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Combining Organic Agriculture With A Reduction In The Use Of Concentrate Feed And A Reduction In Food Waste Can Significantly Increase The Sustainability Of The Luxembourgish Food System

Structured Abstract

Context: Agriculture is not only contributing to the most pressing environmental challenges of our time, such as greenhouse gas (GHG) emissions and climate change, nitrogen over-supply and biodiversity loss, but it is also affected by them. The sustainability of the agricultural sector is also influenced by consumers through their food choices.

Objective: The aim was to identify changes in agricultural practices and dietary habits to increase the sustainability of the Luxembourgish food system.

Methods: The Sustainable and Organic Livestock model (SOLm), a bottom-up mass flow model, was used to model the Luxembourgish food system. The model provides detailed results on production patterns and all animal and plant activities are associated with a range of environmental impacts (land use, N and P surplus, non-renewable energy use, GHG emissions, water use, pesticide use, deforestation, soil erosion). SOLm also calculates food availability for each scenario. Three future scenarios for 2050 were calculated: increase in organic agriculture (0 % - 100 %), reduction in the use of concentrate feed (0 % - 100 %) and the reduction of food waste (0 % - 50 %).

Results and Conclusions: Through combinations of the three modelled scenarios, a significant increase of the sustainability of the Luxembourg food system would be possible, mainly through the reduction in animal, especially ruminant, numbers. Overall, the yield losses associated to the increase in organic farming could be compensated by reducing food waste and the use of concentrate feedstuff, maximizing the cultivation of food instead of feed. To reduce GHG emissions, maximise food sovereignty, preserve environmental resources and sufficient nitrogen supply simultaneously, 75 % organic farming, 25 % less food waste and at 50 % less concentrate feed should be targeted. This would result in a 50% reduction in GHG emissions, a 50% reduction in ammonia emissions and attain 32% caloric self-sufficiency.

Keywords: Food system, organic agriculture, Feed no Food. Food waste reduction, Luxembourg

1. Introduction

Agriculture is not only contributing to the most pressing environmental challenges of our time, such as greenhouse gas (GHG) emissions and climate change, nitrogen over-supply and biodiversity loss, but it is also affected by them (Bohn et al., 2011; Godfray et al., 2010; Molotoks et al., 2021; Muluneh, 2021; United Nations, 2018; Zlatanova et al., 2024). Not only the negative environmental impacts, but also population growth poses new challenges for food security of the entire world population (Barrett, 2021; Molotoks et al., 2021). Luxembourg has one of the highest population growth rates in the EU. Current projections indicate that Luxembourg's population will grow by more than 50% to 1 million people by 2050 (EUROSTAT, 2023).

The Luxembourg government aims to find solutions for the above-mentioned environmental problems at the national level. In the governmental programs of the last two legislative periods, organic agriculture is identified as a promising avenue to do so (Gouvernement du Grand-Duché de Luxembourg, 2018, 2023). In the "3rd Industrial Revolution Study for the Grand-Duchy of Luxembourg", the need for a more sustainable food system was acknowledged and organic agriculture was named as a starting point (Grand Duchy of Luxembourg Working Group and TIR Consulting Group LLC, 2016). Here, in the pillar "Food", the vision was to achieve 100% organic agriculture in Luxembourg by 2050. With 149 of the 1843 farms in Luxembourg in 2022 farming according to organic agriculture principles, Luxembourg is still a long way from realising this vision (Ministère de l'Agriculture, de la Viticulture et du Développement rural, 2023). While the environmental benefits of organic agriculture and its potential to deal with many of the above mentioned challenges are scientifically recognised (Sanders & Hess 2019), the lower yields in organic production systems need to be considered when it comes to feeding a growing population (Seufert et al., 2012).

Although changes in agricultural practices are needed to meet the environmental challenges and ensure food security for future generations, the sustainability of the agricultural sector is also influenced by factors outside the farm boundary. Consumers influence the sustainability of agriculture through their food choices. The impact of dietary habits on food system sustainability has been the focus of several papers in recent years and it has been shown that dietary changes can improve the sustainability of food systems (e.g. Aiking, 2011; Bellarby et al., 2013; Godfray et al., 2010; Godfray and Garnett, 2014; Hedenus et al., 2014; Scarborough et al., 2014; Schader et al., 2015; Soussana et al., 2010; Springmann et al., 2016; Stehfest et al., 2009; Tilman and Clark, 2014; Tukker et al., 2011; Wirsenius et al., 2010). Thus, diets need to be considered when developing strategies for sustainable food systems. There is generally agreement that animal proteins in Western diets need to be reduced, but disagreement on what animal source food should be reduced and by how much (Frehner et al., 2020). For example, should animal proteins from pork or poultry be favoured over ruminants, or vice versa? Especially, as ruminant husbandry can valorise grassland resources that would otherwise be unsuitable for food production.

Since 50% of Luxembourg's agricultural land is permanent grassland (68,681 ha of 132,520 ha), ruminant husbandry is the most important farming sector in Luxembourg (1,071 out of 1,843 farms specialised in ruminant husbandry in 2022 (Ministère de l'Agriculture, de la Viticulture et du Développement rural, 2023)). The question therefore arises which changes in agricultural practices and which changes in dietary habits are needed to increase the sustainability of the Luxembourgish food system.

2. Materials and Methods

The Sustainable and Organic Livestock model (SOLm) was used to model the Luxembourgish food system. SOLm is a bottom-up mass flow model that depicts agricultural production and the food sector. The model provides detailed results on production patterns and all animal and plant activities are associated with a range of environmental impacts (land use, N and P surplus, non-renewable energy use, GHG emissions, water use, pesticide use, deforestation, soil erosion). SOLm also calculates food availability (expressed as calorie, fat and protein supply per capita per day) for each scenario (Muller et al., 2017, 2020; Schader et al., 2015).

2.1. Data Sources and adaptations for Luxembourg

The model is based on FAOSTAT data, in particular the food balance sheets, and covers 192 countries, 180 primary crop activities and 22 primary animal activities as defined in FAOSTAT. For the present study, FAOSTAT data from 2016 to 2020 were used (FAOSTAT, 2025) and the GHG inventory report for Luxembourg was used to calibrate the model (Administration de l'Environnement, 2024).

The following adjustments were made:

- The agricultural activity report from Luxembourg (Ministère de l'Agriculture, de la Viticulture et du Développement rural, 2023) was used to implement the animal numbers and herd structure in SOLm.
- The feeding ratios of different food groups were adapted according to Zimmer et al. (2021), and the results from data collected at farm-level using the Sustainability Monitoring and Assessment RouTine (SMART)-Farm Tool (RRD: SCR_018197) (Evelyne Stoll et al., 2023; Stoll et al., 2020; Stoll and Zimmer, 2019).
- The quantity shares of crop residues were adjusted to reflect that nearly no crop residues are left on fields in Luxembourg and is mostly used as bedding in animal husbandry. These changes were made based on the data from the SMART assessments mentioned above (Evelyne Stoll et al., 2023; Stoll et al., 2020; Stoll and Zimmer, 2019).
- Irrigation was adapted to national regulations, as it is only allowed in vegetable production. Irrigation amounts were adjusted according to irrigation practices recorded in the above-mentioned SMART assessments (Evelyne Stoll et al., 2023; Stoll et al., 2020; Stoll and Zimmer, 2019).
- Several assumptions for emission factors, nitrogen contents of residues, mineral fertilizer quantities, milk yields, etc. were adapted to the data from the GHG inventory for Luxembourg (Administration de l'Environnement, 2024).

2.2. Scenario description

The following description was taken from Muller et al. (2017) and supplemented with information on the Luxembourg scenarios.

(i) A baseline scenario ('base year') based on 2016 to 2020 data as provided by FAOSTAT, additional data from Luxembourg and on the results from the farm-level sustainability assessment using the SMART-Farm Tool (Evelyne Stoll et al., 2023; Stoll et al., 2020; Stoll and Zimmer, 2019) and the current farming practices identified herein with regard to crop production (fertilization, crop protection, crop rotation, etc.) and animal husbandry (productivity, feed, etc.) was adapted in SOLm.

(ii) A reference scenario for the Luxembourgish food system for 2050 was extrapolated based on "business as usual (BAU)", serving as a reference for comparison with the other future scenarios. This scenario was based on the FAO BAU-scenario as described in Alexandratos and Bruinsma (2012) and Muller et al., (2017) and concretized by projections for Luxembourg such as from ECO2050 Vision (Ministère de l'Economie, 2023) and Fondation IDEA (2023). It was assumed that Luxembourg would have 1 million inhabitants in 2050 (EUROSTAT, 2023). Projections on land-use change were made, using data from the Service d'Economie Rurale (2023) and Statec (2023), assuming a slight decline by 2050 of the agricultural area (from 132850 ha to 127142 ha), with 51.4% permanent grassland and 49% arable land.

(iii) For the scenario 'transition to 100% organic agriculture', an incremental increase in organic agriculture in 25%-steps was modelled (0%, 25%, 50%, 75% and 100%). It was assumed that there would be no difference in animal husbandry, except for a 10% yield gap and minor differences in the feeding rations (based on Zimmer et al., 2019). For crop production, more differences were implemented: no use of synthetic-chemical pesticides, no use of mineral fertilizers, 20% share of legumes in crop rotation and a yield gap of 25%. The crop rotations were further adapted based on data from the SMART assessments by excluding maize and rapeseed from the organic crop rotations, as they play no role in organic crop rotations in Luxembourg (Evelyne Stoll et al., 2023; Stoll et al., 2020; Stoll and Zimmer, 2019).

(iv) For the 'reduction of food waste' scenario, existing food waste was gradually reduced by 25% and 50% compared to the regional and commodity group specific values from FAO ((FAO, 2013). In the model, this resulted in a corresponding quantity of each commodity not being produced, leading to reduced input demand and impacts. Data for food waste in Luxembourg was obtained from Administration de l'Environnement (2023).

(v) For the 'feed no food' scenario, the feeding of food-competing feedstuff was reduced by 50% and 100%. The 100% reduction assumed ruminant production that is entirely grass-fed, and monogastric animals that are only fed by-products from food production (Muller et al., 2017).

As SOLm defines and implements 192 countries, normal trade patterns between countries based on FAOSTAT data are also implemented in the model. The above-described scenarios were therefore calculated in two modes, one with normal trade patterns in place (as in the reference scenario), only adjusted in accordance with the scenario assumptions (e.g. reducing concentrate feed imports for the scenarios with reduced concentrate feed use), the other with international trade artificially switched off. In the calculations without trade, only the import of production-relevant resources was assumed (mineral fertilisers, pesticides, electricity, fuels), while the import of feedstuff and food was stopped, to obtain unbiased results for the production potential Luxembourg's agricultural areas. In the scenarios without trade, it was assumed that ruminants were raised grass-fed, without food-competing feed, as otherwise, with the given shares of concentrate feed produced in Luxembourg, no solutions were possible to feed ruminants during the base year on their 'normal' feeding rations while simultaneously using the full grassland area. This was done to keep all grasslands in production and evaluate the production potential from the available agricultural land.

3. Results

The impact of the different scenarios and their option spaces were evaluated based on the following parameters: the number of cattle, chickens and pigs that can be raised, the amount of kilocalories (kcal) per capita per day, the amount of protein (in grams of protein per capita per day) and the amount of fat (in grams of fat per capita per day), emissions from enteric fermentations (in tCO_{2eq}), emissions from manure management (in tCO_{2eq}), emissions from fertilizer application (in tCO_{2eq}), ammonia emissions (in tNH_3) and nitrogen (N) balance (in tN/ha). These were chosen to provide insights into the animal production potential, the potential of food sovereignty for Luxembourg and the potential of GHG and nutrient emission reductions. The results are presented in the form of spider diagrams (Figures 1 - 5). In each diagram, the results for the BAU scenario with and without trade are shown, with the results for the BAU with trade being set to 100%. The results of the other scenarios without trade were then compared to the results of the BAU with trade.

In the non-trade scenarios, ruminants were switched to a grass-fed feeding. As a result, the number of ruminants decreased drastically from 186,442 with trade to 116,373 without trade (Figure 1). The number of pigs and chicken increased significantly as the domestically produced concentrate feed was allocated to their production. The reduction in cattle numbers had an add-on effect by reducing emissions from enteric fermentation, manure management, and fertilizer application (due to reduced manure production) and reducing ammonia emissions. Finally, the BAU without trade scenario showed a large reduction in food sovereignty by a reduced availability of calories (from 1,729 kcal/capita/day with trade to 769 kcal/capita/day without trade), grams of protein (from 66 g/capita/day with trade to 34 g/capita/day without trade) and grams of fat (from 74 g/capita/day with trade to 41 g/capita/day without trade) per capita per day. When focussing on calories only, this would mean a drop from 73% self-sufficiency to 32% self-sufficiency.

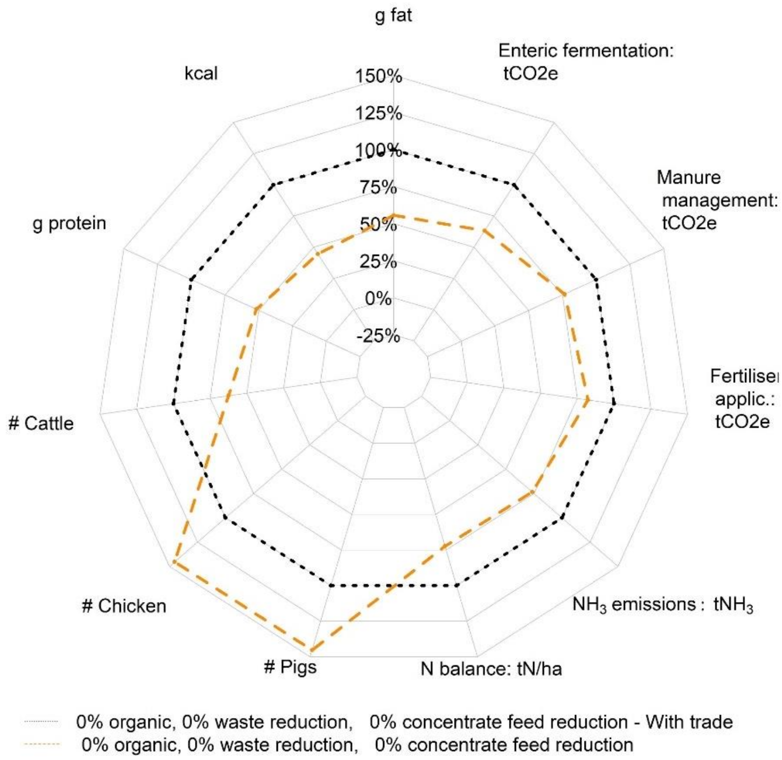

Figure 1: Impact of trade and no trade on the results of the reference scenario 'Business as Usual' (BAU). The dotted black line at 100% is the BAU situation 2050 with trade. The orange dashed line is the same as the reference scenario, just without trade. Without trade means that except for mineral fertilizer, pesticides and fuel, no other production relevant products, no feed and no food could be imported or exported – trade was artificially switched off. In the scenarios without trade, ruminants were grass-fed only (cf. above). This freed up domestically produced concentrate feedstuff for monogastric husbandry.

With increasing organic production, the food produced in terms of calories, grams of protein and grams of fat per capita per day generally dropped (Figure 2). This was most pronounced for grams of fat (from 65 g/cap/day for 0% organic agriculture to 35 g/cap/day at 100% organic agriculture), as the assumed crop rotations had no oil crops compared to the conventional production systems. The decrease in grams of protein per capita per day with increasing share of organic production (from 53 g protein/capita/day at 0% organic agriculture to 39 g/capita/day at 100% organic agriculture) was less pronounced, as a higher share of legumes was assumed in the organic crop rotations. The caloric self-sufficiency parameter dropped from 32% at 0% organic agriculture to 24% at 100% organic agriculture. The number of cattle that can be raised did not react as strongly to the increase in organic share. This was in part due to the fact, that ruminants were already by default grass-fed in the scenarios without trade.

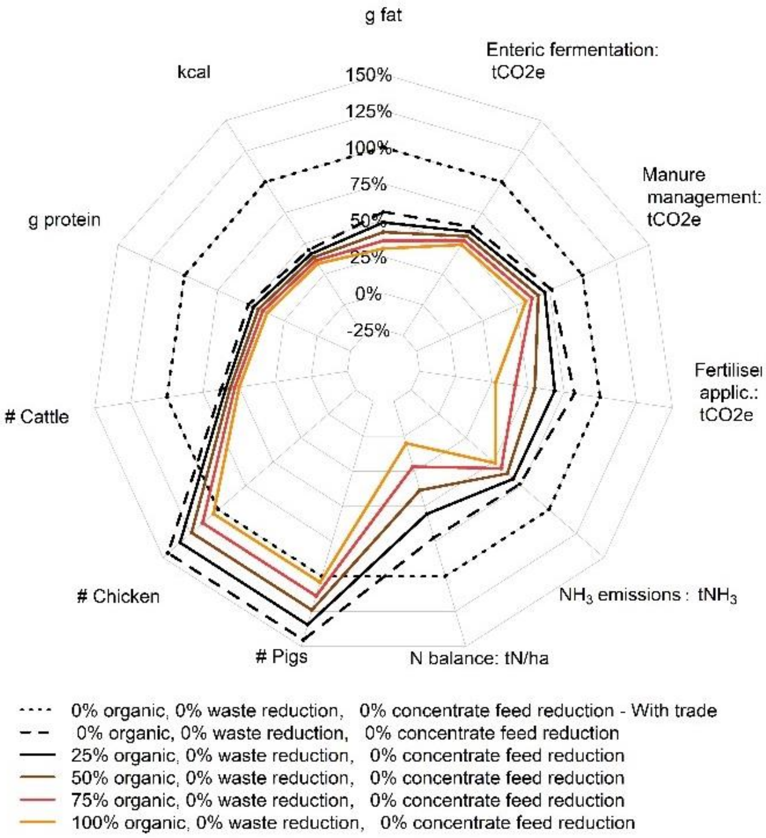

Figure 2: Impacts of an increasing share of organic agriculture. Reference scenario (dotted black line at 100%) is the BAU situation 2050, with trade. The other scenarios are without trade; indicator values given relative to the BAU with trade scenario. The dashed line is the same as the reference scenario, just without trade. Without trade means that except for mineral fertilizer, pesticides and fuel, no other production relevant products, no feed and no food could be imported or exported – trade was artificially switched off. In the scenarios without trade, ruminants were grass-fed only (cf. above). This freed up domestically produced concentrate feedstuff for monogastric husbandry.

As cattle numbers changed only slightly, the overall reduction in animal numbers with increasing share of organic agriculture had little effect on environmental emissions. At 100% organic agriculture, mineral fertilizer use was reduced to 0, significantly decreasing emissions related to fertilizer application (from 124,985 tCO_{2eq} at 0% organic agriculture to 42,026 tCO_{2eq} at 100% organic agriculture). Ammonia emissions were strongly reduced with increasing share of organic agriculture with a near 30% reduction at 100% organic agriculture compared to those at 0% organic agriculture. The nitrogen balance also decreased with increasing share of organic agriculture to 0.008 tN/ha at 100% organic agriculture.

When the use of concentrate feed was progressively reduced, the number of pigs and chickens that could be raised drastically decreased (Figure 3). The number of cattle did not vary as they were already grass-fed in the BAU without trade scenario. The stark reduction in monogastric animals lead to reduced manure production, which in turn reduced emissions from manure management and ammonia emissions (Figure 3, left panel). A 100% reduction in concentrate feed use resulted in an increase in caloric self-sufficiency (from 32% to 40% at 100% FnF) as the freed-up area, previously used to produce fodder, was now utilized to grow crops directly for human consumption. While the model showed that protein supply was maintained through the cultivation of protein plants (an increase from 34 g of protein/capita/day at 0% FnF to 45 g/capita/day at 100% FnF), fat supply decreased by nearly 50%. Combining Feed no Food with increasing shares of organic agriculture (Figure 3, middle and right panel), decreased the number of animals that can be kept further in turn decreasing environmental emissions even more, while the food sovereignty parameters were only marginally impacted. However, at 100% FnF and 100% organic agriculture, the N balance became negative (-0.019 tN/ha).

A reduction in food waste did not impact any of the emission parameters, as the full production potential was still exploited from the system (Figure 4). However, the reduction in food waste did impact the food sovereignty parameters with higher levels of calories, protein and fat availability per capita and per day (e.g. 34 g of protein/capita/day at 0% food waste reduction and 40 g of protein/capita/day at 50% reduction). Naturally, as less food was wasted, more of that food was available for consumption. This increase in food availability in terms of calories, protein and fat was observed to offset some of the reduction in food availability observed with increasing share of organic agriculture due to lower yields (e.g., 25 g of protein/capita/day at 100% organic agriculture and 0% food waste reduction and 30 g of protein/capita/day at 100% organic agriculture and 50% food waste reduction, thus nearly achieving the 34 g of protein/capita/day of the BAU without trade scenario).

Summing up the GHG emissions from the various sources showed that with the most restricting option space of the modelled scenarios (100% Org, 50% WRed and 100% FnF), a reduction in total GHG emissions of 60% was possible compared to BAU with trade, from 632 kt CO_{2eq} to 261 kt CO_{2eq}. The still drastic but less extreme changes to 50% Org, 50% WRed and 50% FnF would still allow almost halving the GHG emissions to 346 kt CO_{2eq} (a 45% reduction).

Rating the reduction of GHG emissions, the reduction of ammonia emissions and the increase in food sovereignty equally important, a compromise solution could be calculated within the option space: with 75% organic agriculture, 25% reduction in food waste and 50% reduction in the use of concentrate feed would achieve a 50% reduction in GHG emissions, a 50% reduction in ammonia emissions and attain 32% caloric self-sufficiency (Figure 5).

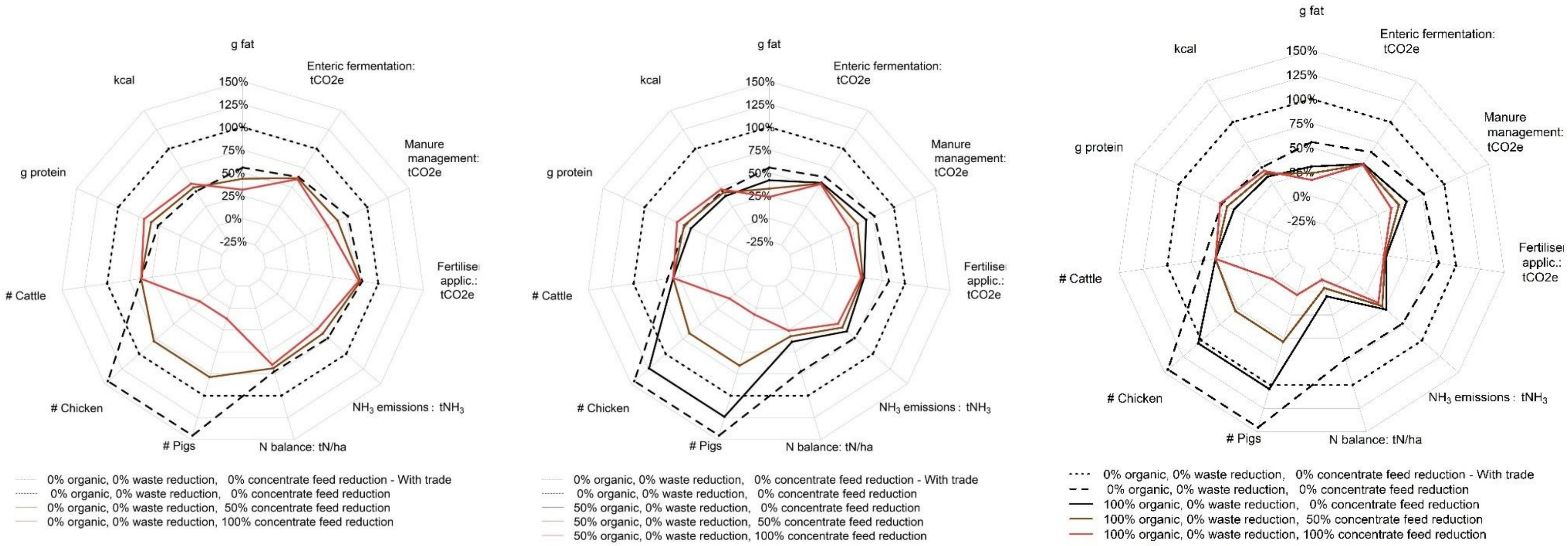

Figure 3: Impacts of Feed no Food at different shares of organic agriculture. Reference scenario (dotted black line at 100%) is the BAU situation 2050, with trade. The other scenarios are without trade; indicator values given relative to the BAU with trade scenario. Scenarios with 0% (left), 50% (middle) and 100% (right) organic production, further differentiated by reduction in food-competing feed by 0%, 50% and 100% (black, brown, red lines). The dashed line is the same as the reference scenario, just without trade. Without trade means that except for mineral fertilizer, pesticides and fuel, no other production relevant products, no feed and no food could be imported or exported – trade was artificially switched off. In the scenarios without trade, ruminants were grass-fed only (cf. above). This freed up domestically produced concentrate feedstuff for monogastric husbandry.

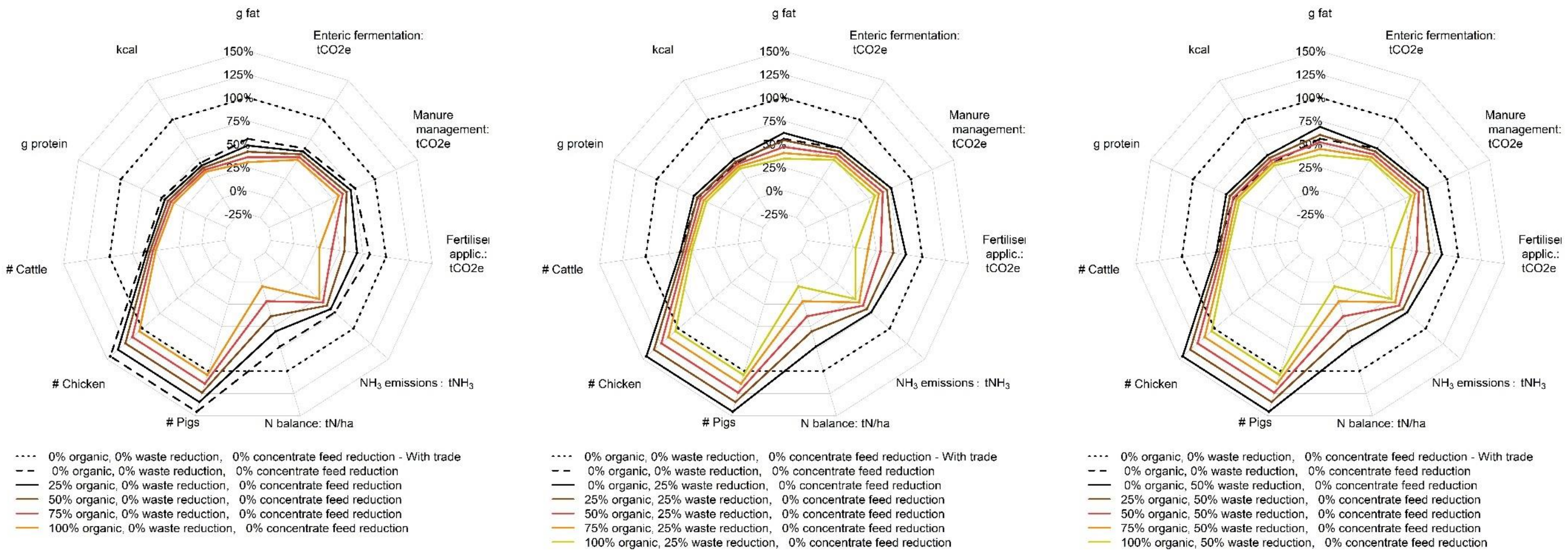

Figure 4: The effect of food waste reduction at different shares of organic agriculture. Reference scenario (dotted black line at 100%) is the BAU situation 2050, with trade. The other scenarios are without trade; indicator values given relative to the BAU with trade scenario. Scenarios with 0% (left), 25% (middle) and 50% (right) food waste reduction, further differentiated by increasing share of organic agriculture by from zero 0% to 100%, in steps of 25% (black, brown, to yellow lines). The dashed line is the same as the reference scenario, just without trade. Without trade means that except for mineral fertilizer, pesticides and fuel, no other production relevant products, no feed and no food could be imported or exported – trade was artificially switched off. In the scenarios without trade, ruminants were grass-fed only (cf. above). This freed up domestically produced concentrate feedstuff for monogastric husbandry.

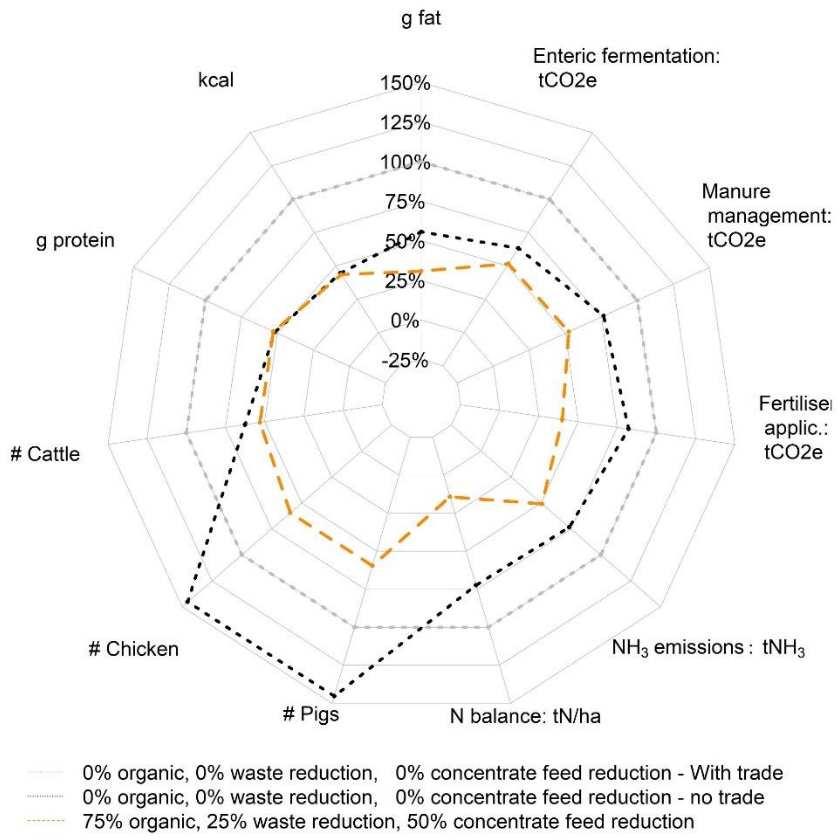

Figure 5: Impacts of 75% organic agriculture, 25% waste reduction and 50% concentrate feed reduction. Reference scenario (dotted black line at 100%) is the BAU situation 2050, with trade. The other scenarios are without trade; indicator values given relative to the BAU with trade scenario. The dashed line is the same as the reference scenario, just without trade. Without trade means that except for mineral fertilizer, pesticides and fuel, no other production relevant products, no feed and no food could be imported or exported – trade was artificially switched off. In the scenarios without trade, ruminants were grass-fed only (cf. above). This freed up domestically produced concentrate feedstuff for monogastric husbandry.

4. Discussion and conclusions

Luxembourg is a relatively small country with a high population density and limited resources for agricultural production and therefore relies heavily on imports. Nevertheless, there are endeavours to develop a resilient, diversified and sustainable agricultural system that can ensure a high share of food sovereignty for the Luxembourgish population while addressing the goals of the Paris Agreement and preserve environmental resources (United Nations, 2015). The transition to a sustainable food system requires systemic changes, as the here-described modelling efforts have shown. Reducing food waste, increasing organic agriculture and reducing feeding food-competing feedstuff, with corresponding reduction in animal numbers, can be important levers to significantly decrease various environmental emissions while simultaneously maintain food sovereignty.

The drop in food supply with increased organic agriculture shares was mitigated by reduced food-competing feed use, which freed up feed production areas for direct food production, thus compensating for lower organic yields. Reducing food-competing feed use had strong impacts particularly on the number of animals that can be raised. While monogastric animals were, in the Feed no Food scenarios raised on by-products not suitable for human consumption, the ruminants valorised the permanent grassland areas of Luxembourg. The results showed that grassland-based feeding of both meat and dairy producing cattle should be promoted and better valorised. This would also have ramifications on cattle breeding efforts, with the focus, especially in dairy production, having to shift to less intensive cattle, i.e. cattle bred with lower yield potential that are better adapted for rearing systems without concentrate feed inputs. This is a real problem, as (organic) farms currently have problems finding breeding bulls for comparatively 'lower' milk yields (personal communications to the authors during the SMART assessments).

The scenarios without trade showed the potential of Luxembourg to feed its growing population. This was based on the caloric self-sufficiency calculations. It was assumed that the average adult requires 2,350 kilocalories per day. The results highlighted the strong dependence of Luxembourg on imports and showed that this dependence will continue until 2050, especially with the estimated population increase to 1 million inhabitants by 2050. Nevertheless, the different scenarios also showcased, that a reduction of food-competing feed and a reduction of food waste can significantly increase the caloric self-sufficiency while also improving on many of the environmental parameters. These allowed the caloric self-sufficiency to increase from about a third in the reference scenario to 40% at 100% Feed no Food and 50% food waste reduction. When these measures were coupled with an increase in organic agriculture, it allowed to keep self-sufficiency constant in comparison to the reference scenario while simultaneously further improving environmental parameters. These results mirror results from Müller et al. 2017 and Frehner et al 2021, which also showcased that organic agriculture in conjunction with 'feed no food' and reduction in food waste are potential pathways towards a more sustainable food system, while simultaneously maintaining or increasing food supply.

However, it must be emphasized that the self-sufficiency results of the study at hand did not account for overall diet quality (i.e. covering all required nutrients), as it was based only on food energy supply. The results presented above did also not consider the self-sufficiency at food commodity level. This means that crop rotations and production areas overall were not optimised to increase self-sufficiency across food commodities, e.g. for vegetables, fruits, dairy and meat. Luxembourg is known for its high dairy and beef production (e.g., 137% self-sufficiency for total fresh dairy products in 2022 (Service d'Economie Rurale, personal communication, 2024), while fruit and vegetable self-sufficiency is generally well below 100% (in 2021: 49% potatoes; in 2018: 16% lettuce, 11% carrots, 0.6% strawberries, 0.1% tomatoes (Service d'Economie Rurale, personal communication, 2024)). Such optimisation was beyond the scope of this study but should be investigated in further studies.

The results also showed how important it is to involve consumers in the transition to a sustainable agri-food system. When strategies such as 'feed no food' are to be implemented, the consumers will need to drastically reduce their demand for animal products. The ORISCAV-LUX study (Alkerwi et al., 2015) showed that the daily intake of the Luxembourgish participants was 28.6 g of protein from meat, 8.7 g from fish, 1.7 g from eggs and 14.9 g from milk, thus a total of 53.9 g of protein per day (overall protein needs of an adult hovers around 60 g of protein per day (0.8g/kg bodyweight/day) (European Commission, 2021)). With a protein content of approx. 20 g per 100 g of meat, one can assume that 142.5 g of meat per day were consumed by the ORISCAV-LUX participants resulting in an annual consumption of 52.2 kg. The authors of the study themselves temporise that the stated quantities tend to have a clear bias towards underestimation (portion size) and that health-conscious people are more likely to take part in the study. In the follow-up study, the daily protein intake from animal sources even totalled 60.6 g of protein per day, which would imply an even higher meat consumption per day (Vahid et al., 2021). The 52.2 kg figure also does not include food waste, as it is based on real food intake. The EAT-Lancet planetary health diet recommends around 43 g of meat per day, which equates to 15.7 kg of meat per year for a healthy diet, as too high meat consumption, especially including processed meats, has been associated with a number of chronic diseases including type 2 diabetes and cardiovascular diseases (Li et al., 2024; Shi et al., 2023). Thus, from a health point of view, a more sustainable food production with 'feed no food' strategies and accompanying reduction in animal products, could have a lasting effect toward a healthier Luxembourgish population.

It is also important to look at the results of the proposed option spaces and to what extent they could help reach national environmental goals. Luxembourg's National Inventory Report (Administration de l'Environnement, 2024) showed that the agricultural sector contributed 8.12 % to Luxembourg's GHG emissions in 2022. Here, emissions from managed soils, manure management and enteric fermentation account for the largest share of emissions. GHG emissions from agriculture were relatively stable between 1990 and 2022 (Administration de l'Environnement, 2024). However, modelling with SOLm showed that a significant reduction in GHG emissions is possible. A combination of 50% organic agriculture, 50% waste reduction and 50% reduction in concentrate feed use would allow for halving current GHG emissions of 632 kt CO_2eq to 346 kt CO_2eq and would support the efforts of the agricultural sector to achieve the climate targets by 2050.

With the highest share of organic agriculture, the emissions of NH3 and CO_2eq reduced the most. However, at 100% organic agriculture and over 50% reduction of concentrate feedstuff, the N balance (t N/ha) tended towards zero and even became negative, meaning that the N-supply for crops was not ensured. This was not the case for scenarios with 75% organic agriculture, where the balance remained slightly positive. Similar results have also been found by Barbieri et al 2021. They concluded that, while "the global option space towards organic agriculture is delimited by nitrogen availability", "public policies could support a transition towards organic agriculture in 40–60% of the global agricultural area even under current nitrogen limitations thus helping to achieve important environmental and health benefits" (Barbieri et al., 2021). As such, organic agriculture can be a powerful lever to achieve the government's climate targets, while simultaneously also reduce nitrogen emissions and improve other environmental parameters, most notably pesticide related impacts on biodiversity and on soil and water quality (Sanders and Heß, 2019). Many of these other environmental issues cannot yet be (fully) captured by modelling efforts. Particularly regarding biodiversity, which is a focus of national and European environmental objectives, there is still a lack of suitable indicators and monitoring to be able to model the effects of agricultural practices on species diversity or generally ecosystem health and services (Burland and Von Cossel, 2023; Duru et al., 2015).

Overall, the modelling results showed that Luxembourg can considerably reduce the environmental impacts from the food system, in particular GHG emissions and nutrient surplus, while producing more and more diversified food than today. However, this is only possible with thorough transformations of the food and agricultural system, primarily by reducing food-competing feed, reducing waste and by increasing the share of organic agriculture. By implementing the three proposed strategies together, the central trade-off from organic agriculture (lower yields), can be compensated by the shift away from food-competing feed and thus in direction of increasingly plant-based diets. Diet quality needs to be kept in mind, and future studies should look at adapting crop rotation to nutritional needs (higher share of protein and oil crops) and pedo-climatic conditions. A big challenge on the environmental side is plant nutrient deficit, which may arise with high shares of organic production, if not complemented with additional measures to increase nutrient recycling and support additional biological nitrogen fixation. When looking at future organic cropping systems, nitrogen supply needs to be considered when choosing the different cropping elements.

Overall, a clear prioritization of environmental and food system related objectives at national level would be needed to be able to calculate how best to achieve them in Luxembourg. Is it more important to reduce GHG emissions compared to increasing food production and food sovereignty? If one were to rate the reduction in GHG emissions, the reduction of ammonia emissions and the increase in food sovereignty as being equally important, then a compromise solution within the option space could be achieved with 75% organic agriculture, 25% reduction in food waste and 50% reduction in the use of concentrate feed. This would result in a 50% reduction in GHG emissions, a 50% reduction in ammonia emissions and attain 32% caloric self-sufficiency.

Finally, while the physically based mass-flow model provides option spaces on how the food system can be changed regarding the agricultural production system, it does not make any statements about the underlying markets and the costs associated with sustainable food production. However, the economic context will be one of the key issues that will hinder the transformation towards a sustainable agricultural and food system (Allen et al., 1991) and the economic sustainability for farmers needs to be kept in mind when deciding on strategies to be implemented for the improvement of the food system. Furthermore, diversification and changes in the agricultural systems will most likely entail necessary changes in the food processing and packaging offers in Luxembourg and the Greater Region, before the benefits of growing new crop for human consumption becomes a real viable option for farmers, and efforts in this direction also need to be supported.

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