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Recoupling livestock and feed production in the Netherlands to reduce environmental impacts

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ABSTRACT

In many places on earth, livestock and feed production are decoupled, as feed is grown in one region and fed to livestock in another. This disrupts nutrient cycles by depleting resources in feed producing regions and accumulating resources in livestock areas, which leads to environmental degradation. One solution is to recouple livestock and feed production at a more local level, which enhances nutrient circularity. Recoupling livestock and feed production creates a natural ceiling for livestock numbers based on the feed producing capacity of a region. In this study we assess the consequences of recoupling livestock and feed production (i.e., by avoiding the import and export of animal feed) on ammonia and greenhouse gas (GHG) emissions, with and without feed-food competition. To this end, we used FOODSOM, an agro-ecological food system optimisation model representing the Dutch food system in this study. The Netherlands is one example of a region with high livestock densities and resource accumulation. We found that recoupling decreased livestock numbers (beef cattle: −100 %; dairy cattle: −29 %; broiler chickens: −57 %; laying hens: −67 %; pigs: −62 %; sheep −100 %) and animal-sourced food exports (−59 %) while still meeting the current human diet in the Netherlands. Consequently, ammonia emissions and GHG emissions decreased, and the nitrogen use efficiency increased from 31 % to 38 % at the food systems level. Recoupling alone was almost sufficient to meet national emission targets. Fully meeting these targets required further small changes in livestock numbers. Avoiding feed-food competition decreased livestock productivity and GHG emissions but did not improve nitrogen use efficiency. Total meat production could not meet domestic consumption levels while avoiding feed-food competition, and resulted in additional beef cattle. We show that recoupling livestock and feed production is a promising next step to enhance circularity while decreasing agricultures environmental impact.

1. Introduction

Currently, the global food system is characterised by substantial trade of food and raw materials including animal feed (Billen et al., 2014). Trade in the food system is driven by biophysical, economic, and technological drivers (resulting in differences in productivities of crops and animal systems), which unlock local production and economic efficiencies (Campi et al., 2020). However, the trading of animal feed decouples livestock from feed production, which disrupts regional carbon and nutrient cycles and can lead to resource depletion in some regions (e.g., exporting biomass for animal feed), and resource accumulation in other regions (e.g., through livestock manure) (Harder et al., 2021; Wang et al., 2022). Resource depletion may increase the use of artificial fertilisers and/or decrease biodiversity (Dalin and Rodríguez-Iturbe, 2016; Grote et al., 2005). Resource accumulation, especially when accompanied with an excessive use of animal manure, can exacerbate local environmental problems e.g., acidification and eutrophication leading to biodiversity loss (Bai et al., 2021; Uwizeye et al., 2020). One solution is to recouple livestock and feed production again at a local level to create a more circular food system (De Boer and Van Ittersum, 2018; Schut et al., 2021). The recoupling of livestock and feed production creates a natural ceiling for livestock numbers based on the feed producing capacity of a region.

In the Netherlands, economic and technological development, combined with its geographical location and proximity to the port of Rotterdam has enabled the livestock population to grow beyond the

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national feed production capacity (Van Grinsven et al., 2019). Large quantities of animal feed are imported to sustain high animal numbers and the export of animal products. Livestock production is decoupled from feed production, especially in monogastric animal systems which are fed primarily on imported feed. The livestock density in the Netherlands is currently the highest in Europe (Eurostat, 2023). This has resulted in a surplus of nutrients from animal manure causing groundwater pollution, greenhouse gas (GHG) emissions, and excessive ammonia emissions, the latter leading to high nitrogen deposition rates damaging fragile natural ecosystems (Erisman, 2021; Stokstad, 2019).

The food system in the Netherlands is now at a crossroads. The government wants to address environmental challenges by reducing agricultures ammonia emissions by 50 % and GHG emissions by 30 % by 2030, compared to 2018 levels (RIVM, 2022; Van Den Born and Van Der Zanden, 2023). This requires a significant transformation of the agricultural sector (Gies et al., 2023; Gonzalez-Martinez et al., 2021). At the same time, the government acknowledges the potential of circular food systems as a promising pathway to address existing environmental challenges (De Boer and Van Ittersum, 2018; Ministry of Agriculture Nature and Food Quality, 2018). In circular food systems biomass is prioritised for basic human needs (e.g., food production) while the non-essential use of biomass and unnecessary losses are avoided (Muscat et al., 2021). Another aspect of more circularity in food systems is to better recycle nutrients (e.g. eliminating manure surpluses). A logical next step towards a more circular food system and to reduce environmental impacts would be to recalibrate livestock numbers in the Netherlands by recoupling livestock to local feed production. In this study, we hypothesise that national agricultural emission targets (i.e. ammonia emissions and GHG emissions) can be met if livestock and feed production are recoupled in the Netherlands. This could well be conflicting with a prime principle of circular food systems, i.e., to prioritise biomass for human consumption (rather than for feed) on fertile agricultural lands or in other words to avoid feed-food competition i.e., the competition for biomass between humans and animals (Muscat et al., 2021; Van Selm et al., 2022; Van Zanten et al., 2019). Therefore, recoupling livestock and feed production may help the Netherlands achieve environmental targets but may also conflict with a prime principle of circularity. To explore alternative perspectives, we determined the carrying capacity of livestock in the Netherlands when (1) livestock are fed locally produced animal feed only; (2), proposed national environmental targets for ammonia emissions and GHG emissions are respected; (3), feed-food competition is avoided.

2. Model & methods

In this study the FOOD System Optimisation Model (FOODSOM) was employed to quantify the livestock carrying capacity of the Netherlands when livestock and feed production are recoupled. Four scenarios were developed. The first scenario represents the current Dutch food system and provides a reference for this study. The reference year is 2018. The second scenario shows how many animals can be fed in the Netherlands when only feeding domestically produced livestock feed. The third scenario shows how many animals can be fed in the Netherlands when only feeding domestically produced livestock feed while reducing agricultural ammonia emission by 50 % and agricultural GHG emissions by 30 % relative to 2018 before 2030. The fourth scenario shows how many animals can be fed when feed-food competition is avoided, and GHG emission and ammonia emission targets are respected. Animals are fed on fresh and conserved grass, food losses, and by-products only.

2.1. FOODSOM

FOODSOM is an agro-ecological food system optimisation model of the Dutch food system created in GAMS 41. FOODSOM can minimise for environmental objectives (e.g., minimise GHG emissions) or maximise for productivity objectives (e.g., maximise animal protein production) in different countries and regions. In this study we use FOODSOM with an objective function to maximise animal-sourced protein production in the Netherlands.

2.2. Land, crop & fertilisation

Agricultural land in FOODSOM is split into three land use classes: annual cropland, permanent grassland, permanent cropland. Annual cropland and grassland contains four soil texture classes: sand, clay, loess, and peat. Peat land is assumed to be only suitable for growing grass due to high groundwater levels in the Netherlands. The permanent cropland category contains three infrastructure classes: greenhouses, orchards (e.g., apples, pears, etc.) and mushroom sheds. The area of annual cropland and permanent grassland per province and soil texture class is based on soil maps and census data (Hazeu et al., 2014). The area of greenhouses, orchards and mushroom sheds is based on national statistics (CBS, 2019). The conversion of one land use class to another e.g., permanent grassland to annual cropland, was not permitted in this analysis, with the exception of temporary grassland to be grown on annual cropland to diversify and improve crop rotations.

On annual cropland, permanent grassland or permanent cropland, 49 representative crops (one productivity level, based on current management) can be grown. Current crop yields are based on national statistics or survey data and vary per soil texture class if available (CBS, 2019; De Ruijter et al., 2020). Cereal and oil seed crops also produce a crop residue, which can be harvested to fertilise other arable crops. Crop residue yields are based on default coefficients (PPO, 2018). To simulate crop rotations in FOODSOM, a maximum crop share applies, for example, if a crop can only be grown every second year, the maximum area of the crop is 50 % of annual cropland in a given province and soil type combination. Temporary grassland can be grown on annual cropland, while permanent grassland cannot be converted into annual cropland. Crops are fertilised with crop residues, animal manure, compost, and artificial fertiliser to meet current nitrogen and phosphorus requirements. Nitrogen fertilisation uses nitrogen fertiliser replacement values to account for the effective nitrogen in nitrogen inputs. Nitrogen fertiliser replacement values and N fertilisation requirements are based on national legislation (RVO, 2021). Phosphorus fertilisation requirements are based on a balanced fertilisation approach using harvested P and an unavoidable loss fraction (Lun et al., 2018; RVO, 2021). Application of animal manure complies with current N fertilisation legislation (Reference scenario only; 2018) or future legislation which excludes derogation (all other scenarios). Crop fertilisation and yields remained constant across all scenarios.

2.3. Livestock systems

Seven livestock systems (dairy cattle, beef cattle, broiler chickens, sheep for meat, dairy goats, laying hens, pigs) are included in FOODSOM. Two productivity levels (high and medium) are considered for the major livestock systems: dairy cattle, beef cattle, broiler chickens, laying hens and pigs. Only one productivity level is included for dairy goats and sheep. Livestock productivity was based on typical Dutch systems (Van Hal et al., 2019). Parent stocks (e.g., sow in pig system) and reproduction stocks (e.g., heifer in a dairy system) of producing classes of livestock are also included. Veal calves are a component of the dairy system, and were partly imported in the Reference scenario, however this is not permitted in all other scenarios as livestock systems are assumed to be self-sufficient.

Livestock can consume feed-food crops (i.e., crops suitable for human consumption; depending on the scenario), by-products (e.g., wheat bran), food losses (e.g., post-harvest losses), fresh and conserved grass (silage and hay), and synthetic amino acids to meet their nutrient requirements (protein and energy). Feed intake capacity constraints are also included. The nutritional value of animal feed is obtained from the Centraal Veevoeder Bureau (CVB, Spek and Van Wesemael (2021)).

Aside from producing meat, milk and eggs, livestock also produce manure which can be used as a fertiliser for crops and grassland. In the model, all manure is captured in a manure management system except that of grazing ruminants. Manure captured in manure management systems can be applied to arable land. Grazing ruminants excrete manure directly into grassland, the proportion of manure excretion into grassland is based on the portion of grazed grass in the diet (i.e., if 50 % of dry matter is from grazed grass then 50 % of manure excretion is in grassland). Grazing can vary between 12.5 % of DM intake (i.e., 6 h per day, 180 days per year) to 50 % of DM intake (i.e., 24 h per day 180 days per year) and is an outcome of the optimisation.

2.4. Marine fisheries

The top 10 fish species landed in the Netherlands (95 % of total fisheries) are included in FOODSOM (CBS, 2019). Marine fish is only suitable for human consumption, however, the by-product from fish processing can be fed to animals or composted.

2.5. Processing crops, livestock & fisheries products

Crop, livestock, and fisheries products are processed into food (e.g., wheat into flour) for human consumption which also produces by-products (e.g., wheat bran, blood and bone meal). The ratios of food to by-products are based on technical conversion factors (Vellinga et al., 2013). Food is also lost (e.g., during storage or during processing) and food is wasted (e.g., during consumption or in the supermarket) as it moves along the supply chain. The quantity of food lost and wasted is based on food loss and waste fractions (Caldeira et al., 2019).

2.6. Food loss & waste

By-products and food losses (i.e., post-harvest losses and processing and packaging losses) are processed into animal feed or composted. We assumed 50 % of the available food losses and food waste is used as animal feed or compost (Soethoudt and Timmermans, 2020). The feeding of food losses and waste complies with current animal feed regulations. Carbon dioxide emissions related to processing food and animal feed and the transport of food and agricultural inputs were not included in this analysis to allow comparison with national emission targets for agriculture.

2.7. Import & export

Food and raw materials are imported and exported to and from the Netherlands. The quantity of imports and exports is based on FAO food balance sheets. The net import or export is calculated for each product accounting for changes in stock and to exclude raw agricultural products used for non-food purposes. The level of import and export varied depending on the scenario and if the products are plant-sourced or animal-sourced food (See Scenarios section).

2.8. Human diet

The human diet is initially based on current consumption at a food group level (the Reference scenario). The outcome of the Reference scenario subsequently determined the diet composition at a food product level (e.g., potatoes, cabbage), which was kept constant across scenarios except the meat food group. The intake of meat (from ruminants and monogastricts) food group can vary in composition (i.e., more chicken and less beef) or total quantity depending on the scenario (see Scenarios section).

2.9. Greenhouse gas & nitrogen emissions

GHG and nitrogen emissions include emissions from the fertilisation of land and keeping of livestock. Calculations are performed using national GHG inventory methodologies or national emission modelling methodologies (van Bruggen et al., 2020; Lagerwerf et al., 2019). GHG emissions and nitrogen emissions from the fertilisation of land include direct and indirect nitrous oxide (N_2O), ammonia (NH_3), and nitrogen oxides (NO_x) from nitrogen application, mineralisation of peat soils, nitrogen deposition, and nitrogen fixation from legume crops. The emission factors vary depending on the type of product being applied (e.g., manure, artificial fertiliser), land use (e.g., arable or grassland) and soil type (e.g., sand, clay). GHG emissions and nitrogen emissions from livestock include nitrous oxide, ammonia, nitrogen oxide, and methane (CH_4) emissions from manure handling and storage. In addition, methane emissions from ruminant enteric fermentation are included. GHG emissions from livestock are a function of feed intake and vary based on the type of feed consumed. GHG emissions from on-farm fossil fuel use, marine fisheries, transportation, processing crops and livestock products, producing artificial fertiliser and processing animal feed are not included in this study to align with and enable comparison with national emission targets.

2.10. Nutrient use efficiency

Nutrient use efficiency is calculated at the Dutch food system level. Nutrient inputs include: nutrients in artificial fertiliser, nitrogen fixation, nitrogen deposition, nitrogen mineralisation, and nutrients in imports (i.e., food and animal feed). Nutrient outputs include: nutrients in exports, and nutrients consumed in the human diet.

2.11. Scenarios

Here we further describe the four additive scenarios developed to analyse the recoupling of livestock and feed production in the Netherlands (Table 1). These scenarios vary based on the model objective, the inclusion of animal feed imports, the inclusion of environmental emission constraints, and the exclusion of feed-food competition.

The first scenario, (further referred to as the Reference scenario) represents the current state of the food system in the Netherlands and provides a reference and model evaluation for this study (Supplementary Material). The model objective of the Reference scenario is to minimise the deviation between the modelled reference diet and the current diet (based on the national food consumption surveys; (van Rossum et al., 2020)). In the Reference scenario, the area of crop (e.g., hectares of wheat), number of animals (e.g., pigs), and quantity of food and raw materials imported and exported in the Netherlands are fixed to the current values (CBS, 2019; FAO, 2019). The data for the Reference scenario is from 2018.

The second scenario (Recouple) aims to quantify the livestock carrying capacity of the Netherlands when livestock are only fed locally produced feed, while feed-food competition is still allowed. This scenario avoids the import of animal feed, including avoiding oil seeds and beans destined for oil processing, as the primary driver for importing oil seeds and beans in the Netherlands is considered livestock feed. Currently, oil seeds and beans are imported, processed into oil and meal/cake, and the meal/cake is fed to livestock in the Netherlands while much of the oil is exported (FAO, 2019). All other imports and exports (excluding animal feed and animal products) remain unchanged. This includes cereals and oil seeds for human consumption.

The model objective of the Recouple scenario is to maximise the quantity of animal-sourced protein produced in the Netherlands. The human diet is equal to the modelled reference diet at food product level (e.g., broccoli), except for food products in the meat food group. Fixing imports, exports, and the human diet (except meat) ensures only the feed production on arable land can be adjusted to meet livestock demands i.e., supply and demand for other crops (e.g., potatoes) remain unchanged. Additionally, livestock numbers per production system (e.g., dairy) cannot exceed current livestock numbers at a regional level in the

Table 1
Overview of scenarios.

	Reference	Recouple	Recouple-Env	Recouple-Env-NFFC
Feed import	Yes	No	No	No
ASF export	Current	Variable	Variable	Variable
PSF export	Current	Current	Current	Current
ASF diet	Current	Current	Current	Variable[a]
PSF diet	Current	Current	Current	Current
Feed-food competition	Yes	Yes	Yes	No
Feeding food losses	Yes	Yes	Yes	Yes
Feeding by-products	Yes	Yes	Yes	Yes
Feeding slaughter waste	No	Yes	Yes	Yes
Emission ceiling	No	No	Yes	Yes
Model objective	Current diet	Maximise animal-sourced protein production	Maximise animal-sourced protein production	Maximise animal-sourced protein production

Reference: Current situation (2018); Recouple: No import of feed; Recouple-Env: No import of feed while reaching environmental targets; Recouple-Env-NFFC: No import of feed while reaching environmental targets and no food-feed competition; ASF: Animal-sourced food; PSF: Plant-sourced food.

[a] Animal-sourced food was prioritised to meet the requirements of the national diet before exporting in the Recouple-Env-NFFC scenario.

Netherlands.

The third scenario (Recouple-Env) aims to quantify the livestock carrying capacity of the Netherlands when livestock are only fed locally produced feed and national environmental emission targets are respected. This is identical to the Recouple scenario, except a cap is placed on GHG emissions and ammonia emissions based on national emission reduction targets. GHG emissions are summed based on their respective global warming potential (GWP) (i.e., carbon dioxide equivalents; methane: 27.2; nitrous oxide: 273 (Forster et al., 2021)). Ammonia and nitrogen oxides emissions are summed based on their respective acidification potential (AP) (i.e., in sulphur dioxide equivalents; ammonia: 1.88; nitrogen oxides 0.7 (Baumann and Tillman, 2004)). In the Recouple-Env scenario the GWP ceiling is 30 % lower than the result of the Reference scenario and ammonia ceiling is 50 % lower than the result of the Reference scenario (RIVM, 2022; Van Den Born and Van Der Zanden, 2023).

The fourth scenario (Recouple-Env-NFFC, i.e., no feed-food competition) aims to quantify the livestock carrying capacity of the Netherlands when livestock are only fed locally produced feed, national environmental emission targets are respected, and feed-food competition is avoided. Arable land cannot be used to cultivate crops for feed production. However, grassland was still permitted to complete crop rotations (i.e., diversify or improve), but the area of temporary grassland cannot exceed the area of temporary grassland in the Reference scenario. Livestock are only fed with fresh and conserved grass, by-products, and food losses. In the Recouple-Env-NFFC scenario livestock numbers per production system can exceed current livestock numbers to better align the availability of grassland resources, by-products, and food losses with the requirements of the human diet.

3. Results

3.1. Livestock numbers

Our results show that recoupling livestock and feed production resulted in a substantial decrease in livestock numbers as feed production was insufficient to sustain current animal numbers in the Netherlands (Fig. 1). The following livestock production systems decreased in the Recouple scenario compared to the Reference scenario: beef cattle (−100 %), dairy cattle (−29 %), broiler chickens (−57 %), laying hens (−67 %), pigs (−62 %) and sheep (−100 %). The reduction in the dairy cow system was partially due to the exclusion of surplus dairy (veal) calf imports. Applying an emission ceiling in the Recouple-Env scenario resulted in further changes to livestock numbers. The number of dairy cows (6 %), broiler chickens (10 %) and laying hens (3 %) increased compared to the Recouple scenario, while the number of pigs (−4 %) and goats (−14 %) decreased compared to the Recouple scenario. Broiler chickens and laying hens had a high nitrogen use efficiency, producing meat and eggs with lower nitrogen emissions.

Avoiding feed-food competition in the Recouple-Env-NFFC scenario substantially increased the number of beef cattle compared to the reference. Livestock numbers were allowed to exceed current livestock numbers in the Recouple-Env-NFFC scenario to better utilise feed products that don't create feed-food competition e.g., grassland. The

Fig. 1. Total livestock numbers in the Netherlands per animal production system in million animals per scenario. Reference: Current situation (2018); Recouple: No import of feed; Recouple-Env: No import of feed while reaching environmental targets; Recouple-Env-NFFC: No import of feed while reaching environmental targets and no food-feed competition. In the latter scenario, the current Dutch human diet is not met.

current Dutch diet demands significant quantities of meat, which was partly met by beef cattle utilising grassland. The number of broiler chickens reduced to zero, while only 1.7 million pigs remained. Pigs could effectively convert low quality by-products and food losses into meat. Dairy cattle, and laying hens decreased to a level that satisfied dairy product and egg consumption in the Dutch diet. Total livestock production, however, did not meet the current human diet.

3.2. Land use

In the Recouple and Recouple-Env scenarios all available agricultural land was utilised to produce food and feed crops (Fig. 2A). However, avoiding food-feed competition in the Recouple-Env-NFFC scenario decreased agricultural land use (−20 %) as no feed-food crops were grown.

In the Recouple and Recouple-Env scenarios temporary grassland decreased to zero. Grassland in arable crop rotations (i.e., temporary grassland) was replaced with maize silage, grain crops and legume crops in the Recouple and Recouple-Env scenarios, which decreased the temporary grassland area. However, in the Recouple-Env-NFFC scenario grain and legume feed crops could not be included in arable crop rotations to avoid food-feed competition, and instead temporary grassland was grown, which increased the area of temporary grassland back to current levels. The area of maize silage increased in the Recouple and Recouple-Env compared to the Reference scenario. Grain and legume crops were primarily fed to monogastric animals, or they supplemented dairy cattle diets. Demand for grain and legume crops, especially by monogastric animals increased the area of grain and legume crops in the Recouple and Recouple-Env scenarios. Currently, protein rich livestock feeds including oil seed meal and soybean meal are derived from imported oil seeds and soybeans. Removing these imported feed sources increased the national production of legume crops.

3.3. Exports of animal-sourced food

Recoupling crop and livestock production decreased the net export of animal-sourced protein (Fig. 3A). Feed production in the Netherlands was insufficient to sustain the number of animals required to maintain current exports. Total protein export was 59 % lower in the Recouple scenario, and 60 % lower in the Recouple-Env scenario compared to the Reference Scenario. No protein was exported in the Recouple-Env-NFFC scenario, but some excess animal fat (butter) was still exported (Fig. 3B).

When recoupling feed and livestock production, no meat was exported, but some dairy and eggs products were depending on the scenario (Fig. 3B). The export of dairy products (shown in milk equivalents) was always less than the Reference scenario. Dairy exports were highest in the Recouple scenario and decreased slightly in the Recouple-Env scenario when the emission ceiling was applied. A small number of eggs were exported in the Recouple-Env scenario due the lower nitrogen emissions and higher nitrogen use efficiency of laying hens. The Netherlands is currently a net exporter of all livestock products except sheep and goat meat in the Reference scenario (Fig. 3B). Sheep and goat meat remained an import product in all scenarios (not shown).

3.4. Human diet

Recoupling livestock and feed production alone had no impact on the human diet, as enough animal-sourced food could be produced to meet the current diet (Supplementary Material). However, when avoiding feed-food competition in the Recouple-Env-NFFC scenario, insufficient quantities of animal-sourced food could be produced to meet the required diet. Animal-sourced food contributed to 44 % of protein intake in the Reference scenario, but decreased to 34 % in the Recouple-Env-NFFC scenario. However, protein intake was still above recommended protein intake in the Recouple-Env-NFCC scenario. Equal quantities of dairy and eggs were produced, however, only 58 of the required 116 g per capita per day of meat could be produced. This implies that if feed-food competition is avoided in livestock diets, the Dutch population needs to reduce meat consumption, or the Netherlands will become import dependent to meet the present animal-sourced protein consumption.

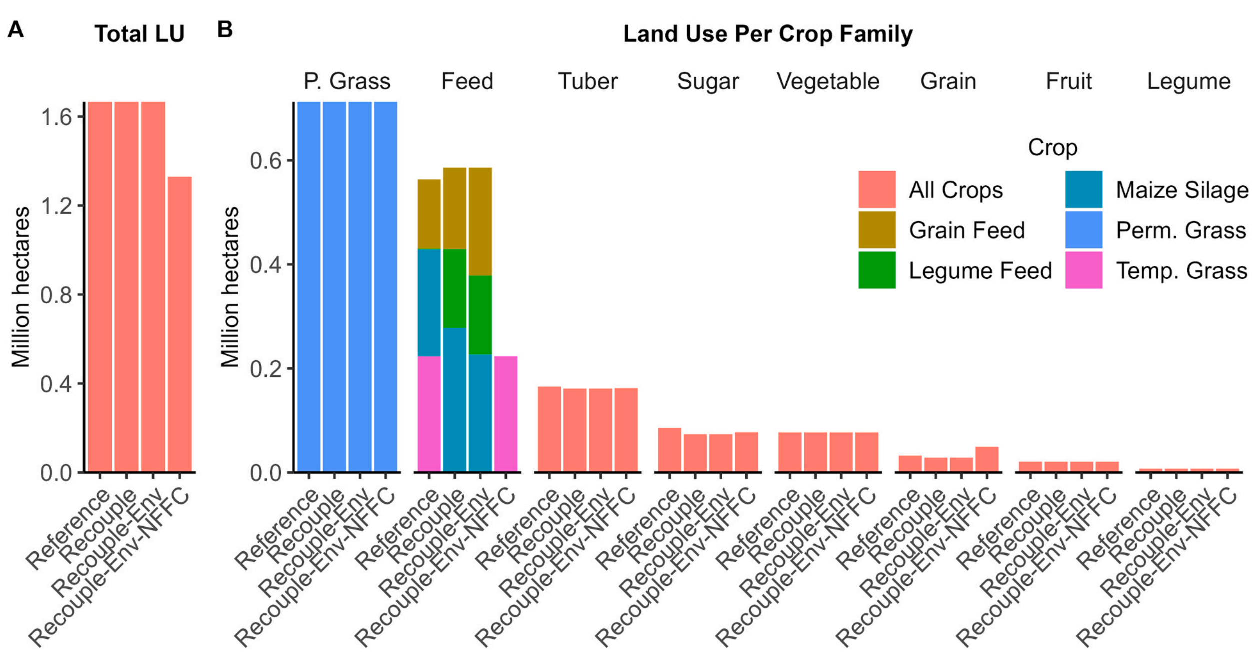

Fig. 2. A: Total agricultural land use (LU) in the Netherlands in million hectares per scenario; B: Total land use per crop family in the Netherlands in million hectares per scenario. P. Grass: Permanent grassland; Reference: Current situation (2018); Recouple: No import of feed; Recouple-Env: No import of feed while reaching environmental targets; Recouple-Env-NFFC: No import of feed while reaching environmental targets and no food-feed competition. In the latter scenario, the current Dutch human diet is not met.

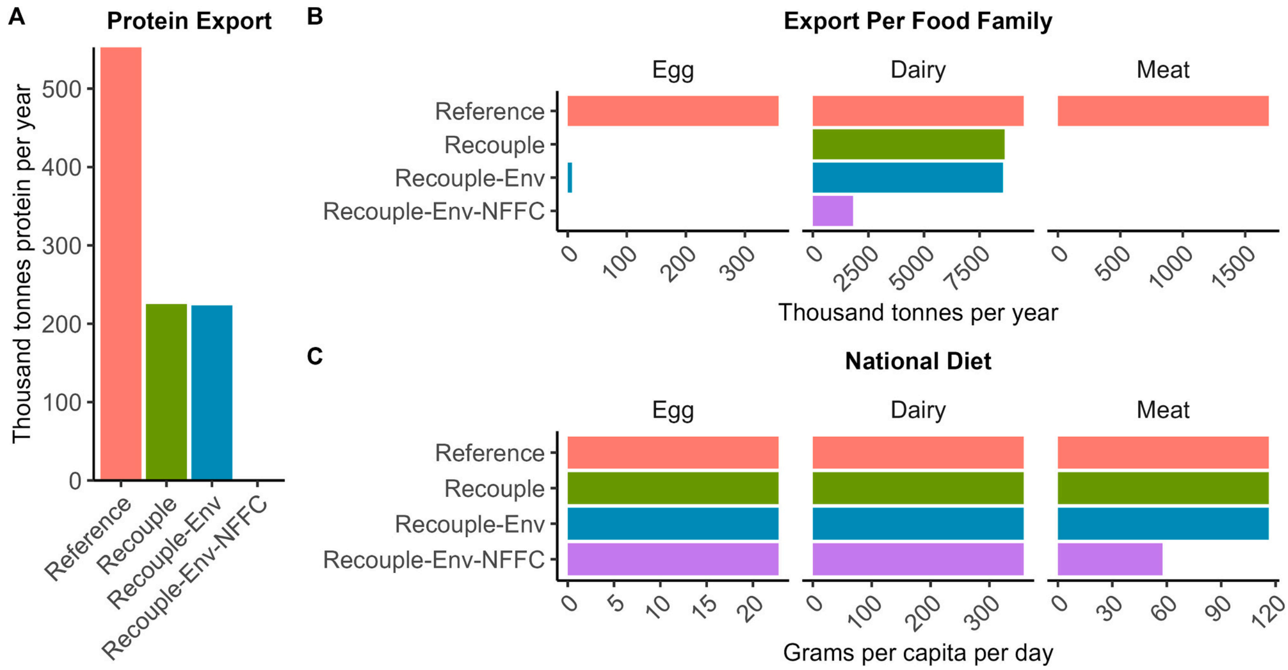

Fig. 3. A: Net export of animal protein in thousand tonnes per year; B: Net export of different animal-sourced food group in thousand tonnes per year. Dairy is shown in milk equivalents C: Human diet in the Netherlands of animal-sourced food groups in grams per capita per day. The human diet and trade at a food product level is available in the supplementary material. Reference: Current situation (2018); Recouple: No import of feed; Recouple-Env: No import of feed while reaching environmental targets; Recouple-Env-NFFC: No import of feed while reaching environmental targets and no food-feed competition. In the latter scenario, the current Dutch human diet is not met.

3.5. Nutrient use efficiency

Recoupling livestock and feed production increased nitrogen and phosphorus use efficiency of the Dutch food system (Fig. 4). Nitrogen use efficiency was higher in the Recouple (38 % vs. 31 %) and Recouple-Env (39 % vs. 31 %) scenarios compared to the reference scenario. However, in the Recouple-Env-NFFC scenario, nitrogen use efficiency was only 27 %. Less livestock and animal manure resulted in more efficient use of manure and, less by-products (i.e., slaughter waste), which increased nitrogen and phosphorus use efficiencies of the food system. Phosphorus use efficiency was highest in the Recouple scenario (72 %), because applying emission ceilings in the Recouple-Env scenario optimised the food system to reduce nitrogen emissions at the expense of the phosphorus use efficiency. Avoiding feed-food competition increased the number of beef cattle, which are less efficient at converting nutrients from feed into animal-sourced food, resulting in more losses and a lower nutrient use efficiency.

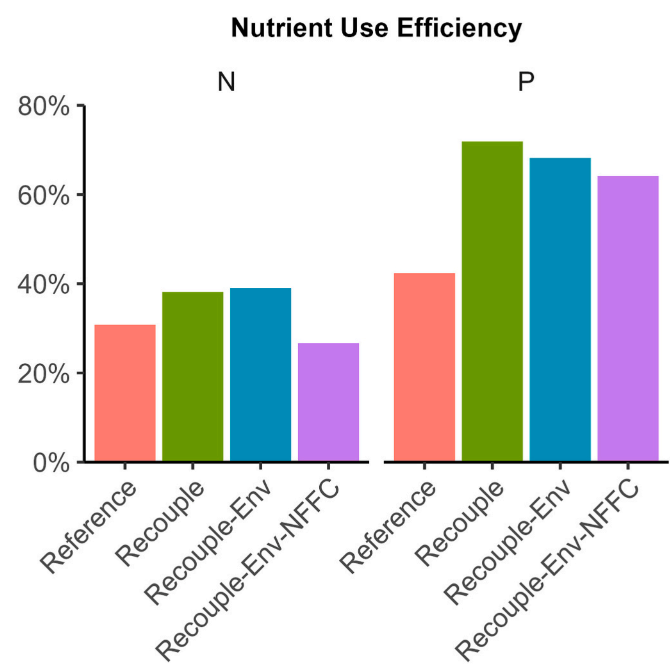

Fig. 4. Nitrogen (N) and phosphorus (P) use efficiency of the Dutch food system across scenarios. Inputs included nitrogen fixation, nitrogen deposition, nitrogen mineralisation, nutrients in feed and food imports, and artificial fertiliser. Outputs included nutrients in food and feed exports, and nutrients in food products. Reference: Current situation (2018); Recouple: No import of feed; Recouple-Env: No import of feed while reaching environmental targets; Recouple-Env-NFFC: No import of feed while reaching environmental targets and no food-feed competition. In the latter scenario, the current Dutch human diet is not met.

3.6. Environmental impacts

The reduction in livestock numbers, driven by recoupling livestock and feed production, nearly met ammonia emission and GHG emission targets in all scenarios (Fig. 5). Only when an emission ceiling was applied in the Recouple-Env and Recouple-Env-NFFC scenarios, could emission targets be met entirely (Fig. 5).

Reductions in nitrogen acidifying emissions (i.e., ammonia and nitrogen oxides) were dominated by reductions in ammonia emissions. Notably, nitrogen emissions from livestock in the Recouple-Env-NFFC and Recouple-Env scenarios were similar due to high demands for meat consumption and a limited supply of high-quality feed, which resulted in less efficient livestock e.g., beef cattle. The main source of nitrogen oxides was from the fertilisation (including manure) of grassland and arable land (Reference: 90 %). Less livestock resulted in less fertilisation with manure and more fertilisation with artificial fertiliser, which reduced nitrogen oxides emissions compared to the Reference

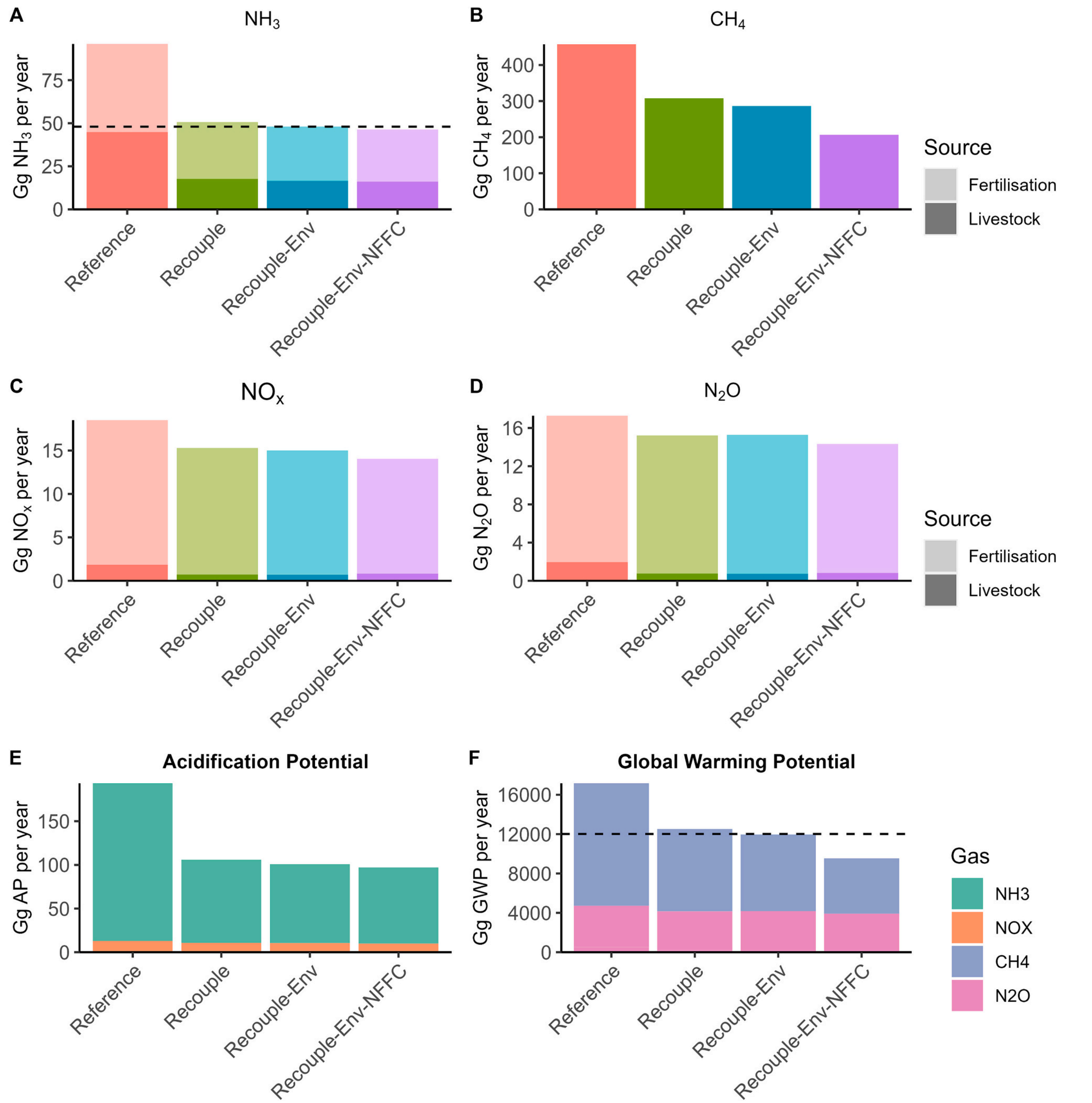

Fig. 5. Environmental emissions in the Netherlands. Solid colours show emissions from livestock, shaded colours show emissions from fertilisation (fertilisation emissions include emissions related to the application of animal manure). A: Ammonia emissions in Gg per year; B: Methane emissions in Gg per year; C: Nitrogen oxides emissions in Gg per year; D: Nitrous oxide emissions in Gg per year; E: Acidification potential in Gg per year; F: Global warming potential in Gg per year. Reference: Current situation (2018); Recouple: No import of feed; Recouple-Env: No import of feed while reaching environmental targets; Recouple-Env-NFFC: No import of feed while reaching environmental targets and no food-feed competition. In the latter scenario, the current Dutch human diet is not met. Dashed horizontal lines indicate national emission targets for 2030.

scenario (Recouple: −17 %; Recouple-Env: −19 %; Recouple-Env-NFFC: −24 %). Overall, the acidification potential was reduced by −45 % in the Recouple Scenario, −48 % in the Recouple-Env scenario, and −50 % in the Recouple-Env-NFFC scenario compared to the Reference scenario. However, avoiding feed-food competition in livestock diets also reduced the production of animal-sourced food.

Reductions in GHG emissions (i.e., nitrous oxide and methane) were dominated by reductions in methane emissions. Methane emissions are primarily caused by ruminant enteric fermentation. Reducing ruminant numbers e.g., dairy cattle, reduced methane emissions (Recouple: −33 %; Recouple-Env: −37 %; Recouple-Env-NFFC: −55 %). On the other hand, similar to nitrous oxide emissions, nitrogen oxide emissions mainly come from fertilising grassland and arable land. Therefore, the mitigation potential was limited (Recouple: −12 %; Recouple-Env: −12 %; Recouple-Env-NFFC: −17 %). Overall, GHG emissions were reduced by −27 % in the Recouple Scenario, −30 % in the Recouple-Env scenario, and − 44 % in the Recouple-Env-NFFC scenario compared to the Reference scenario. Notably, methane emission reductions in the Recouple-Env and Recouple-Env-NFFC scenarios were greater than 30 %, and therefore within the global methane pledge (not included in this study).

4. General discussion

4.1. The current Dutch diet can be met by recoupling feed and livestock production in the Netherlands

Recoupling livestock and feed production is shown to lead to much lower environmental impacts while diets can be largely maintained, but at the expense of animal-sourced food exports. Ammonia emissions were reduced by 47 % and GHG emissions were reduced by 27 %, which were both 3 % short of national emission targets. Livestock numbers reduced to a level that could be sustained by local feed production (Fig. 1), while local feed production changed (e.g., more grains and less grassland) to meet livestock demands for the present diet (Fig. 2). Sufficient animal-sourced food was produced to meet current consumption in the Netherlands, with surplus dairy exported (Fig. 3). No meat or eggs were exported in the Recouple scenarios. Future technologies e.g., improved manure management (De Vries et al., 2015), may help reduce environmental emissions further in the Recouple scenario to within national emission targets. Without improved technologies, some further changes in livestock numbers (i.e., more dairy and broiler, less goats and pigs) beyond the local feed production capacity would be required to meet environmental targets (i.e., Recouple-Env scenario). High agricultural productivity in the Netherlands is driven by the import of animal feed, which externalises the environmental impact of feed production (i.e., the environmental impact of imported feed production is not assigned to the Netherlands). This means that the true environmental impact of the Reference scenario is higher. On the other hand, this analysis focuses on local environmental targets and the environmental impact of exported food items is also not assigned to the respective import country.

4.2. Avoiding food feed competition is not compatible with the current Dutch diet

Trying to meet current animal-sourced food consumption while avoiding feed-food competition creates inefficiencies in the food system (Fig. 4). Avoiding feed-food competition in circular food systems is only meaningful in combination with dietary change and reduced animal-sourced food consumption (to a level where feed demand does not drive crop production). The types of livestock selected e.g., ruminant or monogastric animals were determined by the feed available e.g., grassland or food-feed crops. When avoiding food-feed competition, ruminant production systems were favoured due to their ability to convert grassland resources into animal-sourced food. Temporary grassland i.e., indirect feed-food competition, was still required in the Recouple-Env-NFFC scenario to extend arable crop rotations, however, crop rotations could also be extended using grain crops for human consumption to eliminate indirect feed-food competition as well. This would, however, require a dietary change.

Feeding food waste, which is currently prohibited may increase the production of monogastric animals (especially pork) in a situation where food-feed competition is avoided (Van Selm et al., 2022), but, again, not enough to meet the current diet. Changing to healthier whole-grain diets will also reduce the amount of by-products available and scope for monogastric animals (Van Selm et al., 2022). If diets are left unchanged, feeding monogastic animals with feed-food crops is a more efficient option than avoiding feed-food competition and feeding ruminants with grass. While recoupling livestock and feed production does not necessarily avoid feed-food competition we show that recoupling offers a substantial step towards a more circular food system.

In the Recouple and Recouple-Env scenarios permanent grassland could not be converted to arable land due mostly to the unsuitability of soil/land and associated soil carbon losses contributing to GHG emissions (Knotters et al., 2022). Converting permanent grassland to arable land would increase the available land for food-feed crops, which may increase the number of monogastric animals at the expense of ruminants. Additionally, monogastric animals have a higher nutrient efficiency than ruminants and produce less methane emissions (Gerber et al., 2014). However, decreasing grassland (including temporary grassland) would have a negative impact on biodiversity and, on soil carbon sequestration, which in turn contributes to GHG emissions. It may also have implications for the types of animal-sourced food exported i.e., less dairy (Schils et al., 2022; Van Selm et al., 2022).

4.3. Recoupling feed and livestock production is a promising next step towards circularity

The model objective in the Recouple and Recouple-Env scenarios was to maximise protein production from livestock in the Netherlands, which fits within the 'feed the world vision' shared by the agricultural sector. The Netherlands is part of a river delta, with very fertile soils. As such, grasslands and feed production can sustain higher livestock numbers, even without feed imports. The high productivity of Dutch agriculture makes it logical to export food products. Reducing livestock production in the Netherlands may not be beneficial for global GHG emissions, if production is absorbed by another country with less efficient production and a higher GHG emission intensity than global GHG emissions may increase. However, ammonia emissions have a local environmental impact and therefore, reducing livestock production will always be an effective method to reduce the local impact of nitrogen deposition rates associated with ammonia emissions. However, agricultural production must remain within environmental limits, therefore, it remains questionable how much the Netherlands should be exporting given the local environmental challenges, and especially in terms of livestock products, given the push to reduce the production and consumption of livestock products.

Moving towards recoupled livestock and feed production should include accommodating associated economic and social impacts (e.g. by developing alternative employment schemes and/or supporting increased economic returns on investment), especially for monogastric livestock farmers. Recoupling may increase the cost of production (due to higher feed prices) and reduce the overall competitiveness of the Dutch livestock sector. Additional economic support for farmers may be required, along with policies to protect Dutch livestock products from lower cost imported alternatives. This would require careful consideration, given the large changes to the livestock sector. In some scenario's land was left unused, which could allow for less intensive crop production with lower nitrogen fertiliser inputs and lower crop yields. Alternatively, the Netherlands could utilise arable land to produce more plant-sourced foods, which can feed more people (outside the Netherlands) an adequate and balanced diet (Van Zanten et al., 2023). However, recoupling livestock and feed production still offers a next step towards a more circular food system. Regional carbon and nutrient cycles can be better balanced resulting in less emissions, as imported feed isn't contributing to resource accumulation, and exported feed isn't contributing to resource depletion. Recoupling livestock and feed production also fits with Dutch policy objectives, as for example, the annual nutrient cycling assessment carried out by dairy farmers in the Netherlands includes indicators on how much protein feed is produced on their own land (Ministry of Agriculture Nature and Food Quality, 2018; de Vries et al., 2020). Further reductions in GHG emissions (specifically CO_2 emissions) could also be achieved by including other GHG emission sources e.g., on-farm electricity use.

Integrating nutrient balances into recoupled food systems may offer opportunities to import animal feed without disturbing nutrient cycles. Importing animal feed unlocks local production and technological efficiencies (i.e., higher yields) (Campi et al., 2020). Some regions are more efficient at producing (feed) crops than others. For example, the Netherlands is an efficient producer of energy crops, but less efficient at producing protein crops. An alternative is to determine the feed production capacity of a region and associated livestock numbers, but still allow the import and export of animal feed using a nutrient balance (e.g., nitrogen, phosphorus) of animal feed. In this way, nutrient cycles can be maintained while taking advantage of local production efficiencies (Van Selm et al., n.d.).

5. Conclusion

Recoupling livestock and feed production will contribute to reducing ammonia emissions and GHG emissions in the Netherlands. In this study, livestock numbers in the Netherlands were recalibrated to the local feed production capacity. As a result, ammonia emissions were reduced by 47 % and GHG emissions were reduce by 27 %, which is close to national targets for 2030. Fully meeting the national targets led to further changes in livestock composition. Avoiding feed-food competition in livestock diets showed little promise to reduce ammonia emissions, due to an increase in beef cattle, which have a lower nitrogen efficiency than monogastric animals fed on feed-food crops. Avoiding feed-food competition should therefore only be considered in combination with a dietary change towards less animal products. The natural ceiling created by recoupling livestock and feed production is one pathway for achieving a more circular food system while reducing environmental impacts. Our food system explorations may be used in the policy process to reform the food system.

CRediT authorship contribution statement

Benjamin van Selm: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing. **Renske Hijbeek:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Martin K. van Ittersum:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Ollie van Hal:** Conceptualization, Methodology, Writing – review & editing. **Corina E. van Middelaar:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Imke J.M. de Boer:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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