N. The four aspects were defined as follows:

Aspect 1 allocation of crops: To keep the scenarios similar to the current situation, which requires the least systemic change, it was assumed that the types of crops produced and the production volumes would not change but only the allocation of crops (e.g. to animal production vs human consumption). Moreover, feed crops (maize silage) was not reallocated to human consumption. N in non-exported crops was allocated to:

- human consumption (food);
- animal production (feed);
- usage as substrate for biogas (biogas substrate).

Aspect 2 livestock composition: The overall composition of livestock (percentage cattle, pigs, poultry, others (sheep, goats and horses)) would change.

Aspect 3 livestock reduction: The overall livestock number would change.

Aspect 4 allocation of manure: manure N was allocated to:

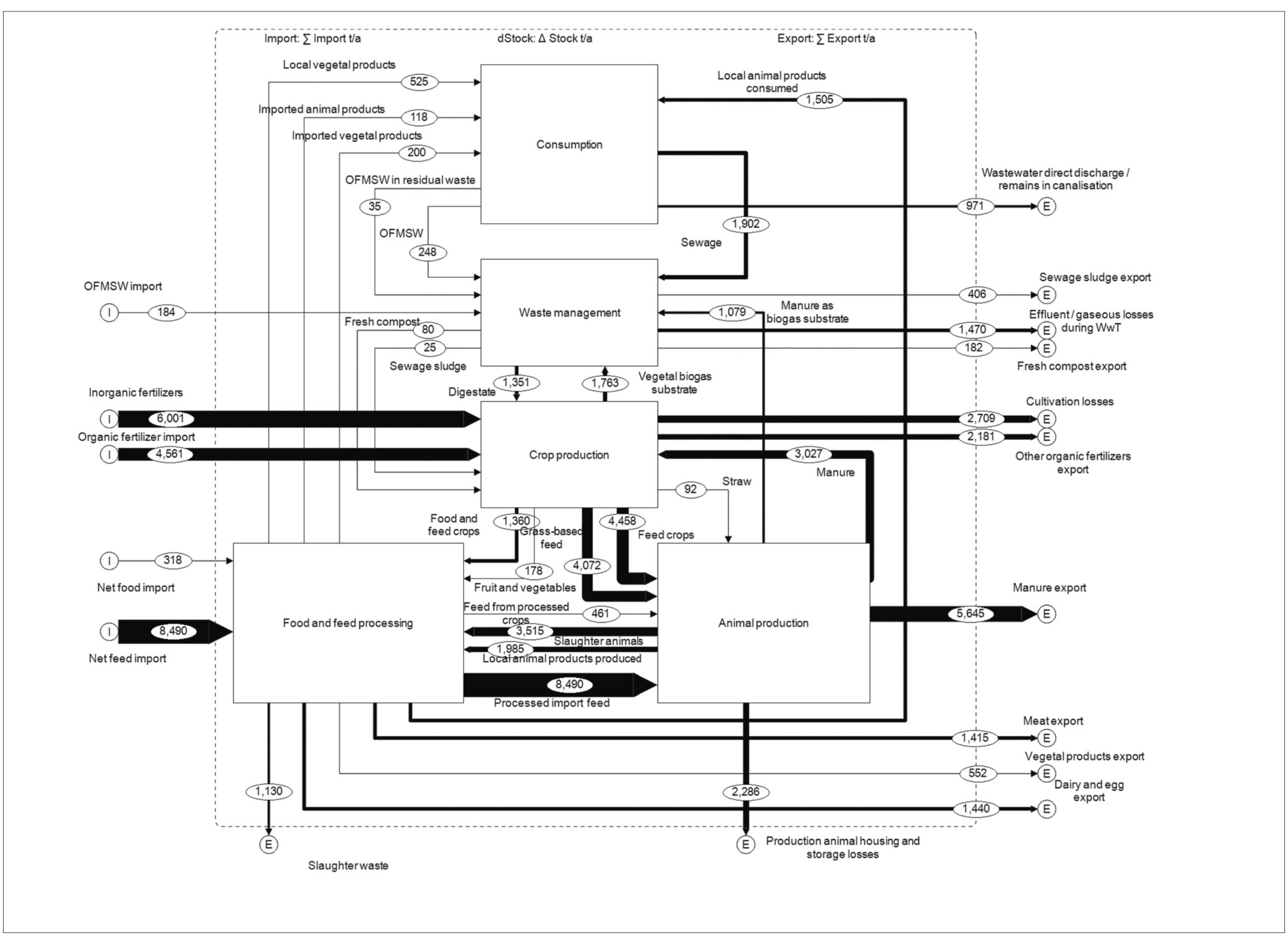


**Fig. 1.** N flow chart of the reference year 2020, expressed in t N year$^{-1}$. The width of the arrows represent the size of the flow in comparison to the other flows. The flows indicated with an “I” are imports into the AFWS and the flows indicated with an “E” are exports out of the AFWS. The five blocks are the five subsystems of the AFWS. OFMSW stands for the Organic Fraction of Municipal Solid Waste.

- local application;
- export;
- biogas substrate, with the digestate used locally as fertilizer.

During the interviews stakeholders were informed on the reference year values of the different aspects. The stakeholders were free to envision also non-consistency between the aspects. This reflects the impact of feed import elimination on the system more accurately as stakeholders would likely not consider consistency when reacting to a policy that would eliminate feed import.

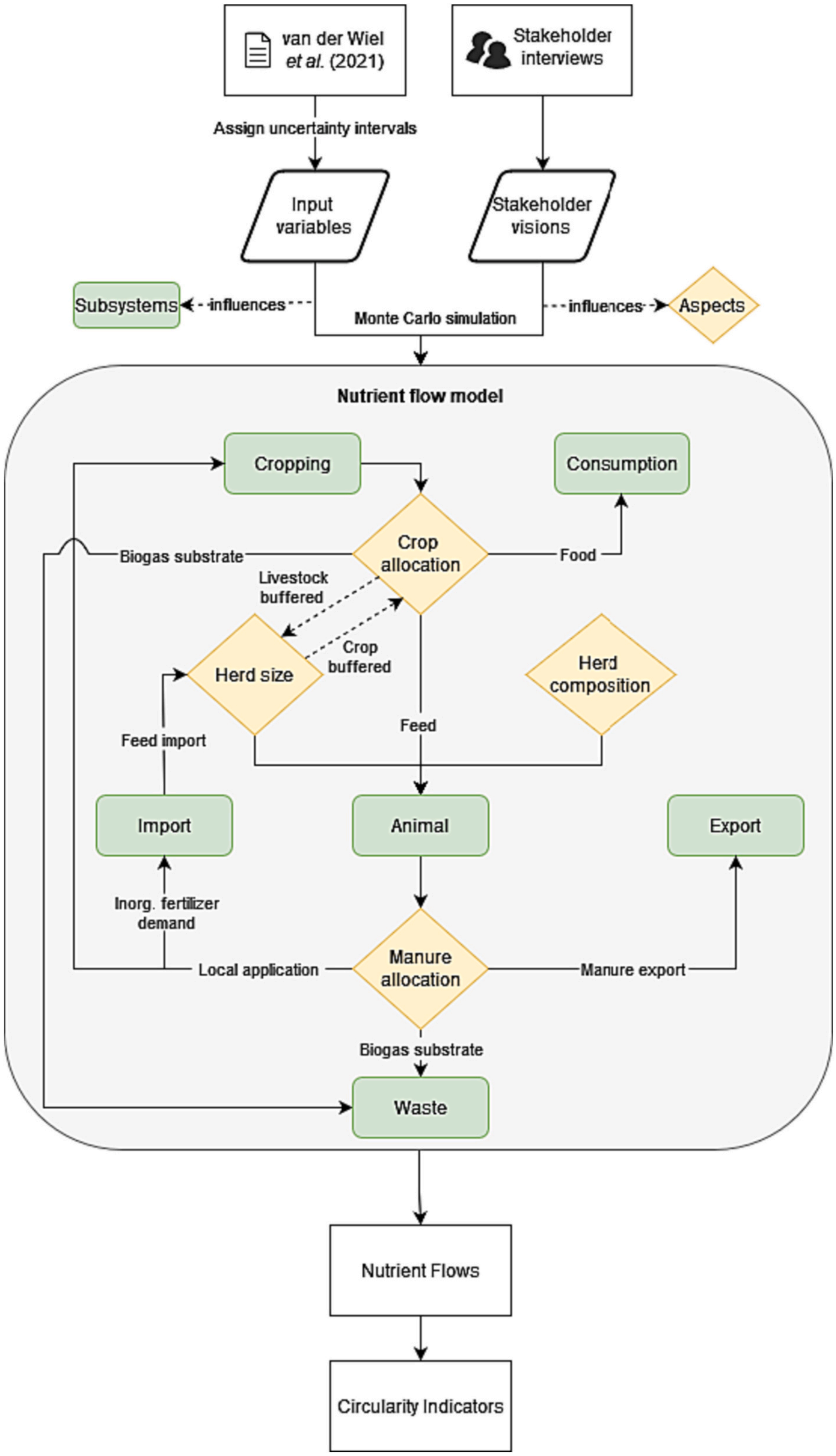


**Fig. 2.** Methodological approach from base model and different uses of the stakeholder visions in the scenarios to modelling the nutrient flows and circularity indicators.

### 2.3. Nutrient flow model

We modified a model quantifying nitrogen, phosphorus, potassium and carbon mass flows for the AFWS for the year 2016 in the district Cleves, Germany (van der Wiel et al., 2021). The model was updated for the reference year 2020. The base model was based on data gathered from expert consultation, databases, peer-reviewed literature and data supplied by local companies (Caspersen et al., 2023). The main change in the modelling approach is that the flows within the model were linked to allow for quantification of the consequences of a change in the system. For example we calculated animal (by-) products like milk, meat and manure based on production levels and livestock numbers rather than deriving them directly from databases. This made it possible to simulate for example the impact of adjusting livestock numbers. To analyze the impact of changes regarding crop allocation, livestock composition, livestock reduction and manure allocation, these aspects were variable in the model, and modified based on stakeholder visions.

After quantifying mass flows for the AFWS for the reference year 2020 (Fig. 1), the stakeholder ($n = 9$) input regarding the four aspects was fed into the model (Fig. 2). The input of the stakeholders was treated as one answer. We used the range of numerical estimates from the stakeholders regarding the four aspects to represent uncertainty intervals at the 5 % and 95 % percentiles. When the stakeholder input did not follow a normal distribution, a skewed normal distribution was fitted and random samples were drawn from it using the R package *sn* (Azzalini, 2023). This was done for two allocation destinations of Aspect 1, crop allocated to feed and food as well as for all three allocation destinations of Aspect 4 manure allocated to local application, export and biogas.

Any gap between the demand and supply of manure as fertilizer, resulting from the reduction in livestock numbers, was assumed to be compensated by inorganic fertilizers. As the nutrient use efficiency of inorganic N could be higher than that of organic N (Verstraten et al., 2023), the model was programmed to substitute 1 kg N of manure with 0.9 kg of N of inorganic fertilizers. The import of manure (contained in organic fertilizer import) was assumed to reduce to the same extent as local manure production as feed import restrictions would reduce livestock numbers in neighboring supplying areas as well. The dietary behavior of the local human population in the study area was expected not to change, which means that reduced locally available plant-based and animal-sourced food was compensated by food import. The protein (N) requirements of the livestock was moreover assumed to remain stable as well as the feed conversion efficiency, regardless of the composition of livestock. The total agricultural area was moreover kept stable.

To calculate the nutrient flows, we assigned a 90 % confidence interval and a distribution (normal, normal truncated between zero and one or constant) to variables within the model, based on available information, expert knowledge, and our own calibrated estimates.

We carried out a Monte-Carlo simulation with 10,000 model runs to calculate the nutrient mass flows. This approach allows uncertainty to propagate throughout the calculations (Luedeling et al., 2022b) and transparently identifies the uncertainty behind the calculated nutrient mass flows. The model was designed to describe the effects on N flows in the AFWS resulting from changes in Aspects 1–4 as envisioned by the stakeholders for the year 2050. The model (Caspersen et al., 2023) was coded using R (R Core Team, 2022) with functions from the decisionSupport package (Luedeling et al., 2022a).

No pattern was visible regarding stakeholder groups and visions (Fig. 3). No difference in the visions between the groups could be discerned. This implies that a change in the composition of the stakeholders would not influence the modelling outcome. In many cases the stakeholder estimates for Aspect 1 allocation of crops to animal production (feed) and Aspect 3 livestock reduction, did not match. The livestock numbers envisioned by the stakeholder would demand more feed than was envisioned to be allocated to animal production. This would result in deficits in N provision to livestock. The mismatch was dealt with through three different scenarios: i. The mismatch was kept as it is and as such resulted in a negative nutrient balance of the animal production subsystem, called Participatory Scenario (PS) in the text below. ii. The mismatch was resolved by changing the allocation of crops to feed, if necessary, also by using originally exported crops. As the elimination of

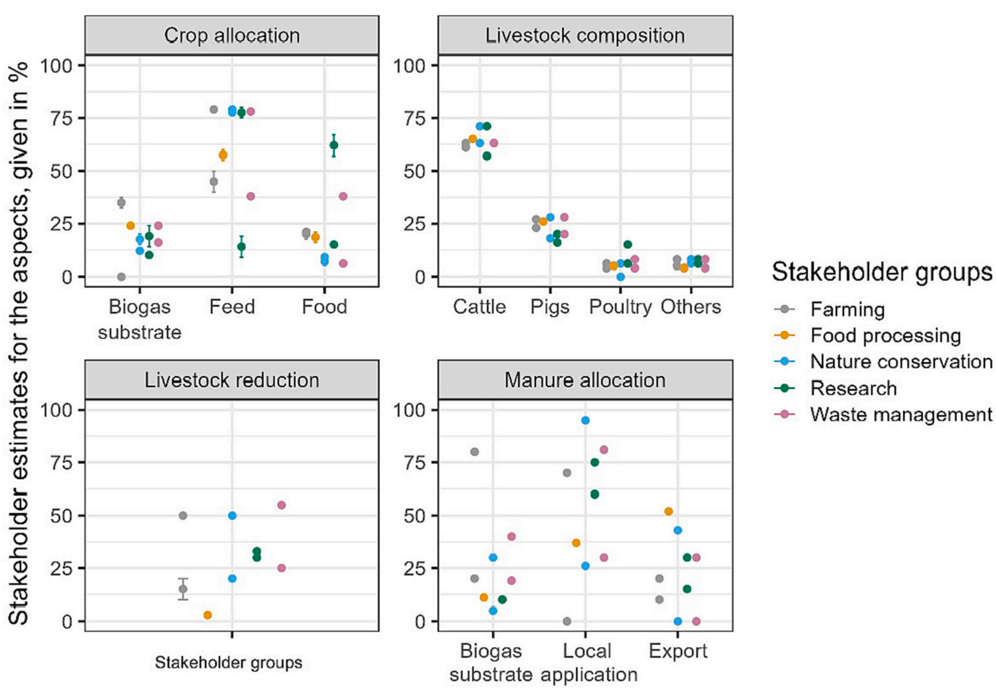


**Fig. 3.** The stakeholder input at each aspect: allocation of crops, composition of livestock, livestock population and allocation of manure. Each point is an answer from a stakeholder. The answers were given by the stakeholders in percentages, such as the percentages of crops allocated to biogas substrate, feed and food. The allocation of crops and the allocation of manure are given in percentage of N. The points with an error bar were answers by stakeholders that were given as a range. The colours represent the different groups of stakeholders involved. The Farming group consisted solely of animal production.

feed import is compensated by buffering through reallocation of crops, we called this scenario Crop Buffered Scenario (CBS). iii. Finally, the mismatch was resolved by matching reductions in livestock numbers with locally available feed, called Livestock Buffered Scenario (LBS).

### 2.4. Analysis of model outcomes

The nutrient flow model was run for the reference year and the three scenarios, and resulting density plots were created. Overall, 42 flows were modelled. The 16 flows which changed substantially are presented in Fig. 4.

We followed Papangelou and Mathijs (2021) in capturing several aspects of circularity with these nutrient indicators: total input of N to the AFWS (kg N year$^{-1}$), N losses from the AFWS (kg N year$^{-1}$), the recycling ratio of N within the AFWS, the share of reused N to the input and the N use efficiency (NUE). Total input is the sum of all the input into the system from outside the study area (inorganic fertilizers, organic fertilizers, feed import, food import and OFMSW from elsewhere). Losses is the sum of the N losses during cultivation, the animal housing and manure storage losses and the N lost with effluent and gaseous losses from waste water treatment plants. The recycling ratio indicates how much of the N contained in locally produced biomass is recycled as input to other subsystems. The share of reused to total input indicates the volume of inputs to the subsystems crop production, animal production and consumption from local sources. The NUE indicates the percentage of all the input into crop and animal production that leads to products. For the calculation of the system NUE, manure was not considered a product of animal production but it was taken as an input to crop production. Moreover, vegetal biogas substrate and manure were not seen as product outputs from respectively crop and animal production, but digestate was taken as an input into crop production. The system NUE therefore represents the weighted average NUE of crop and animal production (Caspersen et al., 2023). The median circularity indicators were calculated for the scenarios. Variability of the observed median changes was calculated in form of the interquartile range of the relative change, which is the distance of the 75 % and 25 % quantile.

## 3. Results

### 3.1. Scenarios

In the PS, according to the stakeholders, elimination of feed import would reduce livestock numbers by 4 % to 55 %, with a median of 29 %. The percentage of cattle was envisioned to remain stable. The percentages of poultry and other animals were expected to increase at the expense of pigs. Available manure was envisioned by the stakeholders to be allocated more to local application at the expense of export (Table 1). Furthermore, more of the manure was predicted to be supplied to biogas substrate and thereafter as digestate to local application. Less of the locally produced crops were thought to be used as vegetal biogas

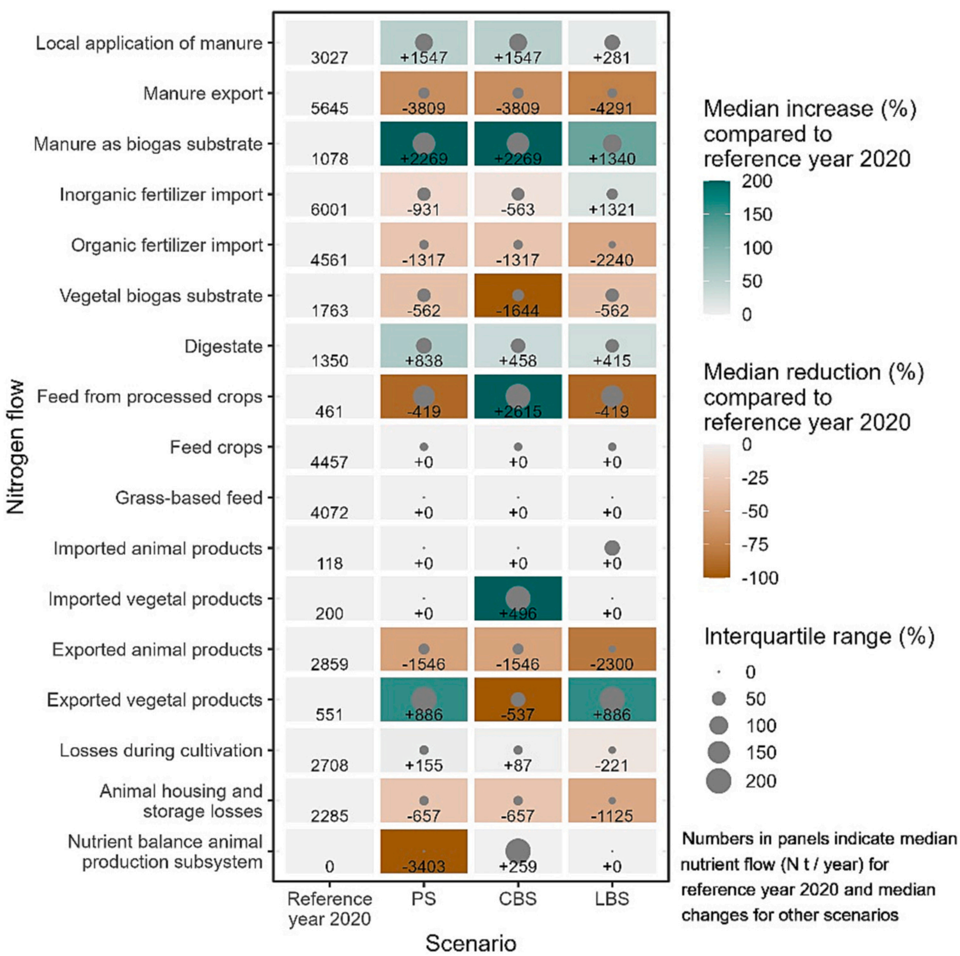


**Fig. 4.** N Flow differences for each scenario (participatory scenario (PS), crop-buffered scenario (CBS) and livestock-buffered scenario (LBS)) compared to the reference year 2020. Brown tiles indicate a decrease as compared to the reference year and green tiles indicate an increase as compared to the reference year. The grey circles indicate the interquartile range of the relative change, which is the distance of the 75 % and 25 % quantile. Numbers in tiles indicate median nutrient flow (t N year$^{-1}$) for the reference year and changes in nutrient flow (t N year$^{-1}$) for the scenarios PS, CBS and LBS compared to the reference year. The negative nutrient balance for the animal production subsystem for PS conveys that there is a deficit in the amount of N supplied to animals as feed.

**Table 1**
The characteristics used as input to the model for each scenario. PS stands for Participatory Scenario, CBS stands for Crop Buffered Scenario and LBS stands for Livestock Buffered Scenario. All the scenario characteristics are expressed in percentages. The allocation of crops and manure are expressed in percentage of N. The composition of livestock is expressed in percentage of total LLU (Large Livestock Units, which is used as a standard unit of measurement to be able to aggregate the various categories of livestock.). The livestock reduction is for the total number of LLUs.

| Scenario characteristics | | Reference (2020) | PS | CBS | LBS |
|---|---|---|---|---|---|
| Allocation of crops (%) | Human consumption | 14 | 26 | 2 | 26 |
| | Animal production | 63 | 58 | 98 | 58 |
| | Biogas substrate | 23 | 16 | 0 | 16 |
| Composition of livestock (%) | Cattle | 64 | 64 | 64 | 64 |
| | Pig | 28 | 23 | 23 | 23 |
| | Poultry | 4 | 7 | 7 | 7 |
| | Others | 4 | 6 | 6 | 6 |
| Livestock reduction (%) | | N/A | 29 | 29 | 49 |
| Allocation of manure (%) | Local application | 31 | 47 | 47 | 47 |
| | Export | 58 | 19 | 19 | 19 |
| | Biogas substrate | 11 | 34 | 34 | 34 |

substrate. The stakeholders estimated that 58 % of the crops would be allocated to feeding livestock, which was 63 % in the reference year (Fig. 4).

In the Crop Buffered Scenario (CBS) the allocation envisioned by stakeholders was set aside to calculate the crop allocation needed to fulfill feed N demand by livestock numbers envisioned by stakeholders. In the CBS the percentage of crops allocated to animals was 98 %, resulting in only 2 % of the locally produced crops being available for food and none for export. The proportion of manure to be used for local application, export or biogas substrate and the composition of livestock remained unchanged and were the same as in the PS. Furthermore, the same reduction in livestock numbers was used as in the PS.

The Livestock Buffered Scenario (LBS) does not consider the stakeholder envisioned livestock numbers. It rather calculates a new median livestock number based on the locally available feed according to the reallocation of crops envisioned by the stakeholders. This new median livestock number was 49 % lower than the one in the reference year (Table 1). The proportion of manure to be used for local application, export or biogas substrate and the composition of livestock were the same as in the PS. Furthermore, the same percentages of crops were allocated to food, feed and biogas substrate as in the PS.

### 3.2. *Circularity of the scenarios*

The scenarios mainly affected the animal and crop subsystems. The waste management subsystem was affected to a minor extent through the reallocation of crops and manure to biogas production. The negative nutrient balance for the animal production subsystem in the PS (3403 t N year$^{-1}$, more than 30 % of the required feed N) denotes that the livestock numbers envisioned by stakeholders do not fit the locally available feed despite an increase in the crops allocated to feed (Fig. 4).

In the CBS the increase in locally produced feed crops resulted in an increase in the import of plant-based products while the export of plant-based products for human consumption was completely eliminated. In the PS and LBS compared to the reference year, more crops are allocated to human consumption, while less are allocated to animals or biogas production. As consumption of food crops in the region is assumed unchanged, this will increase the export of food crops. In the LBS the livestock reduction by 49 % as compared to the reference year could still fulfill the local demand for animal-sourced food. Moreover, there is still production in excess of local consumption. The reduction of livestock numbers in each scenario, leads consequently to a reduction of N losses during housing of animals and storage of manure. The biggest reduction in N losses was seen in the LBS. The reduction of livestock numbers in each scenario furthermore reduced the animal products available for export. The stakeholders envisioned allocating a greater share of manure to crops and biogas substrate. In the LBS, despite halving the livestock numbers, more locally available manure is allocated to crops than in the reference year (Fig. 4). In the PS and CBS the reallocation of locally available manure could compensate for the reduced import of organic fertilizers. However, in the LBS the reduced import of organic fertilizers was assumed to be compensated by increased import of inorganic fertilizer. In the LBS the shift from manure to inorganic fertilizers, due to higher NUE of inorganic fertilizer, led to reduced N surplus applied. Consequently, this was assumed to lead to reduced N losses during cultivation as local soils are N-saturated. In the CBS, most feed was locally available as a result of the reallocation of crops towards animal production. In this scenario, however the import of plant-based food was increased (+496 t N year$^{-1}$ compared to the reference year), externalizing the production of food crops. Despite less crops allocated to biogas substrate the manure reallocation to biogas substrate, in all scenarios resulted in more digestate being available for local application.

The median amounts of manure supplied to crops and biogas plants, the feed from processed crops, and the net food import in the CBS are uncertain as these flows are modelled based on the estimates of the stakeholders (Fig. 4). The uncertainty ranges indicate that these flows can deviate up to 200 % from the presented median. The uncertainty stems from the source of data underlying these flows and the wide range of visions of the different stakeholders. For example, livestock numbers were expected to decrease by 4 % to 55 %. The amount of manure supplied to crops and biogas, depending on the number of livestock, is therefore more uncertain compared to other flows. The same reasoning for the uncertainty applies to the circularity indicators (Fig. 5).

With a 20 % reduction compared to the reference year, nitrogen losses reduced most in the LBS (−1364 t) (Fig. 5). The reduction was due to reduced animal housing and manure storage losses and losses during cultivation (Fig. 6). Total input is lowest for the PS. However, the nutrient balance for the animal production subsystem is negative. The nutrient balance of the animal production subsystem is the sum of all the inputs and outputs of the subsystem. A negative nutrient balance conveys a deficit in the amount of N supplied to animals as feed, in other words there is not enough feed available to produce the same amount of animal-sourced products with the kept number of animals. This negative nutrient balance means that the total input, recycling ratio, reuse to total input and NUE comparable to the LBS, are misleading. The total input to the system is reduced in each scenario due to the elimination of feed import. The total input of the LBS is least decreased compared to the reference year as the reduced manure availability is compensated for by increasing the import of inorganic fertilizers (Fig. 6). The input into the subsystems is modelled so to retain the same production intensity, except for the animal production subsystem in the case of PS. The NUEs of the scenarios are therefore not substantially influenced. The NUEs for the reference year, PS, CBS and LBS are respectively, 51 %, 60 %, 55 % and 57 % (Fig. 5). The NUE for the PS is highest. However this is misleading as a negative nutrient balance of the animal production subsystem occurred. This means that more animal products are produced with less feed input into the subsystem, compared to the other scenarios. The animal production subsystem and with that the total system therefore achieves an unrealistically high NUE. The recycling ratio and reuse to total input of the CBS are most improved compared to the reference year. The higher recycling ratio and reuse to total input of the CBS, as compared to the LBS, is because more manure was available for local application in the CBS (Fig. 5). The higher NUE of the LBS is because more inorganic fertilizers are used to substitute reduced manure availability.

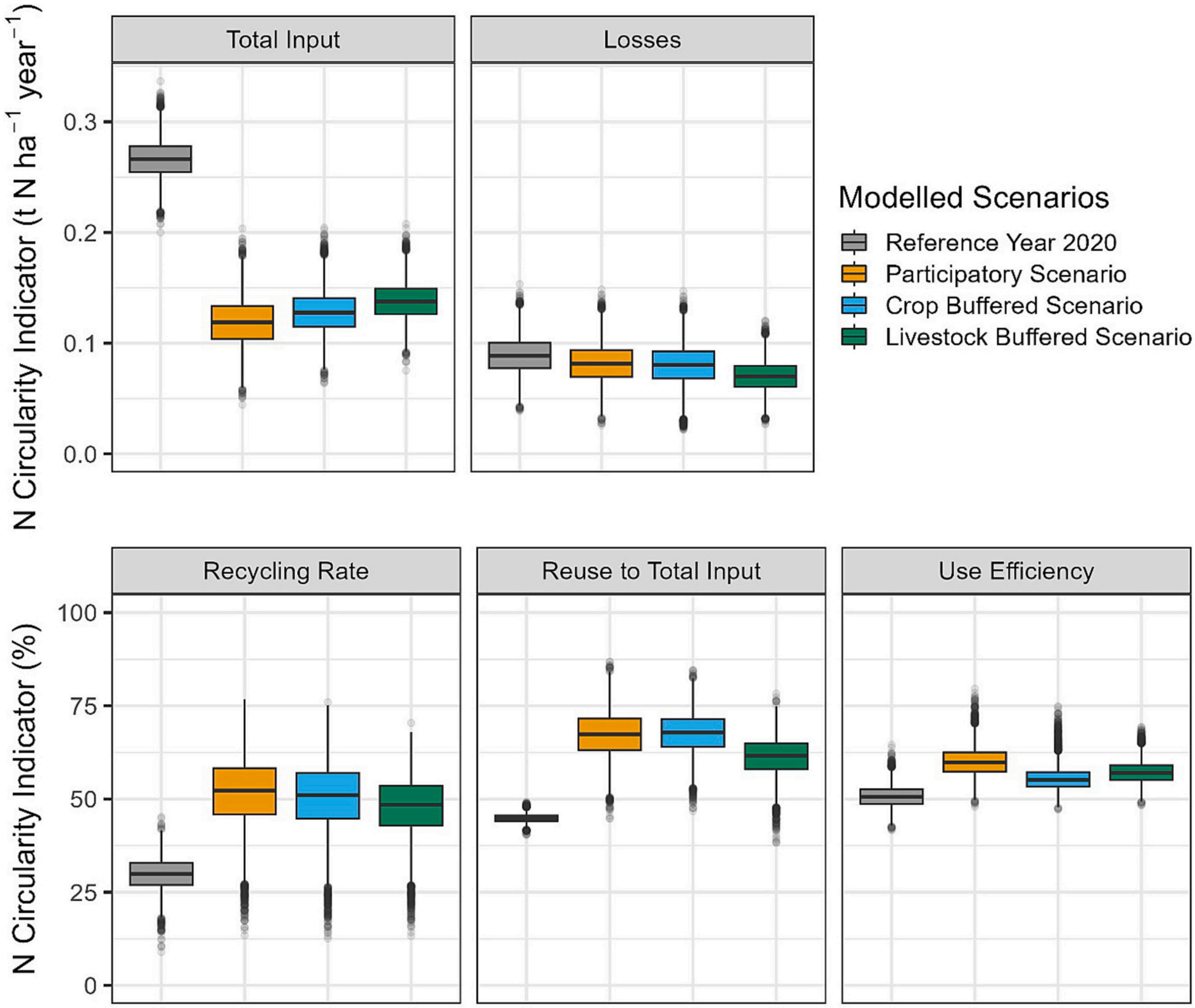


**Fig. 5.** Boxplots depicting the circularity indicators for the reference year (2020) and the three scenarios: Participatory Scenario (PS), Crop Buffered Scenario (CBS) and Livestock Buffered Scenario (LBS). The box of the boxplot contains 50 %, which lies between 25 % and 75 % percentile. The whisker is the 25 % percentile minus 1.5 * interquartile range for the lower end and 75 % percentile +1.5 IQR for the upper end. The top row of indicators is expressed in t N ha$^{-1}$ agricultural land year$^{-1}$.

## 4. Discussion

### 4.1. Limitations

This study shows the potential of using stakeholder visions in scenario SFAs through participatory modelling to find plausible solutions to reduce N losses and damage to the environment. Stakeholder input and ideas can be influenced by many factors, including their knowledge and understanding about the subject at stake. Providing stakeholders with new insights can therefore influence the outcome of a participatory modelling approach. In this study, limited additional information was provided. Critical information that could have influenced the outcome of the study and can be considered in future research or processes with stakeholders include, among others, information on: i) economic consequences of plausible adaptation in the AFWS; ii) plausible alternatives for local feed sources to support animal production; iii) possible opportunities for processing biomass as alternative fertilizers for livestock manure; iv) opportunities for improving NUE of manure as bio-based fertilizers as they can even have a higher NUE than inorganic fertilizers (Phillips et al., 2022; Verstraten et al., 2023). Providing such information can help stakeholders envision opportunities to move away from their current practices. The circularity indicators and flows based on the visions of the stakeholders have a high uncertainty. Providing information regarding above points could reduce the range in the answers from the stakeholders, increase certainty of the modelling outcome and alter the results of a participatory modelling approach.

### 4.2. Stakeholder visions in scenario modelling

The participatory modelling in this study shows that following the elimination of feed import, stakeholders regard it unlikely that livestock numbers will reduce to the level that can be supported by locally available feed, under current cropping systems. To fit livestock numbers to locally available feed, either more extreme crop reallocation or further reduction of livestock numbers is necessary. As a continued iterative process with stakeholders is crucial for improving circularity and reducing environmental damage, it is important to communicate the discrepancy between stakeholder visions and adaptation needed for a more circular system, sensitively (Cabrera et al., 2008; Karlsson et al., 2018; Olabisi et al., 2010; Vanhamäki et al., 2020). Thereafter a match can be sought between that what people are willing to do and that what is necessary to do to reduce environmental problems. Future research should use the results of this study, showing that more adaptation is necessary than what was envisioned by stakeholders. Through participatory modelling it can be determined whether stakeholders can envision a scenario including adaptation of more extreme reallocation of crop or further reduction of livestock numbers, or a bit of both.

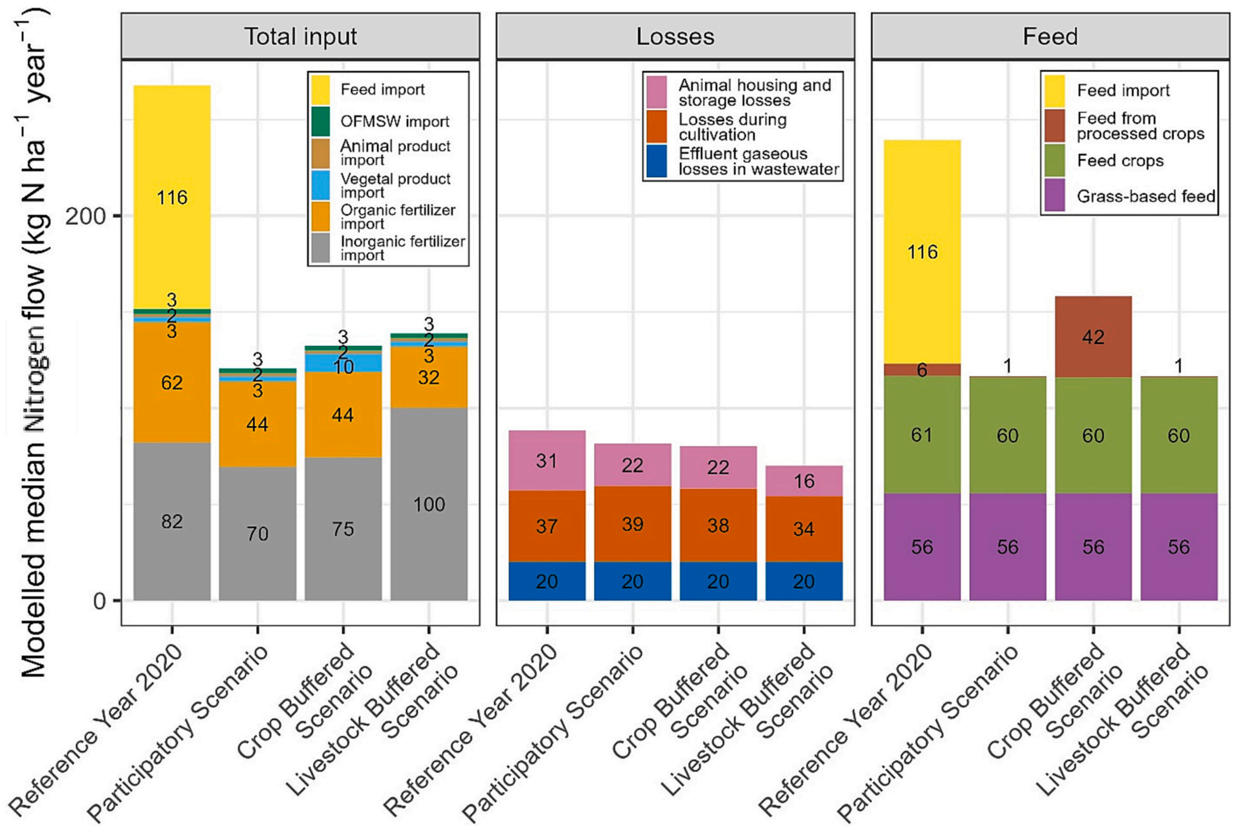


**Fig. 6.** The circularity indicators Total input, the circularity indicator Losses and feed composition for the reference year and the different scenarios. The medians are expressed in kg N ha$^{-1}$ agricultural land year$^{-1}$ and presented as round numbers. The numbers represent the median values of the flows. Each color stands for a different flow.

### *4.3. Plausible solutions to reduce N losses and damage to the environment*

#### *4.3.1. Reducing livestock numbers to reduce environmental damage*

The results of the LBS show that fitting livestock numbers to locally available feed does not substantially improve all circularity indicators of the AFWS. While N losses reduced with a reduction in livestock numbers, other circularity indicators remained largely unchanged. In this study, total N losses amounted to 6472 t in the reference year and reduced with 21 % in the LBS to 5109 t N year$^{-1}$. For this reduction of 1363 t N year$^{-1}$ in the LBS, the livestock numbers were nearly halved. The 49 % livestock reduction compared to the reference year did not lead to substantial improvements of the other circularity indicators, including NUE. No management changes were modelled, except for the use of fertilizers, they could however improve the NUE of the subsystems. The overall NUE is therefore also not substantially altered. This conveys that to improve on more aspects of circularity there is more adaptation required than eliminating feed import and reducing livestock numbers. Kleinpeter et al. (2023) considered two concepts for reducing local environmental damage of AFWS, namely besides improving circularity also improving the efficiency of its subsystems. As the same subsystem input intensity and production levels are maintained in this study, the NUE of its subsystems is not addressed. Similar to what Kleinpeter et al. (2023) concluded, the two concepts of circularity and subsystem efficiency should not be set as separate objectives to reduce environmental damage but used as simultaneously implemented means. In accordance with Spiller et al. (2023) this strategy should be extended to include reduced consumption of animal-based products and precision fertilization.

#### *4.3.2. Livestock composition change to reduce environmental damage*

In the scenarios the composition of livestock was adjusted based on stakeholders' visions. However, the envisioned livestock composition might not represent the most circular option (Van Selm et al., 2022). Increasing the numbers of poultry is envisioned by the stakeholders. Increasing the percentage of chickens in the total number of livestock also increases the poultry meat and eggs available. Poultry meat and eggs, are preferred according to the EAT-LANCET diet but the suitability of poultry in a circular food system can be questioned as poultry generally requires more high quality human-edible feed than pigs or ruminants (Van Zanten et al., 2018). This is in conflict with one of the circularity principles that aims to prevent food-feed competition (de Boer and van Ittersum, 2018; Van Selm et al., 2022; Van Zanten et al., 2018). Moreover, in this study about half of the locally available N in feed is grass-based (Fig. 6). This would suit better as feed for ruminants (Van Zanten et al., 2014). However, the stakeholders did not envision a substantial increase in ruminant numbers. Moreover, stakeholders envisioned a decreased percentage of pigs in the total number of livestock. Also this shift in livestock composition can be questioned as the most suitable choice for utilizing waste streams (Lybæk and Kjær, 2022; Van Selm et al., 2022; Van Zanten et al., 2018) as pigs are capable of consuming food processing by-products otherwise unsuitable for anything else but composting (Uwizeye et al., 2019). To be able to appraise the full potential of feeding livestock with locally available feed it is important to attain data on locally available grass-based feed, food processing by-products as well as food waste, the so-called low-opportunity-cost feeds (Frehner et al., 2022).

#### *4.3.3. Adjusting consumption to reduce environmental damage*

In addition to improving recycling and NUE, accepting lower production levels, would reduce over-fertilization (Fernandez-Mena et al., 2020). Consumption thereafter would also have to be adapted to adjust to the lower production levels (Billen et al., 2018). Other studies have found that reducing the percentage of animal-sourced food, fits to a healthy diet and the local reconnection of livestock and crop farming (Billen et al., 2018; Desmit et al., 2018; Garnier et al., 2016; Garnier et al., 2023). Billen et al. (2018) found for example that in France employing organic farming practices, reconnecting crop and animal production and adopting a demitarian diet, would supply enough food nationally and still there would be room for export, while improving environmental performance of the AFWS. Environmental problems could be displaced to where the production has to compensate the reduced production in a study area if over-consumption is not reduced and the percentage of plant-based food not increased. In this case study, local consumption was assumed to remain unchanged and there was still a surplus and therefore even room for export. However, less animal-source products can be exported. As agriculture in the district under study does not only produce for local consumption but also for urban areas, consumption patterns in either the urban areas or elsewhere would have to adjust by consuming less animal-source food to prevent an increase in livestock numbers and environmental emissions in another location. Billen et al. (2021) demonstrated that the European population can be fed without imports of feed, if systemic change expands to include dietary change of the population. This required change would result in a more plant-based diet. This current study modelled nearly halving the livestock numbers when fitted to locally available feed. Preventing the displacement of animal production for urban areas, now taking place in the study area, would require a reduction in animal-sourced food consumption elsewhere. This adjustment is similar to diets proposed by others (Billen et al., 2018; Frehner et al., 2022; Garnier et al., 2023). Frehner et al. (2022) found that in Switzerland about half of the protein could be supplied by animal-sourced products when only low-opportunity-cost biomass is used as feed. Halving the livestock numbers and with that also the available animal-sourced food consumed in the study area, would result in about a similar ratio between animal-sourced and plant-based N consumed.

#### 4.3.4. Processing biomass to reduce environmental damage

In the LBS locally available manure had to be supplemented with more inorganic fertilizers. This is often seen as trade-off of adjusting livestock numbers and used as an argument to sustain livestock numbers. It is important to realize, however, that the nutrients in manure come from feed that is either produced locally or imported into the area. For the production of this feed, fertilizers are needed as well. Relying on imported feed to sustain livestock numbers simply externalizes the need for inorganic fertilizers if soil depletion is to be prevented and manure is not being returned to the field where the feed is produced. However, the gained improvement in the indicator total losses in the LBS is partly due to the increased use of inorganic fertilizers, as the inorganic fertilizers can be taken up by crops more efficiently (Verstraten et al., 2023). Nevertheless, increasing dependency on non-renewable sources is not desired in improving circularity (Daramola and Hatzell, 2023). This emphasizes that sourcing local fertilizers is essential for circularity (Egan et al., 2022). An option to use manure and other locally available biomass such as sewage sludge more efficiently is to process it to bio-based precision fertilizers (Klop et al., 2012; Mayer and Kaltschmitt, 2022). The nutrients in bio-based precision fertilizers are better taken up by crops, improving NUE, leading to lower N losses during cultivation (Macura et al., 2021; Ntostoglou et al., 2021; Sigurnjak et al., 2017; Vaneeckhaute et al., 2018). Another option to decrease dependency on inorganic N fertilizers, is to facilitate more biological N fixation (Anglade et al., 2015) by including leguminous cover crops, grain legumes or legume-grass mixtures for feed in crop rotations. It can therefore be concluded that there is more potential for local circularity than addressed in this paper.

### 4.4. Externalized environmental damage

Both the CBS and the LBS reduce the export of N in the form of food to urban human population. The lack of recycling between urban areas and their so called hinterland, complicates nutrient management (Wang et al., 2021). The N exported in the form of food ends up in human waste, remaining in the urban areas. Recycling sewage sludge from urban areas through processing could reduce the system's dependency on inorganic resources. On the other side, the areas that produce feed for an animal production-dominated area such as Cleves, experience N cultivation losses during feed production. Eliminating feed import would decrease the dependency on inorganic fertilizers in feed producing areas, while simultaneously reducing N losses during cultivation and increasing the land area available for food production (Van Zanten et al., 2018). Moreover, an area such as Cleves, would become more independent for its food provision. Although the improvement of circularity indicators are limited with the elimination of feed imports and local livestock number reduction, the externalized environmental impact and the advantage of independence are not considered. Using the externally freed up land directly for human food production, avoids the losses related to intensive livestock farming (Garnier et al., 2023). To further improve nutrient cycling, investments should be made to recover nutrients from human faeces. A way to acknowledge the externalized effects of local systemic changes is to study connected areas together in future research such as Harder et al. (2021b) did.

### 4.5. Implications

Participatory modelling employed in this study shows that stakeholders do not envision a system in which the livestock numbers are constraint by the locally available feed. Stakeholders have a hard time envisioning systemic change (Koole, 2022). This case study shows that more extreme reallocation of crops or further reduction of livestock numbers are necessary to recouple livestock and crop production on a local scale than regarded necessary or fruitful by stakeholders. Future participatory modelling should therefore build trust in the process and the profitability of N circularity, alongside a common vision, to match that what is needed to improve the environmental performance of the system to what stakeholders are willing to do.

## 5. Conclusions

This scenario SFA, where stakeholder visions were incorporated through participatory modelling to find plausible solutions to reduce N losses and damage to the environment in the animal production-dominated Cleves district in Germany, shows that stakeholders do not envision livestock numbers being constrained by locally available feed. More extreme reallocation of crops or further reduction of livestock numbers is necessary to size livestock numbers to locally available feed. Halving the livestock numbers is necessary to match the locally available feed. To compensate for reduced manure availability, more inorganic fertilizer will be imported. Large N losses from the system remain. This causes continued environmental damage and dependency on N inputs. Therefore, next to reducing feed import and livestock numbers, system adaptations towards N circularity should expand to include livestock composition adaptation, NUE, recycling of other biomass, the N application intensity and consumption. The results provide policy makers with the recommendation to provide stakeholders with new insights, such as into processing biomass to bio-based fertilizers, to improve stakeholders' visions of a circular agro-food-waste system.

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## CRediT authorship contribution statement

**Bernou Zoë van der Wiel:** Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lars Caspersen:** Visualization, Methodology, Formal analysis. **Cory Whitney:**

Writing – review & editing, Methodology. **Corina van Middelaar:** Writing – review & editing, Supervision. **Jan Weijma:** Writing – review & editing, Supervision. **Florian Wichern:** Writing – review & editing, Supervision, Funding acquisition.

## Declaration of competing interest

All authors declare that they have no conflict of interests.

## Data availability

The data is available in the provided Zenodo reference

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