SustEATable – Integrated analysis of dietary patterns and agricultural practices for sustainable food systems in Luxembourg.

Final Report

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Zusammenfassung

Landwirtschaft und Ernährung stehen in einem engen Zusammenhang und beide sind nicht nur Verursachende, sondern auch Betroffene der Umweltprobleme, der Klimakrise und des Biodiversitätsverlustes. Die luxemburgische RISK 2050-Studie stellt fest, dass es einen besorgniserregenden Trend zum Verlust der biologischen Vielfalt und eine Verschlechterung der Bodengesundheit gibt, der sich vermutlich auf die Ernteerträge auswirken wird. Der beispielsweise mit dem Klimawandel zu erwartender Temperaturanstieg, ebenso wie Kälteperioden und Starkregenereignisse, wird sich u.a. auf die Arten und Sorten der angebauten Pflanzen auswirken. Hitzewellen und daraus resultierende Dürreperioden werden bei den aktuell angebauten Kulturen zu Ertragsausfällen führen. Starkniederschläge und Trockenheit verändern die Bodenverhältnisse und verstärken Erosion und den Nährstoffaustrag, um nur einige der zu erwartenden Auswirkungen zu nennen. Diese Veränderungen in der Lebensmittelproduktion haben nicht zuletzt Auswirkungen auf die Verfügbarkeit von Lebensmitteln.

Es sind Änderungen der landwirtschaftlichen Praktiken erforderlich, um die natürlichen Ressourcen zu schützen, ihre Auswirkungen auf das Klima zu verringern und die Ernährungssicherheit für künftige Generationen zu gewährleisten. Nachhaltige Landwirtschaft wird dabei oft nur mit Umweltvariablen in Verbindung gebracht, aber auch wirtschaftliche und soziale Faktoren, sowie die Unternehmensführung, bzw. Governance der Betriebe spielen bei der Bewertung des Nachhaltigkeitsaspekts eine Rolle. Besonders der soziale Hintergrund findet bei der Nachhaltigkeitsanalyse oft wenig Beachtung. Die Nachhaltigkeit des Agrarsektors wird jedoch auch von Faktoren außerhalb der Grenzen des landwirtschaftlichen Betriebs beeinflusst. KonsumentInnen beeinflussen die Nachhaltigkeit der Landwirtschaft durch ihre Entscheidungen beim Lebensmittelkonsum, indem sie eine Nachfrage nach bestimmten Lebensmittelgruppen oder Produktionsverfahren schaffen. Für die Untersuchung dieses Zusammenhangs zwischen den Ernährungsgewohnheiten und ihren Auswirkungen auf die Umwelt ist es wichtig, über die Ebene der landwirtschaftlichen Betriebe hinauszublicken und die Nachhaltigkeit des gesamten Lebensmittelsystems zu bewerten.

Die Kombination von Nachhaltigkeitsbewertungen auf der Ebene der landwirtschaftlichen Betriebe mit der Bewertung der Nachhaltigkeit von Lebensmittelsystemen ermöglicht die Entwicklung differenzierterer Strategien und damit die Formulierung relevanterer und spezifischerer Empfehlungen für Veränderungen in der Ernährung und Produktion, die für die Verwirklichung nachhaltiger Lebensmittelsysteme erforderlich sind.

Im Rahmen dieser Studie wurde eine Nachhaltigkeitsbewertung der landwirtschaftlichen Praktiken auf Betriebsebene durchgeführt. Unter Verwendung des SMART (Sustainability Monitoring and Assessment RouTine)-Farm Tools wurde der Agrarsektor auf seine ganzheitliche Nachhaltigkeit hin bewertet. Die erhobenen Daten der Nachhaltigkeitsbewertung auf Betriebsebene wurden anschließend in einer Nachhaltigkeitsbewertung auf Lebensmittelsystemebene unter Verwendung des Sustainability and Organic Livestock Model (SOLm) für die Entwicklung nachhaltiger Lebensmittelsysteme verwendet.

Die Analyse von 87 landwirtschaftlichen Betrieben in Luxemburg stellte einen Anteil von 4,5 % der Betriebe aus Luxemburg dar. Von diesen waren 33,3 % der mit dem SMART-Farm Tool bewerteten Betriebe Biobetriebe, diese waren somit in der Stichprobe überrepräsentiert. 82,8 % der erhobenen Betriebe waren Mutterkuh- oder Milchviehbetriebe. In der Dimension *Gute Unternehmensführung* zeigten die Betriebe in 2 der 5 Themen eine gute Bewertung der Nachhaltigkeitsleistung (Zielerreichung > 60 %). Im Bereich *Ökologische Integrität* konnten die Betriebe im Mittel in 4 von 6 Themen eine gute Bewertung erzielen, für *Ökonomische Resilienz* in 2 von 4 Themen und in der Dimension *Soziales Wohlergehen* war dies für alle Themen der Fall. Eine getrennte Betrachtung der konventionellen landwirtschaftlichen Betriebe und der Biobetriebe zeigte generell eine höhere Nachhaltigkeitsleistung der Biobetriebe, wobei die größten Effekte in den ökologischen und ökonomischen Dimensionen sichtbar waren. Eine genauere Betrachtung der Betriebe mit Wiederkäuerhaltung zeigte, dass Mutterkuhbetriebe eine höhere Nachhaltigkeitsleistung erzielten als Milchviehbetriebe oder Mischbetriebe mit Mutterkuh- und Milchviehhaltung.

Im Hinblick auf nachhaltige landwirtschaftliche Praktiken setzten von den 87 untersuchten Betrieben lediglich 9 Betriebe Insektizide auf ihren Betrieben ein, dies auf 0-10 % ihrer Flächen. Fungizide wurden auf 36 Betrieben eingesetzt, wovon 7 Betriebe angaben, diese auf 0-10 % ihrer Flächen anzuwenden. Herbizide wurden am verbreitetsten genutzt und lediglich 36 Betriebe, darunter 27 Biobetriebe, nutzen sie nicht. Die meisten Betriebe haben Maßnahmen eingeleitet, um Bodendegradation entgegenzuwirken, wenn sie bereits auf dem Betrieb beobachtet wurde. Direktsaat wurde bisher kaum genutzt. Agroforstsysteme wurden bisher auf 3 Betrieben umgesetzt. Nur ein geringer Teil der Betriebe nutzte das Dauergrünland extensiv. Leguminosen wurden auf etwa 30 % der Ackerflächen angebaut, wobei Biobetriebe die höchsten Leguminosenanteile in ihren Fruchtfolgen aufwiesen.

Das SOLm-Model ist ein Bottom-up-Massenflussmodell, das die landwirtschaftliche Produktion und den Lebensmittelsektor abbildet. Es eignet sich für die Erfassung aller agronomischen und mit Massen- und Nährstoffflüssen verbundenen Aspekte der Veränderungen in der Landwirtschaft und den Lebensmittelsystemen. Nationale Daten, sowie Daten aus den Erhebungen mit dem SMART-Farm Tool wurden verwendet, um das SOLm-Model an die luxemburgischen Gegebenheiten anzupassen, da einige globale Annahmen nicht für den luxemburgischen Kontext gelten. Das nationale Treibhausgasinventar wurde als Referenz für die Kalibrierung des Modells genutzt. Zunächst wurde das Basisszenario für 2020 berechnet und ein Referenzszenario für 2050 unter der Vorgabe „business as usual" erstellt. Einige Szenarien für 2050 hinsichtlich der Erhöhung der biologisch bewirtschafteten Flächen (0 % - 100 %), der Konkurrenz von Flächen für die Futtermittel- und Lebensmittelproduktion (Reduktion des Kraftfuttereinsatzes 0 % - 100 %) sowie der Reduktion der Lebensmittelabfälle (0 % -50 %) wurden berechnet.

Die SOLm-Modellierung hat gezeigt, dass eine erhebliche Steigerung der nachhaltigen Produktionsmethoden möglich wäre, wobei die durch den ökologischen Landbau bedingten Ertragseinbußen durch die Verringerung der Lebensmittelabfälle und die Maximierung des Anbaus von Lebensmitteln anstelle von Futtermitteln kompensiert werden könnten. Dies hätte auch enorme Auswirkungen auf die Umweltverträglichkeit der Landwirtschaft. Je nachdem, welches Ziel als prioritär angesehen wird – Reduktion der Treibhausgasemissionen, Ernährungssouveränität oder Reduktion der Stickstoffverluste – ergeben sich unterschiedliche optimale Szenarien: zur Erreichung der Klimaziele tragen vor allem die biologische Landwirtschaft und die Reduktion des Kraftfuttereinsatzes bei, für die Erhöhung der Ernährungssouveränität spielen vor allem die Reduktion des Kraftfuttereinsatzes und der Lebensmittelabfälle eine Rolle, wohingegen die Stickstoffverluste vor allem in Szenarien mit hohem Anteil an biologischer Landwirtschaft und moderater Reduktion des Kraftfuttereinsatzes und der Lebensmittelabfälle reduziert werden. In Bezug auf die Stickstoffverfügbarkeit jedoch zeigte sich, dass 100 % Biolandwirtschaft zu einem nationalen Defizit führen würde. Um allen Herausforderungen gerecht zu werden - Verringerung der Treibhausgasemissionen, Maximierung der Selbstversorgung, Erhaltung der Umweltressourcen und ausreichende Stickstoffversorgung - sollten 75 % ökologischer Landbau, mindestens 25 % weniger Lebensmittelabfälle und mindestens 50 % weniger Kraftfuttereinsatz angestrebt werden. Dies entspricht Treibhausgasemissionen von 309 kt CO_{2eq}, einem Selbstversorgungsgrad (hinsichtlich Ernährungssouveränität) von 32 % und Ammoniakemissionen von 2.366 kt NH_3.

Langfristig ist ein Systemwechsel, wie er am Ende dieser Studie beschrieben wird, unter Einbeziehung von VerbraucherInnen, LandwirtInnen und LebensmittelherstellerInnen notwendig, um das Ziel von 75 % ökologischer Landwirtschaft, 50 % Kraftfutterreduktion und 25 % Lebensmittelabfallreduktion zu erreichen. Das „Gießkannenprinzip" mit verschiedenen Einzelmaßnahmen wird angesichts der immensen politischen Herausforderungen, die mit der Reduzierung der THG-Emissionen gemäß dem Pariser Abkommen, der Verringerung der Stickstoffverluste und der Erhöhung der Ernährungssouveränität in Luxemburg verbunden sind, nicht ausreichen.

Summary

Agriculture and food are closely linked, and both are not only contributing to environmental problems, climate change and biodiversity loss, but are also affected by them. The Luxembourg RISK 2050 study states that there is a worrying trend towards biodiversity loss and a deterioration in soil health, which is likely to have an impact on crop yields. The rise in temperature expected as a result of climate change, for example, as well as cold spells and heavy rainfall events will have an impact on the types and varieties of crops that can be grown, among other things. Heat waves and the resulting periods of drought will lead to yield losses for the crops currently grown. Heavy rainfall and drought will change soil conditions and increase erosion and nutrient discharge, to name just a few of the expected effects. These changes in food production will also have an impact on the availability of food.

Changes in agricultural practices are needed to protect natural resources, reduce their impact on the climate and ensure food security for future generations. Sustainable agriculture is often only associated with environmental variables, but economic and social factors, as well as governance also play a role in assessing the sustainability aspect. The social background, in particular, often receives little attention in sustainability analysis. However, the sustainability of the agricultural sector is also influenced by factors outside the boundaries of the farm. Consumers influence the sustainability of agriculture through their food choices by creating a demand for certain food groups or production systems. To examine this link between dietary habits and their impact on the environment, it is important to look beyond the farm level and assess the sustainability of the entire food system.

Combining farm-level sustainability assessments with food system sustainability assessments allows for the development of more nuanced strategies and thus the formulation of more relevant and specific recommendations for changes in diet and production systems needed to achieve sustainable food systems.

As part of this study, a sustainability assessment of agricultural practices at farm level was carried out. Using the SMART (Sustainability Monitoring and Assessment RouTine)-Farm tool, the agricultural sector was assessed for its holistic sustainability. The data collected from the sustainability assessment at farm level was then used in a sustainability assessment at food system level using the Sustainability and Organic Livestock Model (SOLm) for the development of sustainable food systems.

The analysis of 87 farms represented 4.5 % of the farms in Luxembourg. 33.3 % of the farms assessed with the SMART-Farm Tool were organic farms, which were therefore overrepresented in the sample. 82.8 % of the farms surveyed were suckler cow or dairy farms. In the dimension of *Good Governance*, the farms showed a good assessment of sustainability performance in 2 of the 5 topics (target achievement > 60%). In the area of *Ecological Integrity*, the farms were able to achieve a good rating on average in 4 out of 6 topics, for *Economic Resilience* in 2 out of 4 topics and in the dimension of *Social Well-being* this was the case for all topics. A separate analysis of conventional farms and organic farms generally showed a higher sustainability performance of organic farms, with the greatest effects visible in the ecological and economic dimensions. A closer look at the farms with ruminant husbandry showed that suckler cow farms achieved a higher sustainability performance than dairy cattle farms or farms with suckler cow and dairy cattle husbandry.

Regarding sustainable agricultural practices, 9 of the 87 farms surveyed used insecticides on their farms, this on 0-10 % of their land. Fungicides were used on 36 farms, of which 7 farms stated that they used them on 0-10% of their land. Herbicides were the most widely used and only 36 farms, including 27 organic farms, did not use them. Most farms have introduced measures to counteract soil degradation if it has already been observed on the farm. Direct seeding was hardly used. Agroforestry systems were implemented on 3 farms. Only a small proportion of farms used permanent grassland extensively. Legumes were grown on around 30 % of arable land, with organic farms having the highest proportion of legumes in their cropping systems.

SOLm is a bottom-up mass flow model that depicts agricultural production and the food sector. It is suitable for capturing all agronomic, and mass and nutrient flow related aspects of changes in agriculture and food systems. The data from the SMART-Farm Tool surveys were used to adapt SOLm to the Luxembourgish context, as some global assumptions did not apply to the Luxembourgish context. The national greenhouse gas inventory was used as a reference for calibrating the model. Once these adjustments were made for Luxembourg, the base scenario for 2020 was finalized and several scenarios for 2050 were calculated. Some future scenarios for 2050 were calculated with regard to the increase in organic agriculture (0 % - 100 %), the reduction in the use of concentrate feed (0 % - 100 %) and the reduction of food waste (0 % - 50 %).

SOLm modelling showed that a significant increase in sustainable production methods would be possible, whereby the yield losses caused by organic farming could be compensated for by reducing food waste and maximizing the cultivation of food instead of feed. This would also have a huge impact on the environmental sustainability of agriculture. Depending on which goal is prioritized - reduction of greenhouse gas emissions, food sovereignty or reduction of nitrogen losses - different optimal scenarios arise: organic farming and a reduction in the use of concentrated feed are the main contributors to achieving the climate targets, while a reduction in the use of concentrated feed and food waste play a major role in increasing the degree of food sovereignty, whereas nitrogen losses are reduced primarily in scenarios with a high proportion of organic farming and a moderate reduction in the use of concentrated feed and food waste. In terms of nitrogen availability, however, it was observed that 100 % organic farming would lead to a national deficit. In order to meet all challenges - reducing greenhouse gas emissions, maximizing food sovereignty, preserving environmental resources and sufficient nitrogen supply – 75 % organic farming, at least 25 % less food waste and at least 50 % less animal feed should be targeted. This corresponded to greenhouse gas emissions of 309 kt CO_{2eq}, a degree of self-sufficiency of 32 % and ammonia emissions of 2,366 kt NH_3.

In the long term, there will need to be a system change, described at the end of this study, that involves consumers, farmers and food producers to achieve the goal of 75 % organic agriculture, 50 % concentrated feed reduction and 25 % food waste reduction. The scattergun approach with various individual measures will not be sufficient in view of the immense political challenges associated with reducing GHG emissions in accordance with the Paris Agreement, reducing nitrogen losses and increasing the level of food sovereignty in Luxembourg.

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List of Abbreviations

SMART	Sustainability Monitoring and Assessment RouTine
SOLm	Sustainability and Organic Livestock Model
EU	European Union
GHG	Greenhouse Gases
UN	United Nations
FAO	Food and Agriculture Organization
FnF	Feed no Food
TIR	Technology, Information and Resources
SAFA	Sustainability Assessment of Food and Agriculture Systems
RRID	Research Resource Identifiers
SCR	Solvency Capital Requirement
h	hour
kg	kilogram
ha	hectare
SER	Rural Economic Service
IBLA	Institute for Organic Agriculture and Agroecology Luxembourg
e.g.	exempli gratia (for example)
Etc.	Et cetera
HSD	Honest Significant Difference
ANOVA	Analysis of Variance
ca.	circa (approximately)
OTE	Technical and Economic Orientation
sd	Standard Deviation
min	minimum
max	maximum
ID	Identification number of indicator
N	Nitrogen
P	Phosphor
km	kilometer
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
OECD	Organisation for Economic Co-operation and Development
CH_4	methane
N_2O	nitrous oxide
NOx	nitric oxide
NH_3	ammonia
BAU	Business As Usual
kcal	kilocalorie
CO_{2eq}	carbon dioxide equivalent
CELL	Centre for Ecological Learning Luxembourg
IPCC	Intergovernmental Panel on Climate Change
bpb	Bundeszentrale für politische Bildung
Wred	Waste Reduction
Org	Organic Agriculture

1 Introduction

Luxembourg is currently facing many environmental problems: the Luxembourgish drinking water resources are threatened by pollution from chemical pesticide residues and their degradation products and nutrient inputs from agricultural activities (Administration de la gestion de l'eau, 2015; Bohn et al., 2011; Zwank, 2015). Agricultural practices are a major contributor to the current loss of biodiversity, particularly the loss of beneficial insects in agriculture. Agriculture is with 69 % the main consumer of freshwater worldwide (United Nations, 2018). In this context, the major challenge is that farming and intact soils, groundwater systems and biodiversity are mutually dependent, but the latter is increasingly in decline (Zlatanova et al., 2024). In addition, soil erosion and degradation are a growing problem, and climate change, with its increasingly extreme and unpredictable weather events, is causing major crop losses and threatening food security (Godfray et al., 2010). The changing climatic conditions pose new challenges for agriculture. Climate change leads to increased drought and rainfall events, which result in increased erosion and lower nutrient levels in the soil. In 2022, 8.12 % of the total GHG emissions in Luxembourg came from the agricultural sector (Administration de l'Environnement, 2024). Food production must be adapted to the new conditions. Impacts on the food trade include higher costs due to product demand, the resulting increase in energy consumption for storage and transportation and possible regional food shortages (Zlatanova et al., 2024). These threats to ecosystems and the loss of natural resources are of course not unique to Luxembourg, but reflect the challenges faced by the food and agriculture sector worldwide (Molotoks et al., 2021; Muluneh, 2021; Schader et al., 2015). 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. According to calculations, Luxembourg's population will grow by more than 50% by 2050, which is the highest relative increase in the EU (EUROSTAT, 2023).

The food and agriculture sector is as much a victim as also a driver of these problems, and changes in farming practices are needed in order to protect our natural resources, reduce its impact on climate, and ensure food security for future generations. This has been recognized by the United Nations in their 2030 Agenda for Sustainable Development (United Nations, 2015) and by the Food and Agriculture Organization of the United Nations (FAO) in their Vision for Sustainable Food and Agriculture (FAO, 2014a).

Sustainable agriculture is often only associated with environmental variables, but economic and social factors also play a role in assessing the sustainability of the sector, the social dimension often receiving only little attention in sustainability analyses (Janker et al., 2019; Opielka et al., 2021). Sustainability can therefore be described using a three-pillar model. These three pillars are also considered in the European Commission's Farm to Fork Strategy (European Commission, 2020). As part of the European Green Deal, this is intended to help accelerate the transition to a sustainable food system. Alongside food safety, public health should also be guaranteed. Agriculture must adapt to the effects of climate change and other environmental stressors in order to sustainably thrive environmentally, economically and socially. In the FAO's SAFA Guidelines – Sustainability Assessment of Food and Agriculture Systems sustainability is even described as a four-pillar model with Good Governance added to the environmental, economic and social dimensions (FAO, 2014b). The Luxembourg government has recognized the challenges facing the food and agriculture sector and aims to find solutions for the above-mentioned environmental problems at the national level. In their governmental program, they indicate organic agriculture as a promising avenue for addressing the above-mentioned challenges (Gouvernement du Grand-Duché de Luxembourg, 2023, 2018). In the "3rd Industrial Revolution Study for the Grand-Duchy of Luxembourg", which was published by the team around Jeremy Rifkin in November 2016, the need for a more sustainable food system was also 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.

According to the FAO, sustainable agricultural development is defined as “the management and conservation of the natural resource base, and the orientation of technological change in such a manner as to ensure the attainment of continued satisfaction of human needs for present and future generations. Sustainable agriculture conserves land, water, and plant and animal genetic resources, and is environmentally non-degrading, technically appropriate, economically viable and socially acceptable” (FAO, 1988). Assessing to what extend specific farms and farming systems, such as organic farming, achieve the FAO’s vision of sustainable agricultural development requires a comprehensive conceptual framework. The FAO has therefore published Guidelines for the Sustainability Assessment of Food and Agriculture Systems (SAFA Guidelines) to provide a universal framework for such an assessment to promote a functional and uniform assessment approach (FAO, 2014b).

The sustainability of the agricultural sector, however, is also influenced by factors outside the farm boundary. Consumers, for example, influence agricultural sustainability through their food consumption choices, by creating demand for certain food groups or certain production practices. To study the link between dietary patterns and their environmental impact, it is important to look outside the farm-level and assess the sustainability of the whole food system. The impact of dietary choices on the sustainability of the food system has been the focus of a number of papers over the past couple of years and it was shown that changes in dietary patterns can greatly 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, dietary changes need to be considered when developing strategies for sustainable food systems. For example, a positive contribution to sustainability in agriculture can be made by a transition in nutrition towards increased legume consumption. The cultivation of more leguminous crops has a positive effect on the nitrogen content in the soil, meaning that the use of mineral fertilizers could be significantly reduced (Beckmann et al., 2021; Guinet et al., 2019; Kumawat et al., 2022). Thus, different management practices need to be clearly considered when modelling different scenarios for the future, such as in the study by Schader et al. (2015).

Huber (2000) grouped strategies to bring about sustainable development in the following three main categories: efficiency strategies (e.g. increase in productivity while reducing environmental impacts), sufficiency strategies (e.g. decrease in demand for animal products) and consistency strategies (e.g. decline of the use of food-competing feed components in livestock rations, which also affects availability of livestock products). Modelling efforts of previous works have mainly focused on the impact of the efficiency (e.g. van Zanten et al., 2016; Wirsenius et al., 2010) and sufficiency strategies (e.g. Hedenus et al., 2014; Scarborough et al., 2014; Stehfest et al., 2009), while the consistency strategy has not been explored to such an extent (e.g. Schader et al., 2015). Nevertheless, efficiency, sufficiency and consistency strategies need to be considered together and as complements of each other, when exploring strategies to improve the sustainability of the agricultural sector, in order to align consumption and production for sustainable food systems.

Studies have also often focussed on only improving one aspect of environmental sustainability, e.g. climate impact (Hedenus et al., 2014; Springmann et al., 2016; Stehfest et al., 2009). By focusing mainly on the effects of changing diets on greenhouse gas production and climate change, these studies ignored other environmental problems linked to agriculture.

Combining farm-level sustainability assessments with food system-level sustainability assessment, allows the development of more differentiated strategies and in turn the formulation of more relevant and specific recommendations on dietary and production-related changes necessary for achieving more sustainable food systems. The aim of this study was to do farm-level sustainability assessments of agricultural practices on a sample being representative for Luxembourg. Due to its size, Luxembourg offered the unique opportunity to do a nation-wide farm-level sustainability assessment and was the first country where the whole agricultural sector was assessed for its holistic sustainability using the SMART (Sustainability

Monitoring and Assessment RouTine)-Farm Tool. Data and information from this data collection were then used in a food system-level sustainability assessment using the Sustainability and Organic Livestock Model (SOLm) to adapt the model to Luxembourg and calculate several scenarios on organic farming, food waste and concentrated feed reduction.

1.1 Objectives and research questions

The project addressed the following objectives:

- to assess and analyse holistically the current sustainability level of the Luxembourgish agricultural sector using the SMART-Farm Tool (*farm-level sustainability assessment*)
- to analyse scenarios for 2050 of different agricultural practices in Luxembourg, with respect to their impacts on key sustainability themes (*food system-level sustainability assessment*)
- to synthesise the results of the farm-level and food system-level sustainability assessment for interpretation and consideration of relevant future options
- to derive recommendations for the realisation of sustainable food systems through sustainable farming practices and dietary patterns

to investigate different possibilities to increase the sustainability of the Luxembourgish food system.

This project contributed to answering the following research questions:

1. What are the current farming practices in Luxembourg and which economic, social and environmental impacts result from these at farm level?
2. How does farm management (organic/conventional) and ruminant husbandry (dairy/meat production/both) impact economic, social and environmental sustainability?
3. How do dietary patterns and agricultural production impact environmental sustainability?
4. What changes in dietary patterns and agricultural production systems are needed to achieve a sustainable food system in Luxembourg?
5. What are practical dietary and agricultural production recommendations and policy implications for Luxembourg to optimise environmental sustainability of the food system?

2 Farm-Level Sustainability Assessment:

2.1 Material & Methods

2.1.1 Farm-level Sustainability Assessment

The Sustainability Monitoring and Assessment RouTine (SMART)-Farm Tool, V5.0, (SMART-Farm Tool; RRID: SCR_018197) is a method for assessing the sustainability performance of farms and companies in the food and agriculture sector (Schader et al., 2016). SMART was designed to operationalise the SAFA sustainability guidelines (Sustainability Assessment of Food and Agriculture systems) of the Food and Agriculture Organization of the United Nations (FAO) in a science-based efficient way through qualitative and quantitative indicators (Curran et al., 2020; Schader et al., 2016). These guidelines contain a globally valid and comprehensive definition of sustainability in a total of 21 themes and 58 sub-themes in the four dimensions of *Good Governance, Environmental Integrity, Economic Resilience and Social Well-being* (Figure 1).

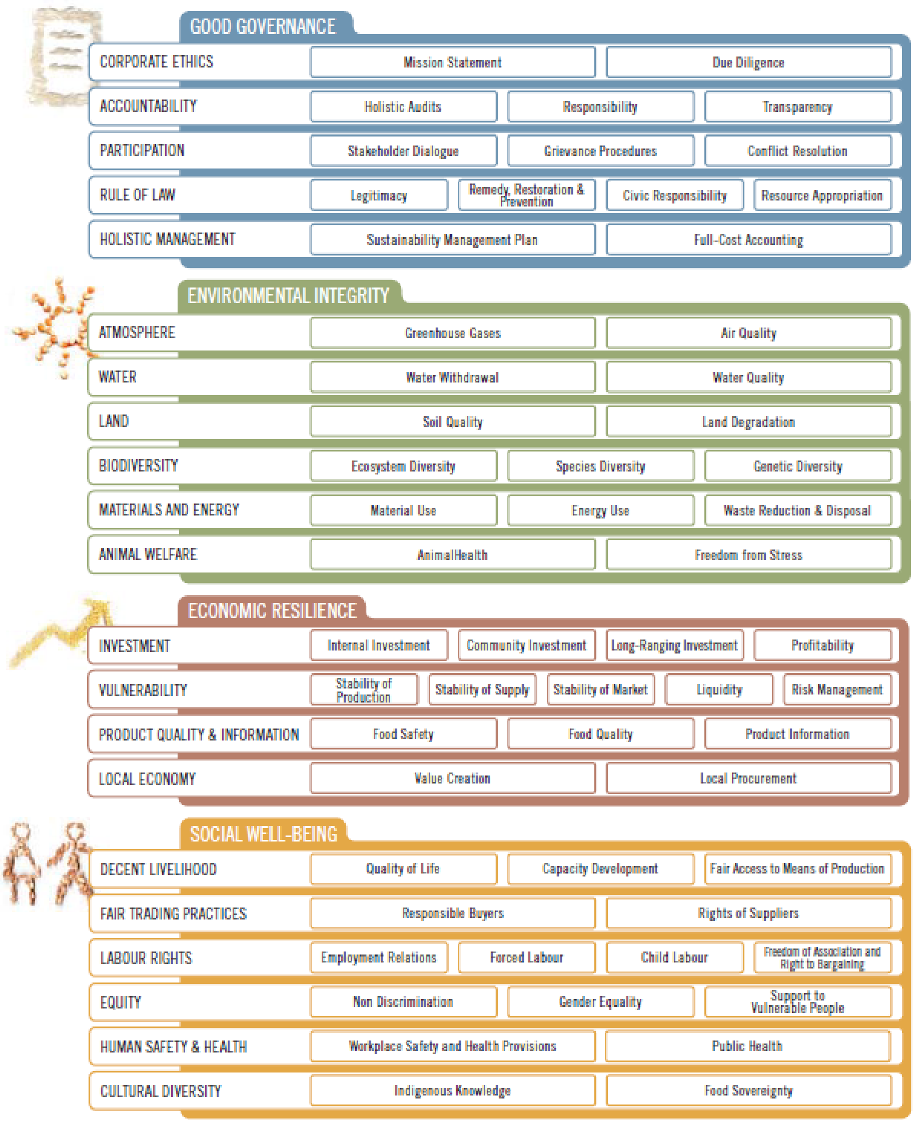

Figure 1: SAFA-Dimensions and themes (FAO, 2014b). The four dimensions of sustainability *Good Governance, Environmental Integrity, Economic Resilience* and *Social Well-Being* are shown, which are in turn divided into 21 themes and 58 sub-themes.

For each sub-theme, the FAO has formulated a specific sustainability goal to which companies and farms should orient themselves. The SAFA guidelines aim to give substance to the concept of sustainability and support actors in the food and agriculture sector to implement targeted improvements in terms of sustainability (FAO, 2014b). They provide a uniform framework and enable a comparable and transparent sustainability assessment of agricultural companies and farms of different types and sizes. The entire area of responsibility of a farm is taken into account, including, for example, the effects caused by the purchase of inputs. The results of a SMART sustainability analysis are not product-specific assessments, but an evaluation of the agricultural production system at farm level. Thus, the SMART-Farm Tool can be used to systematically record, analyse, and evaluate the specific sustainability performance of farms and was used in the study at hand in that capacity for the on-farm sustainability assessment.

The SMART-assessment is based on a farm visit in combination with an interview (approx. 3h) with the farm manager during which the necessary data is collected. While there are over 300 indicators embedded in the SMART-Farm Tool, the actual number of indicators evaluated on a specific farm can vary depending on the farm type and setting. This is because there are some general indicators that apply to all farm types, and more specific indicators that are context-dependent; i.e., indicators on animal husbandry will only be evaluated on farms with animal husbandry (Curran et al., 2020; Schader et al., 2016).

The indicator ratings are used to assess the degree of goal achievement in the 58 sustainability sub-themes. The model is semi-quantitative, meaning that quantitative and qualitative questions are asked, and their answers transferred to quantitative ratings ranging from 0 to 100 %. Indicators can impact multiple sub-themes, both positively and negatively. To reflect the importance of each indicator on a specific sub-theme, the indicators are given different weightings. The respective goal achievement corresponds to the weighted arithmetic mean of the indicator ratings of a sustainability sub-theme (Figure 2). The goal achievement, which is given in percentages, is then assessed using a five-level scale from unacceptable (0% - 20% of the sustainability objective are achieved) via limited (21% - 40%), moderate (41% - 60%), good (61% - 80%) to best (81% - 100% of the sustainability objective are achieved) (Figure 3). A more detailed description of the SMART-Farm Tool can be found in Curran et al. (2020) and Schader et al. (2016).

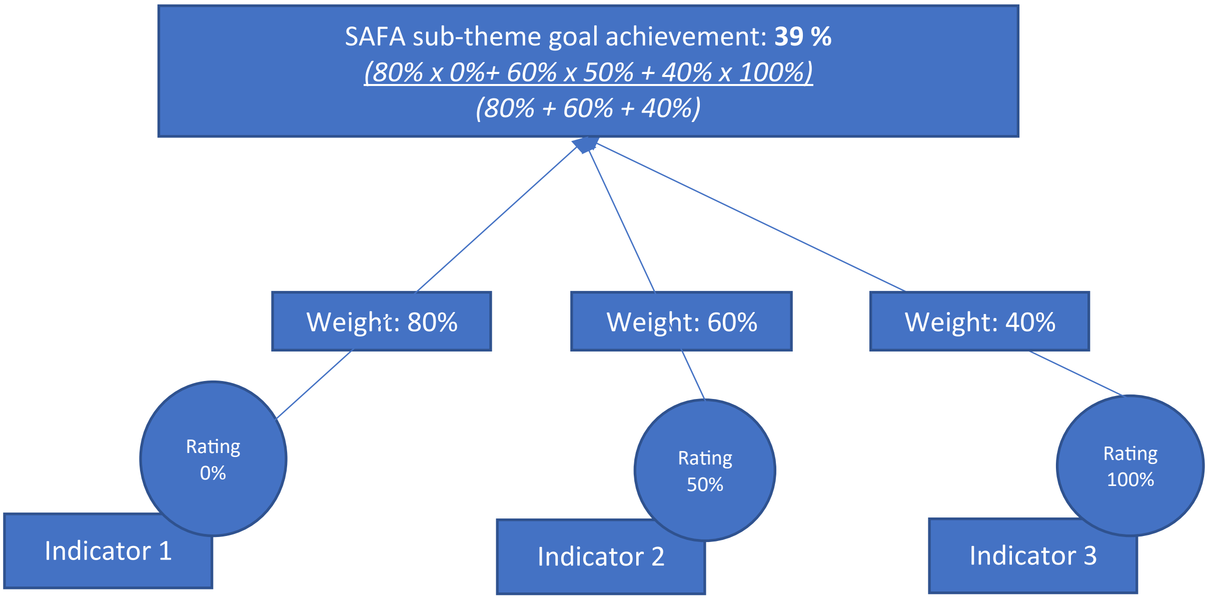

Figure 2: Example of the calculation underlying the goal achievement assessment for each SAFA (Sustainability Assessment of the Food and Agriculture systems) sub-theme.

Figure 3: Scheme for the assessment of the sustainability goal achievement.

Adaptations were made to the tool specifically for Luxembourg: Luxembourg was defined in the tool as its own region with related compliances being implemented regarding the Luxembourgish laws and regulations (e.g. regarding waste management and working conditions). Compliances were also introduced for members of Vereenegung Biolandwirtschaft Lëtzebuerg a.s.b.l.. Pre-defined compliances auto-rate some of the indicators in the SMART-Farm Tool questionnaire helping to reduce the time of the on-farm interview.

2.1.2 Call for the Survey and data collection

At the end of September 2018, a call for participation was sent to 1,513 farmers out of the 1,943 registered farms in Luxembourg. Agricultural holdings that have very specialized production systems (e.g. wine production, mushroom production, tree nurseries, flowers and ornamental plant production, specialised horse keeping and beekeeping) were excluded. To protect privacy, the call was mailed through the Rural Economy Service (SER). The call for participation was also publicly communicated: it was printed in the Newsletter N.06 in November 2018 of the Institute for Organic Agriculture and Agroecology Luxembourg (IBLA). It was also run in a national agricultural newspaper in December 2018 and the different Luxembourgish farmers' organizations were contacted and asked to share the call with their members. Since a sufficient number of farmers answered the initial call for participation, no second call was mailed.

A total of 105 answers to the call were received, out of which 87 farms were progressively contacted and analysed for their sustainability performances. The other 18 responses were either excluded because of their very specialised production system or because farmers no longer wished to participate due to time constraints. Participation in the study was on a voluntary basis. The sampling run was from January 2019 until January 2020, with the main data collection having been done between January 2019 and June 2019. The reference year for the on-farm collected data was 2017. Individual degrees of goal achievements for each of the 58 sub-themes were then calculated using the SMART-Farm Tool software. These individual on-farm sustainability assessment results form the basis for the overarching data analysis detailed below.

2.1.3 Data Analysis

2.1.3.1 Data verification

Several data plausibility and data quality checks were performed on the individual farm data and overarching. A total of 4 auditors were involved in the data collection process and the data was also checked for consistency across auditors to avoid auditor bias in the results.

2.1.3.2 Basic Grouping of Study Sample

In 2017 (reference year of the study at hand), there were a total of 1,943 farms in Luxembourg. Luxembourg is primarily a grassland location, as over half of Luxembourg's agricultural land consists of permanent grassland (67,413 ha of 131,163 ha). It is therefore not surprising that most Luxembourg farms have ruminant husbandry as their main economic activity. In 2017, 1,242 farms raised cattle and there were 202,281 cattle in Luxembourg. Regarding monogastric animals, 101 farms raised 96,761,048 pigs and 357 farms raised 122,609 chickens in 2017 (Ministère de l'Agriculture, de la Viticulture et du Développement rural, 2023). The number of organic farms in Luxembourg has been slightly increasing over the years and with 100 farms in 2017 cultivating 4.33 % of Luxembourg's agricultural land according to the EU organic regulations (Ministère de l'Agriculture, de la Viticulture et du Développement rural, 2023).

The sampled farms were sorted in two basic groupings, according to management system and the focus of the ruminant husbandry farm branch. For management system, the farms were grouped into a) organic (certified organic farms, or farms in the process of becoming a certified organic farm in the reference year 2017) and b) conventional (conventionally managed farms).

Farms with ruminant husbandry, this being the most important farming sector in Luxembourg, were further grouped into a) meat (farms that raise ruminants for meat production) b) dairy (farms that raise ruminants for dairy production) and c) both (farms that raise ruminants for both meat and dairy production). While the focus here lies mainly on the ruminant husbandry branch of the farms, they may also have other farm branches (e.g., farms with ruminant husbandry in combination with monogastric husbandry are also considered).

2.1.3.3 Statistical Methods

Data analysis was performed using R Version 3.6.1 in RStudio Version 2022.07.0.

The following statistical analyses were performed:

- Comparison of the area data of the sample to the average of all Luxembourgish farms (where possible)
- Evaluation of the impact of the treatments 'management systems' and 'focus of ruminant husbandry' on the SAFA-goal achievements at theme and sub-theme level
- Evaluation of the impact of the above-mentioned treatments on the indicator ratings
- Correlation analysis of farms characteristics (e.g. size, livestock unit, livestock unit per ha) and the goal achievements at theme and sub-theme level

Normality of data distribution and equal variance were tested with the Shapiro-Wilk test and the Levene's test, respectively. Area data (agricultural land, arable land, and permanent grassland) of the study sample was compared to the average area data from all farms in Luxembourg using a one-sample t-test when normality was given, otherwise a one-sample Wilcoxon signed rank test was used.

For the assessment of the effect of 'management systems' and 'focus of ruminant husbandry' on goal achievement or indicator rating, the independent two sample t-test (for management system) or one-way ANOVA followed by the Tukey's honest significant difference test (Tukey-HSD Test) (for focus of ruminant husbandry) was applied for testing significant differences on a significance level of α = 5 % ($p \leq 0.05$) when normal distribution and equal variance were given,. In case of heteroscedasticity or non-normality, the Wilcoxon rank sum test or the non-parametric Kruskal-Wallis test (H-test) followed by the pairwise Wilcoxon rank sum test were used, respectively. As not all indicators are relevant for all farm types or farm structures, the sample size (n) for individual indicators can be lower than n = 87. For indicators, that were relevant for less than three farms per treatment level, no statistical analysis was performed, and results are not shown.

For the correlation analysis, the sample was used in full and split into management system and focus on ruminant husbandry. After checking for the prerequisites of the correlation analysis, Pearson and Spearman correlation coefficients were calculated, respectively.

2.2 Results

2.2.1 Sample description

A total of 87 farms was analysed. They represented 4.5 % of the 1,943 agricultural holdings in 2017. The 87 farms laboured 8,666 ha of agricultural land (accounting for 6.6 % of the 131,163 ha of agricultural land in Luxembourg), which in turn was made up of 49.9 % arable land and 49.8 % permanent grassland. These proportions are similar to the overall shares of arable land and permanent grassland of the agricultural land in Luxembourg (Ministère de l'Agriculture, de la Viticulture et du Développement rural, 2023). Table 1 provides a further overview of some farm characteristics for the whole agricultural sector in Luxembourg in 2017, and the study sample, while Table 2 gives insight into some socio-demographic farmer characteristics for the study sample. For the farmer characteristics, no comparison to the whole of Luxembourg was possible as no comparable data was available. Five farms that were transitioning to organic farming in 2017 and already laboured according to the EU regulations of organic farming were classified as being organic in the study sample. The share of organic farms in the study sample (33 %) was overrepresented compared to the whole of Luxembourg, where there was an overall 5.1 % share of organic agriculture.

Table 1: Characteristics of all farms in Luxembourg in 2017 and farms in sample in total and for management system (organic, conventional) and ruminant husbandry (meat, dairy, both) (based on data from (Ministère de l'Agriculture, de la Viticulture et du Développement rural, 2023) and personal communication from Service d'Economy Rural (2023)).

	Number of farms	Agricultural area (ha)	Arable Land (ha)	Permanent grassland (ha)
All Farms in Luxembourg	1943	67.5	31.9	34.7
Management system				
Conventional	1843	68.2	32.1	34.8
Organic	100	54.5	24.0	28.3
Ruminant Husbandry	1274			
Specialist dairying (OTE 45)	544	111.6	55.1	56.5
Specialist cattle-rearing and fattening (OTE 46)	376	70.8	24.0	46.8
Cattle dairying, rearing and fattening combined (OTE 47)	116	113.1	49.5	63.5
Farms in sample	87	99.6*** (75.7)	49.7 (50.6)	49.6** (39.2)
Management system				
Conventional	58	114.5*** (84.2)	56.6 (58.6)	57.9*** (42.5)
Organic	29	69.8 (42.6)	36.1 (23.9)	33.2 (25.2)
Ruminant husbandry	72			
Dairy	26	103.0* (58.7)	54.9** (27.8)	48.1 (28.2)
Meat	25	78.5 (56.4)	31.5 (29.1)	46.8 (28.7)
Both	21	149.5* (62.9)	62.8 (31.5)	86.5* (41.0)

Notes: Standard Deviation (sd) is reported in brackets. Significance levels of differences observed between sample and the overall farms in Luxembourg: *** = $p < 0.001$, ** = $p < 0.01$, * = $p < 0.05$ resulting from a one sample t-test for normally distributed data and from a one-sample Wilcoxon signed rank test for non-normally distributed data.

The average size of the agricultural holdings in the sample (99.6 ha) was significantly bigger than the average of all agricultural holdings in Luxembourg (67.5 ha). While the average size of permanent grassland of the sampled farms was significantly higher than the Luxembourgish average, the sampled farms still had a similar distribution between arable land and permanent grassland (ca. 50 %) than the average of all

Luxembourgish farms. While the conventional farms in the sample were significantly bigger than the overall conventional farms in Luxembourg, no significant difference in size was observed between organic farms in the sample and the overall organic farms in Luxembourg. In terms of ruminant husbandry when comparing the farm size of the ruminant categories in the sample to farms in Luxembourg specialising in grazing livestock, the dairy farms in the sample were significantly bigger than farms in Luxembourg classified according to the European farm typology class "specialist dairying (OTE 45) (European Commission, 2014). The same was observed for the farms in the sample that were producing both dairy and meat, compared to farms in Luxembourg classified as cattle dairying, rearing and fattening combined (OTE 47). No significant difference in farm size was seen between farms in the sample focused on ruminant meat production and farms in Luxembourg classified as specialist cattle rearing and fattening. It is important to note, that the farms in the sample were not classified according to the European farm typology methodology, but rather simply on the presence of ruminants and their husbandry purpose. This was done mainly, because many of the participating ruminant husbandry farms, especially for the organic ruminant husbandry farms, had other lucrative farm branches (e.g., field vegetable production, broiler chicken husbandry) that excluded them from the specialised grazing livestock categories (OTE 45, 46 and 47) which in turn led to not enough farms in the 3 main ruminant husbandry OTEs for further detailed analysis. The comparison here between the sample categorisation and the 3 specialised grazing livestock categorisation has mainly the purpose of serving as reference points to allow for better classification of the study sample and evaluation of the results.

Most of the farms are male headed (94.3 % of the farms, Table 2), where organic farms have with 10.3 % a slightly higher share of female headed farms. The farms with ruminant husbandry are mainly male headed, too, where dairy farms have with 7.7 % a slightly higher share of female farm managers. About 27.6 % of the conventional farmers have a university degree (Bachelor or higher) and 34.5 % of the organic farmers. The portion of farmers with a degree of higher education is much lower for dairy farms (11.5 %) compared to suckler cow farms or farms keeping both (36.0 % and 33.3%, respectively), but most of them have at least a secondary education degree (76.9 %).

The spatial distribution across Luxembourg of the farms in the sample is shown in Figure 4. It is noticeable that no farms were surveyed in the south of Luxembourg, a more densely populated area with fewer farms than in the north of Luxembourg. It is also noticeable that no analyses were performed on farms along the south-east border of Luxembourg (along the Moselle River) as agricultural land here consists mostly of vineyards that were, as previously stated, excluded from the study at hand.

Table 2: Socio-demographic characteristics of all farmers in the study sample, for management system (organic, conventional), and for a deeper view on ruminant husbandry (dairy production, meat production and both dairy and meat production) (Reference year 2017). Standard Deviation (sd) is reported in brackets.

	All farmers in Sample	**Management system**		**Ruminant husbandry**		
		Conventional	*Organic*	*Dairy*	*Meat*	*Both*
Male headed holdings (%)	94.3	96.6	89.7	92.3	96.0	95.2
Average age of farmer (years)	45.9 (11.2)	44.0 (11.7)	49.9 (8.7)	44.0 (11.5)	52.1 (8.4)	43.3 (11.2)
Farmers having secondary education (e.g., high school diploma or equivalent) (%)	58.6	60.3	55.2	76.9	48.0	57.1
Farmers having higher education (Bachelor's Degree or more) (%)	29.9	27.6	34.5	11.5	36.0	33.3

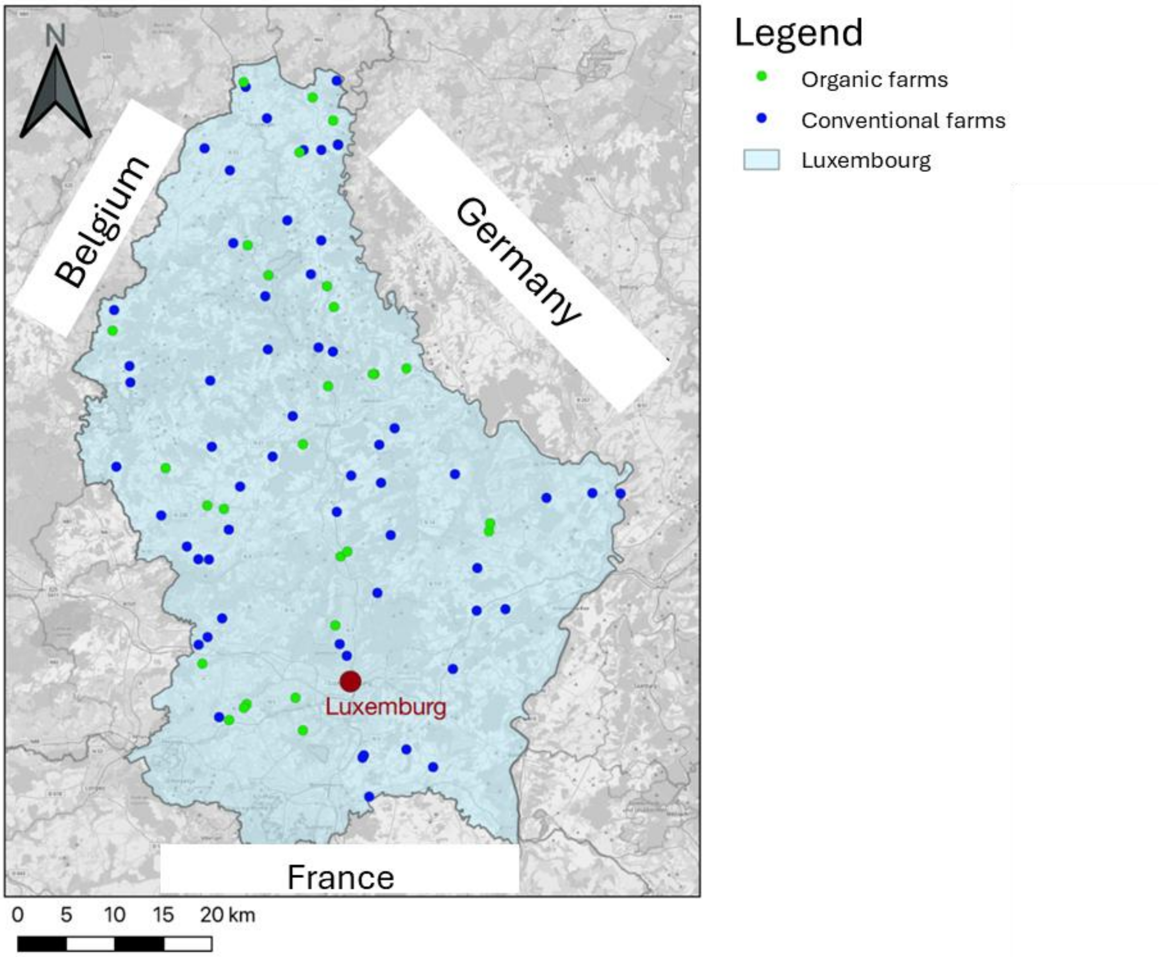

Figure 4: Spatial distribution across Luxembourg of farms in the study sample.

2.2.2 SMART Farm Results

The results for the different themes within the dimensions *Good Governance, Environmental Integrity, Economic Resilience*, and *Social Well-being* showed a wide range of goal achievements. The results of the sustainability analysis of the 87 participating farms are shown in the form of spider web diagrams. Figure 5 shows the minimum, median and maximum of goal achievements for all themes. The minimum and maximum goal achievements are not the results of one single farm, but the worst and the best result achieved by any of the Luxembourgish farms in the sample.

The sustainability performance showed a positive result across all 21 sustainability topics, as the median value per theme is almost exclusively above 50 %. Only in the topics of *Corporate Ethics* (44 %), *Accountability* (37 %), *Holistic Management* (44 %) and *Local Economy* (45 %) showed a median below 50 % and fell within the 'moderate' goal achievement bracket. The topics *Participation* (87 %), *Materials and Energy* (73 %), *Animal Welfare* (75 %) and *Labour Rights* (75 %) showed above 70 % goal achievements, which fall within the 'good' up to 'best' (>80%) goal achievement brackets according to the SMART-Farm Tool.

The minimum and the maximum goal achievement in each sustainability theme indicated the existence of wide differences in the sustainability performances at the individual farm level. Large differences could especially be observed in *Participation* (min: 54 %; max: 95 %), *Corporate Ethics* (min: 24 %; max: 69 %), *Accountability* (min: 18 %; max: 66 %), *Holistic Management* (min: 21 %; max: 67 %), *Biodiversity* (min: 32 %;

max: 85 %), *Local Economy* (min: 14 %; max: 75 %), *Product Quality and Information* (min: 30 %; max: 88 %) and *Cultural Diversity* (min: 34 %; max: 92 %).

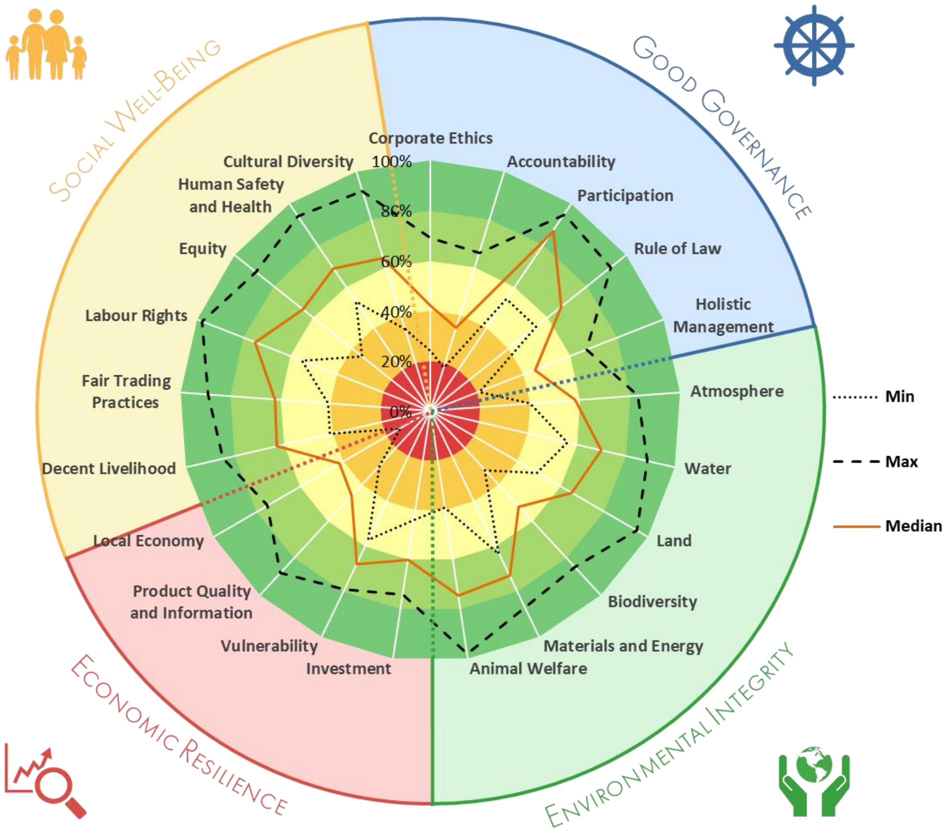

Figure 5: Overall result in the four sustainability dimensions. The average goal achievement at theme level for the analysed farms (n = 87) (full orange line), as well as the minimum (dotted black line) and maximum (dashed black line) result obtained per theme.

2.2.3 Farm management

To evaluate the influence of farm management on the sustainability performance of Luxembourgish farms, the sample was split into conventionally and organically managed farms. Of the 87 farms in the sample, 58 farms were classified as conventional and 29 as organic farms. The organically managed farms showed a higher goal achievement for all themes except of *Equity*, where both farm management types attained the same goal achievement of 65 % (Figure 6;Table 3). Significant differences for management were found in 16 of the 21 themes, and in each of these cases, organically managed farms achieved a significantly higher goal achievement. *Local Economy* was the only theme, where conventional farms realised a higher goal achievement than organic farms, but this was not on a statistically significant level (Table 3).

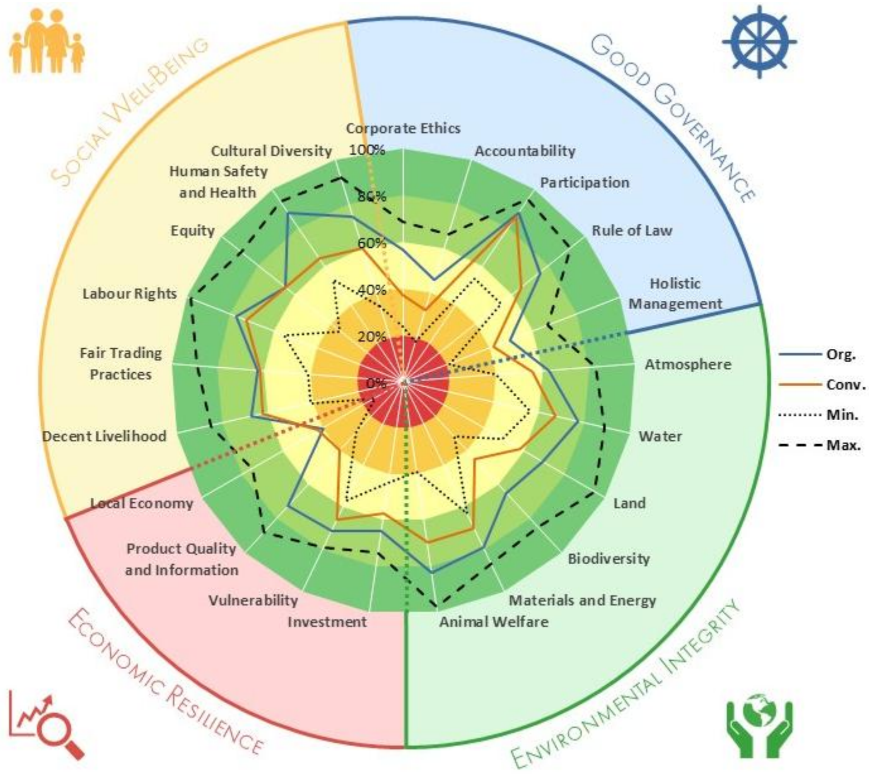

Figure 6: Average overall results of the four sustainability dimensions for the two analysed management systems. Goal achievement at the theme-level shown for the median of the study sample (n = 87) (full black line) and of the different management systems (Org. (Organic): n = 29 (blue line); Con. (Conventional): n = 58 (orange line). The minimum (dotted black line) and maximum (dashed black line) goal achievement values for each theme are also shown.

Figure 7 a-d show the results of the different sub-themes in the four sustainability dimensions *Good Governance, Environmental Integrity, Economic Resilience* and *Social Well-Being*. Conventional and organic farms achieved similar results in many of the sub-themes in *Good Governance* (Figure 7 a) and *Social Well-Being* (Figure 7 d). However, organic farms realised higher goal achievement in the other sub-themes of these two dimensions, most notably in Due Diligence, Public Health and Workspace Safety & Health Provisions. In the sub-themes of *Environmental Integrity* (Figure 7 b), organic farms always achieved significantly higher results. In the theme *Economic Resilience* (Figure 7 c), organically managed farms showed again generally higher results, except for the sub-themes *Profitability* and *Value Creation*. *Here* conventional farms achieved slightly higher goal achievements. For the sub-theme *Profitability,* this difference was significant: conventional farms realised a goal achievement of 66.5 % (median) compared to 61 % for organic farms (Table 4). Overall, there were significant differences in the results of 37 of 58 sub-themes, with conventional farms only achieving significantly higher results in one of the sub-themes (in *Profitability*). For the other 36, it was organically managed farms that realised significantly higher results.

Table 3: Median, minimum (min) and maximum (max), goal achievements at theme level for farm management ($n_{conventional}$ = 58 and $n_{organic}$ = 29), as well as standard deviation (sd) and *p*-values shown for the comparison of the median. Level of significance $p < 0.05$.

Dimensions	Theme	Treatment	Min	Max	Median	sd	*p*-value
Good Governance	Corporate Ethics	*conventional*	24	58	37.5	7.3	
		organic	42	69	57	6.2	**<0.001**
	Accountability	*conventional*	18	49	32	5.6	
		organic	36	66	46	6.2	**<0.001**
	Participation	*conventional*	62	93	86	5.3	
		organic	54	95	88	7.5	0.060
	Rule of Law	*conventional*	54	77	65	5.3	
		organic	64	92	75	5.8	**<0.001**
	Holistic Management	*conventional*	21	56	41.5	7.7	
		organic	34	67	49	8.0	**<0.001**
Environmental Integrity	Atmosphere	*conventional*	40	77	55.5	6.0	
		organic	53	83	63	6.9	**<0.001**
	Water	*conventional*	56	87	67	6.1	
		organic	68	89	77	5.4	**<0.001**
	Land	*conventional*	49	95	58	9.4	
		organic	58	88	69	5.7	**<0.001**
	Biodiversity	*conventional*	32	83	45	12.8	
		organic	56	85	65	6.7	**<0.001**
	Materials and Energy	*conventional*	63	86	70	4.7	
		organic	73	87	79	3.3	**<0.001**
	Animal Welfare	*conventional*	39	98	70	10.1	
		organic	69	95	83	7.2	**<0.001**
Economic Resilience	Investment	*conventional*	44	74	57	5.9	
		organic	57	72	65	4.1	**<0.001**
	Vulnerability	*conventional*	57	74	65.5	4.1	
		organic	61	79	71	4.2	**<0.001**
	Product Quality and Information	*conventional*	30	78	40	10.9	
		organic	66	88	73	4.6	**<0.001**
	Local Economy	*conventional*	26	71	42	11.2	
		organic	14	75	40	15.1	0.058
Social Well-Being	Decent Livelihood	*conventional*	41	80	62	7.6	
		organic	52	85	67	8.1	**0.008**
	Fair Trading Practices	*conventional*	41	82	62	8.0	
		organic	42	89	63	10.2	0.462
	Labour Rights	*conventional*	61	88	72.5	7.7	
		organic	55	98	77	9.8	0.099
	Equity	*conventional*	35	83	65	9.8	
		organic	41	89	65	11.2	0.677
	Human Safety and Health	*conventional*	53	94	64	9.3	
		organic	79	93	88	3.4	**<0.001**
	Cultural Diversity	*conventional*	34	89	60	10.5	
		organic	59	92	74	9.4	**<0.001**

Table 4: Median, minimum (min) and maximum (max), goal achievements at theme level for farm management ($n_{conventional}$ = 58 and $n_{organic}$ = 29), as well as standard deviation (sd) and p-values shown for the comparison of the median. Level of significance $p < 0.05$.

Sub-theme	Treatment	Min	Max	Median	sd	*p*-value
	conventional	52	75	66.5	5.7	
Profitability	*organic*	52	71	61	5.5	**<0.001**

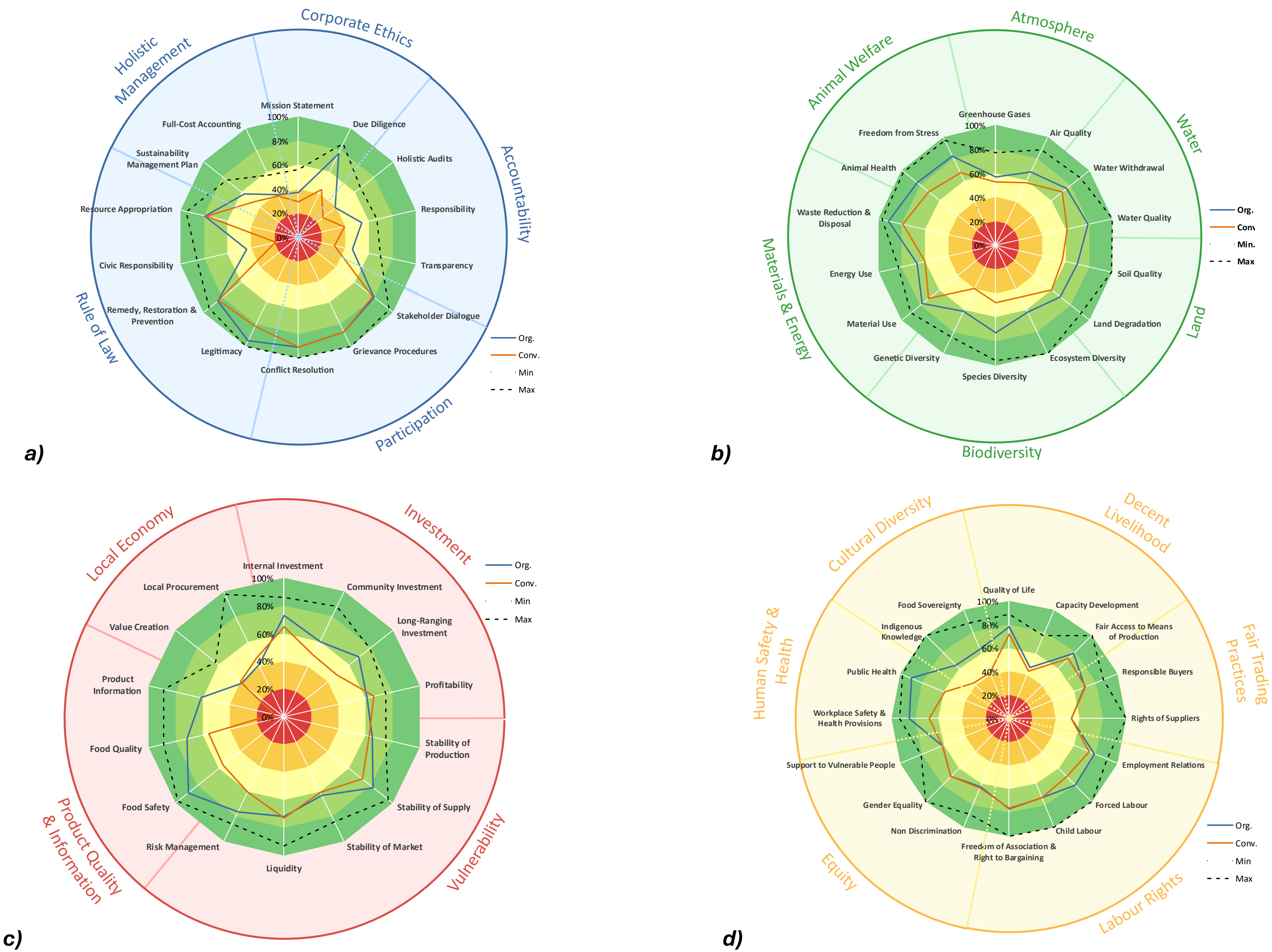

Figure 7 a-d: Result in the sustainability dimension of a) good corporate governance b) environmental integrity c) economic resilience and d) social well-being. The median goal achievement at sub-theme level for the analysed conventional farms ($n_{conventional}$ = 58; orange line), the organic farms ($n_{organic}$ = 29, blue line) as well as the minimum (dotted black line) and maximum (dashed black lines) achieved per sub-theme.

2.2.4 Ruminants

As mentioned in the previous chapter, Luxembourg is a predominantly grassland location and the majority of the farms are based on ruminant husbandry. To assess the sustainability performance of the different branches of ruminant husbandry, the farms with ruminant husbandry were classified according to the focus of this farm branch; meat production, dairy production, or a combination of both. Out of the 87 farms in the sample, 72 raised ruminants, and out of these 72, 26 farms focussed on suckler cow husbandry, 25 farms were dairy farms, and 21 farms raised cattle for both meat and dairy production. Figure 8 shows that suckler cow husbandry (meat) generally achieved higher results in terms of sustainability performance than dairy farms and farms raising cattle for both meat and dairy production. There were not many differences in results between farms keeping both and dairy farms.

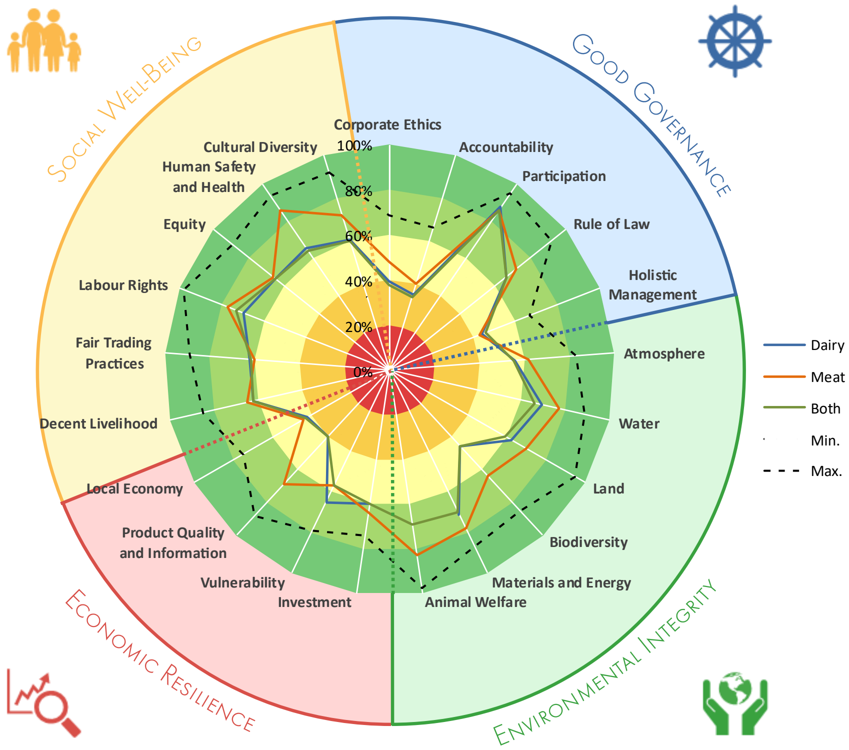

Figure 8: Overall results in the four sustainability dimensions for the two analysed ruminant husbandry types. The median goal achievement at theme level for the analysed farms with suckler cow husbandry (meat, n = 26; orange line), for dairy farms (n = 25, blue line), for farms keeping both (n = 21, green line) as well as the minimum (dotted black line) and maximum (dashed black lines) results achieved per theme.

There were significant differences in 11 of 21 themes for ruminant husbandry (Table 5), with meat production generally obtaining a significantly higher goal achievement compared to dairy or both. In *Corporate Ethics* suckler cow husbandry obtained a significantly higher goal achievement than farms raising both but not compared to dairy farms. Meat production showed significantly higher results for all themes belonging to *Environmental Integrity.* The biggest difference was observed in *Biodiversity,* where suckler cow farms achieved a result in the 'good' results bracket (64 %) and dairy farms and those keeping both achieved results in the 'moderate' bracket, with 46 % each.

Table 5: Median, minimum (min) and maximum (max) goal achievements at theme level for each ruminant husbandry type (n dairy = 26; n meat = 25; n both = 21), as well as standard deviation (sd) and *p*-values shown for the comparison of the median of the 3 groups. Level of significance *p* < 0.05. Rows with medians not sharing the same alphabetic letter (a, b, etc.) are statistically significant different.

Dimensions	Theme	Treatment	Min	Max	Median		sd	p-value
Good Governance	Corporate Ethics	*dairy*	24	61	39.5	ab	11.1	
		meat	28	64	48	a	10.4	
		both	28	62	38	b	8.6	**0.018**
	Accountability	*dairy*	22	53	35		8.1	
		meat	18	52	40		9.4	
		both	24	57	34		7.3	0.292
	Participation	*dairy*	54	95	87.5		7.8	
		meat	76	93	86		4.7	
		both	62	91	86		6.5	0.483
	Rule of Law	*dairy*	58	83	66		7.0	
		meat	56	84	72		8.4	
		both	54	76	66		6.0	0.143
	Holistic Management	*dairy*	27	63	44		7.6	
		meat	21	62	43		9.6	
		both	21	57	46		8.7	0.977
Environmental Integrity	Atmosphere	*dairy*	48	65	56	a	4.8	
		meat	40	77	62	b	8.5	
		both	51	63	55	a	3.4	**0.006**
	Water	*dairy*	56	85	69	a	6.1	
		meat	63	87	77	b	6.1	
		both	59	78	66	a	5.3	**<0.001**
	Land	*dairy*	49	72	62.5	a	7.0	
		meat	56	88	70	b	9.9	
		both	51	71	59	a	6.4	**<0.001**
	Biodiversity	*dairy*	32	71	46	a	11.7	
		meat	41	85	64	b	12.5	
		both	33	69	46	a	10.6	**<0.001**
	Materials and Energy	*dairy*	63	80	71	a	4.7	
		meat	67	86	78	b	5.3	
		both	65	80	70	a	4.0	**<0.001**
	Animal Welfare	*dairy*	54	88	70	a	9.3	
		meat	65	98	83	b	9.3	
		both	53	79	69	a	8.1	**<0.001**
Economic Resilience	Investment	*dairy*	49	72	60		6.3	
		meat	44	71	64		7.2	
		both	48	66	60		4.5	0.165
	Vulnerability	*dairy*	59	76	65	a	4.6	
		meat	57	78	57	b	4.9	
		both	57	72	57	a	4.0	**0.008**
	Product Quality and Information	*dairy*	31	75	40.5	a	16.1	
		meat	30	82	69	b	16.3	
		both	32	73	40	a	11.2	**0.006**
	Local Economy	*dairy*	26	71	42		10.2	
		meat	14	75	44		15.1	
		both	24	64	43		11.0	0.743
Social Well-Being	Decent Livelihood	*dairy*	53	74	62		6.3	
		meat	46	85	65		10.2	
		both	41	72	62		7.3	0.821
	Fair Trading Practices	*dairy*	55	78	62.5		5.3	
		meat	42	80	60		10.7	
		both	41	77	62		7.5	0.947
	Labour Rights	*dairy*	55	88	69.5		7.7	
		meat	61	86	77		7.4	
		both	61	88	73		7.1	0.099
	Equity	*dairy*	35	77	65		10.1	
		meat	46	79	66		11.2	
		both	50	83	65		9.1	0.073
	Human Safety and Health	*dairy*	55	91	65.5	a	12.2	
		meat	53	91	86	b	13.0	
		both	58	86	64	a	8.1	**0.004**
	Cultural Diversity	*dairy*	44	88	60.5	a	11.1	
		meat	51	90	72	b	10.0	
		both	49	71	60	a	6.2	**<0.001**

Figure 9 a-d show the results for the different sub-themes of the four sustainability dimensions *Good Governance*, *Environmental Integrity, Economic Resilience* and *Social Well-Being*. Dairy farms and farms producing both showed almost the same results for all sub-themes; farms with focus on meat production generally achieved higher results at sub-theme level. There were significant differences in 28 out of the 58 sub-themes. In general, for these 28 sub-themes with significant differences, farms with suckler cow husbandry realised significantly higher results compared to both dairy farms and farms with dairy and meat production. This was most notably the case in *Environmental Integrity,* where meat producing farms achieved significantly higher goal achievements compared to the other two ruminant groupings in all 14 environment-related sub-themes (Figure 9 b). However, for the sub-theme *Profitability* in the *Economic Resilience* dimensions*,* a significantly lower goal achievement was observed for meat producing farms (62 %) compared to dairy farms (66 %) and farms keeping both (68 %) (Table 6).

There were a few sub-themes with significant differences, where a significant difference was only observed between 2 of the 3 ruminant groupings. For example, in the dimension *Good Governance* (Figure 9 a), meat production showed a significantly higher goal achievement for *Legitimacy* compared to farms with both dairy and meat production, but no significant differences was observed between dairy farms and meat farms. In the *Social Well-Being* dimension (Figure 9 d), the observed significant difference in the sub-theme *Non Discrimination* was between suckler cow farms and dairy farms, while no significant difference was observed in regards to farms with both ruminant husbandry branches. This was the same for the sub-theme *Stability of Market* in *Economic Resilience dimension* (Figure 9 c): the observed significant difference was only between meat production and dairy production. For the sub-theme *Stability of Supply*, the observed difference was between meat production and farms with both meat and dairy production, while not significant difference was observed between dairy farms and the other two groupings.

Table 6: Median goal achievements at theme level for each ruminant husbandry type (n dairy = 26; n meat = 25; n both = 21), as well as standard deviation (sd) and *p*-values shown for the comparison of the median. Level of significance $p < 0.05$. Not sharing the same alphabetical letter indicates significant difference between the medians.

		Treatment						
Sub-theme	**Metric**	**dairy**		**meat**		**both**		***p*-value**
	Median	66	a	62	b	68	a	
Profitability	sd	5.1		5.3		5.7		**0.003**

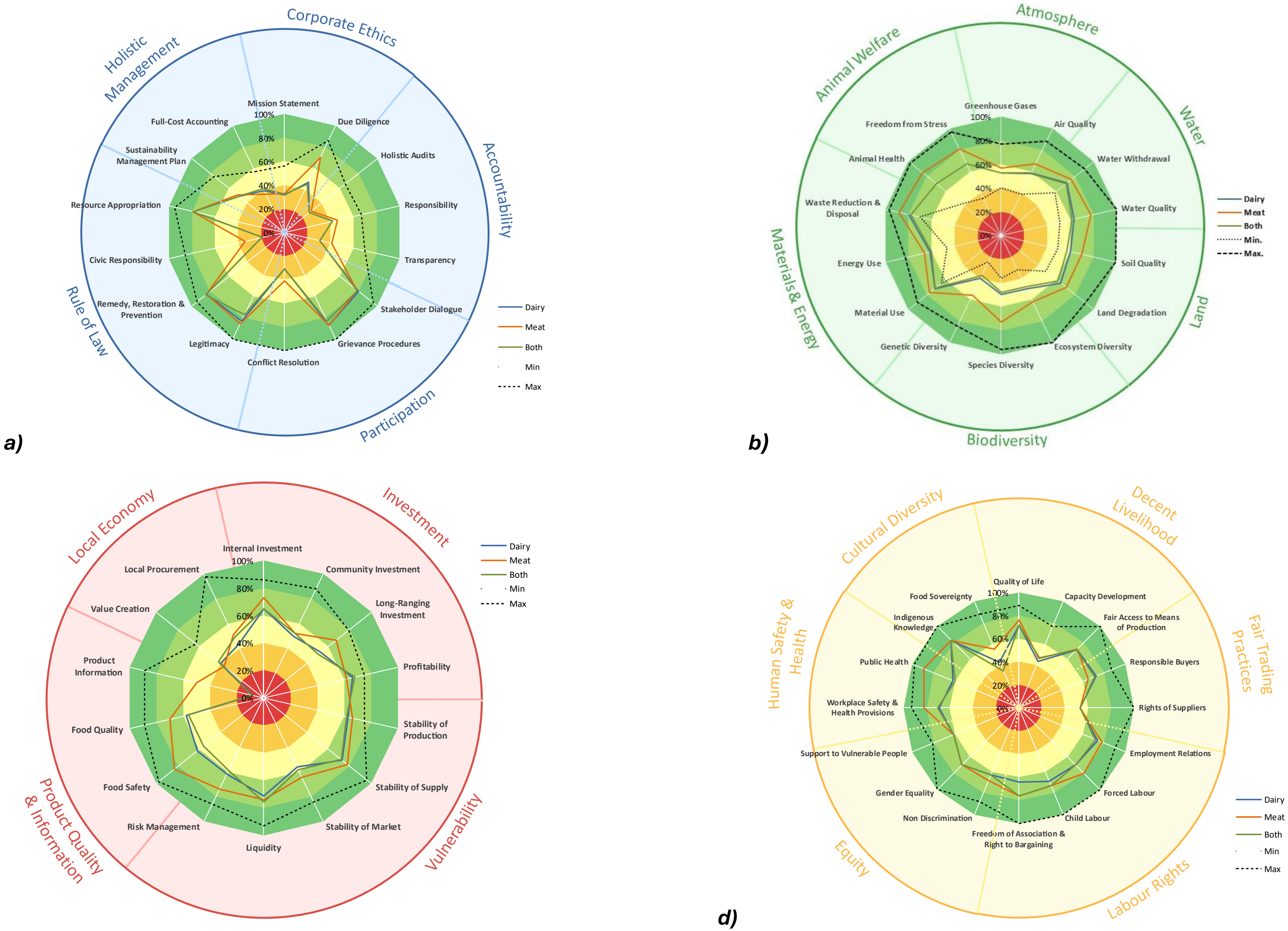

Figure 9 a-d: Result in the sustainability dimension of a) good governance b) environmental integrity c) economic resilience and d) social well-being. The median goal achievement at sub-theme level for the analysed farms with suckler cow husbandry (meat) (n = 28; orange line), the dairy farms (n = 24, blue line), farms keeping both (n = 28, green line) as well as the minimum (dotted black line) and maximum (dashed black lines) results achieved per sub-theme.

2.2.5 Indicator-based results

More specific information on the agricultural land and the thereupon implemented practices was gained by looking at a selection of indicators relevant for the sub-themes in the *Environmental Integrity* dimension. Of the more than 300 indicators implemented in the SMART-Farm tool around 180 were used to assess goal achievement in the Environmental Integrity dimension and a selection of these are described in the following. The indicator identification numbers (IDs) used in the text and the tables below are the IDs used to identify the various indicators in the SMART- Fram tool.

Agroforestry was only established on 3 out of the 87 farms (ID 202). Most farms owned at least a small portion of forest (ID 208, Table 7), while on 12 farms, small areas of woodlands were deforested. However, only one farm cleared forest to gain agricultural land, looking at the past 20 years.

Most of the participating farms did not or managed only a very small share of their *permanent grassland extensively* (0-10 %) (ID 253, Table 7), with higher shares observed among organically managed farms. Looking at the *cutting frequency* of permanent grasslands, half of the participants cut their grasslands on average 1-2 times, while the other half does 3-4 times; no farms realised 5 or more cuts on average (ID 620). *Legumes* generally make up no more than 30 % of arable land (ID 206, Table 7), with higher shares of legumes noted on organic farms. *Calculations of humus balances* are not the norm; however, on the farms, where such calculations were performed, these showed largely a balanced or positive tendency (ID 748). Most farms implemented *measures to counter soil degradation*, when degradation was observed (ID 286). Only 3 farms did not or only partially implement such measures. *Direct seeding* only played a very small role in crop production on the 87 farms that participated in the study (ID 207, Table 7).

Table 7: Sample size (n) and absolute frequency distribution in 10% steps for the indicators related to the main topic „Agricultural land management“.

ID	Indicator	n	0	>0-10	>10-20	>20-30	>30-40	>40-50	>50-60	>60-70	>70-80	>80-90	>90-100
206	*Share of Legumes on Arable Land*	79	12	32	12	14	6	3	0	0	0	0	0
207	*Arable Land: Share of Direct Seeding*	78	67	3	4	1	0	0	0	1	0	0	2
208	*Woodlands: Share of Agricultural Area*	87	27	47	4	5	2	2	0	0	0	0	0
253	*Permanent Grasslands: Extensively Managed*	81	11	32	9	7	1	1	3	0	1	2	14

Pesticide use and *plant protection measures* were assessed based on 9 indicators. *Chemical synthetic insecticides* were used by 16 farms of which 9 only applied them on >0-10 % of their agricultural land, thus the majority of the participating farms did not use any such insecticides (ID 234). *Synthetic chemical fungicides* were used by 36 farms, of which 7 only used them on >0-10 % of their agricultural land (ID 233). The highest share of agricultural land, where such fungicides were applied was 95.1 %. *Synthetic chemical herbicides* were the most widely used form of pesticides (ID 231). A total of 7 conventional farms (on top of the 29 organically managed farms) renounced the use of herbicides on any share of agricultural land, which was 12 % of the conventional managed farms in the sample. The remaining farms applied such herbicides on >0-40 % of their agricultural land. Many of the farms used pesticides that are *highly toxic when inhaled* (ID 377.75) and *growth regulators* (ID 740) were also utilized by most of the participating conventional farms.

The topic of environmental emissions was covered by 5 indicators. Most farms could not completely ensure that there are *no on-farm point sources of nutrients or/and pollutants* on the farm (ID 380). For the rating, the worst-case principle was applied. As a risk for emissions to the environment existed, the farms were accordingly rated negatively. Only a small number of farms had fields close to *heavily travelled roads or highways* with an accompanying risk of contamination from exhausts (ID 511). With the same principle, it could not be concluded with certainty that no *problematic plastic types* were being used on the farms, so that this indicator was also rated negatively (ID 738). *Silage was generally stored* in such a way that losses to the environment and contamination of the silage were minimized (ID 720). *Open burning of green cuttings* was still performed by 4 farmers, thinking that this was still legally allowed in 2017 (ID 788).

Table 8: Sample size (n) and distribution of the answers no/yes for the indicators related to the main topic „ Animal husbandry“.

ID	Indicator	n	no	yes
370.5	*Daily Outdoor Access for All Animals*	77	70	7

Eight indicators specifically referred to animal husbandry. Many of these indicators are answered and rated based on the worst-case principle, meaning that if a condition could not be fulfilled for one animal, group or category, the indicator question was answered negatively. For example, for the indicator "*Daily Outdoor Access for Animals*", if one animal (e.g. breeding bull), animal category (e.g. dairy cows or laying hens) or animal group (e.g. calves, young cattle, heifers or dairy cows) had no daily outdoor access, the indicator was answered overall with "no", even when the majority of the animals on the farm had daily outdoor access. *Daily outdoor access for pigs* was only granted on organic farms; while *daily outdoor access for poultry* was the norm independent of management system; only one conventional poultry farm in the sample did not grant daily outdoor access. The results showed that most farms did not provide *daily outdoor access to all animals* (ID 370.5, Table 8). Similarly, a large proportion of farmers did not provide *access to pasture* for all ruminant categories on their farm; however, when access was granted across the whole herd, the majority were on the pasture for 6-8 months out of the year (ID 371, Table 9). *Dual-purpose breeds in both ruminants* (ID 198) and *poultry* (ID 198.1) played so far only a very marginal role in Luxembourg and were only used on a very small number of farms. Most of the farmers did not know how long the *duration of the transport to the abattoir* took (ID 374). All participating farms used proper *disposal pathways for livestock cadavers* (ID 331).

Table 9: Sample size (n) and absolute frequency distribution (days) for the indicator ID 371 -Access to Pasture for Ruminants related to the main topic „ Animal husbandry“.

ID	Indicator	n	0	>0-60	>60-120	>120-180	>180-240	>240-300	>300-360
371	*Access to Pasture for Ruminants*	72	35	0	0	6	24	4	3
	Organic farms	23	6	0	0	2	11	2	2
	Conventional farms	49	29	0	0	4	13	2	1

Table 10: Sample size (n) and absolute frequency distribution in 10 % steps for the indicators related to the main topic "Feed".

ID	Indicator	n	0	>0-10	>10-20	>20-30	>30-40	>40-50	>50-60	>60-70	>70-80	>80-90	>90-100
199	*Bought-In Concentrated Feed*	77	6	2	5	3	6	5	5	6	3	6	30
626	*Proportion Bought-In Roughage*	75	34	23	11	3	1	2	0	0	1	0	0

Linked to animal husbandry, the topic of feed grouped 4 indicators. All farms with animal husbandry used *concentrated feed* in their feed rations and most bought in over 90 % of their concentrated feed needs (ID, 199, Table 10). Only 6 farms were completely self-sufficient when it comes to concentrated feed needs. When looking at management system, it was observed that a higher relative frequency of organic farms purchased 0% of their concentrated feed needs, while a higher relative frequency of conventional farmers externally sourced more than 90 % of their concentrated feed needs (Figure 10). In terms of feed no food, the majority of farms fed below 1,000 kg per livestock unit per year of feedstuff that is in competition with human food production, with 4 feeding no such feed (ID 517, Table 11). However, 7 farms still fed above 3,500 kg/livestock unit per year. In regards to basic fodder supply, the farms showed a very high autarky: most farms bought in less than 20 % of their roughage needs externally, meaning that over 80 % were produced on-farm, with 34 being 100 % self-sufficient (ID 626, Table 10).

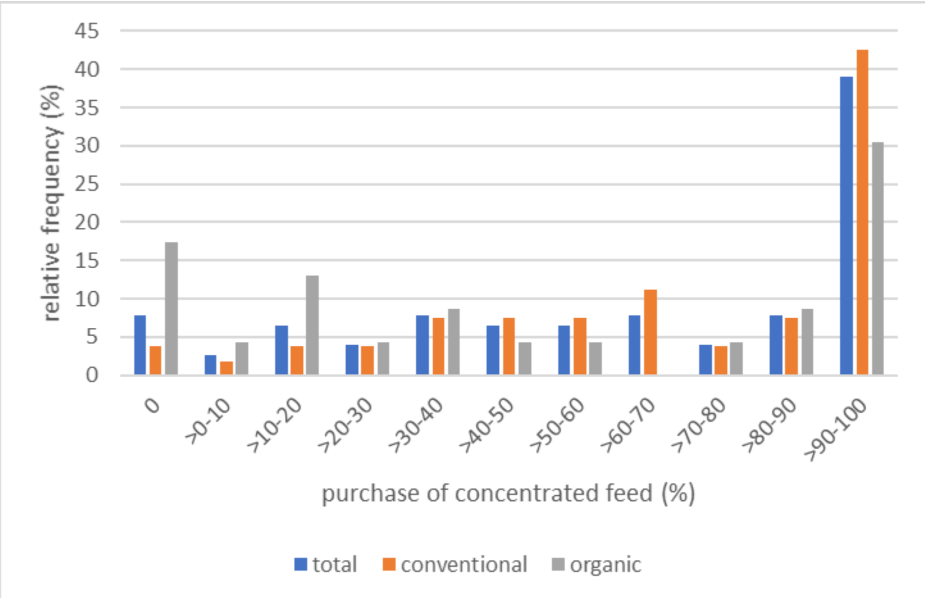

Figure 10: Sample size (n) and absolute frequency distribution in 10% steps for the indicator ID 199 – bought-in concentrated feed for the total sample and for the management systems conventional and organic.

Selected results for the effect of management on the rating of the above discussed indicators are shown in Table 12. Most indicators for which a significant difference was observed are related to the use of plant protection products (e.g., *use of chemical synthetic herbicides* (ID 231), *fungicides* (ID 233) or *insecticides* (ID 234), *the acute toxicity risk linked to the use of pesticides* (ID 377.75), *use of growth regulation products* (ID 740)), and to animal husbandry conditions (e.g., *stocking density* (ID 368), *access to pasture* (ID 371), *outdoor access for pigs* (ID 372)). Other indicators with significant differences are related to the origin of feedstuff (*ID 199 - bought-in concentrated feed*) and feeding practices of ruminants (*ID 517 - Feed No Food:*

Grazing Livestock), crop rotations and their different elements (*arable land: share temporary grassland* (ID 215), *arable land: share legumes* (ID 206) and *arable land: share green cover outside growing period* (ID 225)). For all the above-mentioned indicators, organically managed farms achieved a significantly higher indicator rating. Furthermore, organic farms had significantly lower *nitrogen inputs from fertilizers* (considered were both mineral and organic fertilizers) (ID 323_1) and a higher *share of the permanent grassland that was extensively managed* (ID 253). The latter goes hand in hand with the significantly *higher mowing frequency* observed on conventional farms (ID 620). For the indicator *low energy technology and/or pumps for irrigation* (ID 345), conventionally managed farms also showed a significantly higher indicator score.

Table 11: Sample size (n) and absolute frequency distribution (500 kg/livestock unit/year) for the indicator ID 517 -Feed no Food: Grazing Livestock related to the main topic „Feed “.

ID	Indicator	n	0	>0-500	>500-1000	>1000-1500	>1500-2000	>2000-2500	>2500-3000	>3000-3500	>3500
517	*Feed No Food: Grazing Livestock*	72	4	15	13	9	9	5	7	3	7

A significant difference in indicator rating for ruminant husbandry was observed in 11 indicators (Table 14). For 5 of these indicators (*permanent grassland extensively managed* (ID 253), *N from fertilizers* (ID 323.1), *electricity consumption* (ID 332), *pesticides acute toxicity inhalation* (377.75), and *feed no food grazing livestock* (ID 517)), meat producing farms achieved a significantly higher indicator rating compared to dairy farms and farms producing both meat and dairy. For the two indicators *dual-purpose breeds of ruminants* (ID 198) and *permanent grassland mowing frequency* (ID 620) suckler cow farms realised a significantly lower indicator score compared to the other two ruminant branches. For *share of arable land under green cover outside the growing period* (ID 225) and *share of agricultural land where no synthetic chemical herbicides are used* (ID 231), suckler cow farms achieved a significantly higher indicator rating than farms producing both meat and dairy, while there was no difference to dairy farms. For the indicator *permanent grassland share of agricultural land* (ID 222), meat producing farms had a significantly higher share of permanent grassland to agricultural land compared to dairy farms, while no significant difference was seen between mixed farms and the other two ruminant husbandry types. For *access to pasture* (ID 371), a significant difference was observed between all three ruminant husbandry types, with meat farms granting the highest access to pasture and farms with both dairy and meat production the least. Some of the indicators where significant differences were observed are linked to the inherent structure of the animal husbandry system. For example, farms specialised in meat production achieved a 0 indicator score for share of *dual-purpose breeds* (ID 198) raised on a farm. Similarly, suckler cow farms showed a significantly *higher share of permanent grassland areas* (ID 222) that were *more extensively managed* (ID 253 and ID 620), which is then also mirrored in a less intensive *nitrogen fertilisation strategy* (ID 232.1). Overall, meat producing farms generally achieved a higher indicator score confirming the results seen at sub-theme level.

The above-described indicator results with significant differences in their scoring can explain to some extend the differences seen at sub-theme level and provided starting points for identifying farming practices that should be implemented to increase the sustainability performance of a farm and the overall agricultural sector. However, it is also worth looking at indicators that show no significant difference across treatments and that only achieved low indicator scores. These show areas in the agricultural system with large improvement potential across the board. Such indicators include *plough less soil management* (ID 182.1), *agroforestry systems* (ID 202), *share of direct seeding* (ID 207), *share of areas fostering biodiversity* (ID 229.1), *mulching* (ID 237.1), *catch crops* (ID 285), *crop residues* (ID 289.1)) and *sources of nutrient pollution on farm* (ID 380) (Table 12, Table 14). These mostly relate to practices promoting humus formation and carbon storage in the soil on the one hand (e.g., reduced tillage, direct seeding, and implementation of agroforestry systems), and avoiding emissions on the other hand (growing catch crops and undersown crops and identifying possible on-farm point and diffuse sources for pollution).

Table 12: Sample size (n), mean indicator rating and the standard deviation (sd) of selected indicators related to the *Environmental Integrity* dimension are shown for management.

ID	Indicators	Organic			Conventional			*p* - value
		n	Mean*	sd	n	Mean*	sd	
182	*PloughLessSoilManagement*	26	0.18	0.32	53	0.17	0.25	0.336
199	*BoughtConcentratedFeed*	23	0.48	0.40	53	0.30	0.32	**0.049**
201	*SlurryApplicationDragHoseInjection*	29	0.71	0.45	57	0.50	0.47	**0.038**
202	*AgroForestrySystems_Calculated*	29	0.00	0.02	57	0.02	0.13	0.239
206	*ShareLegumesArableLand*	25	0.65	0.28	54	0.23	0.32	**<0.001**
207	*ArableLandShareDirectSeeding*	25	0.03	0.07	53	0.06	0.21	0.724
215	*ArableLandShareTemporaryGrassland_Calc*	25	0.60	0.33	54	0.36	0.38	**0.006**
219	*ArableLandUnderSownCrops*	26	0.13	0.23	54	0.12	0.26	0.593
222	*PermanentGrasslandsShareOfAgricultur-alArea_Calculated*	29	0.48	0.31	58	0.53	0.27	0.546
225	*ArableLandShareGreenCoverOutsideGrow-ingPeriod*	26	0.93	0.22	54	0.88	0.18	**0.001**
229.1	*BiodivAreaShareOfFarmLand_Calc*	29	0.54	0.35	58	0.50	0.36	0.573
231	*NoUseSynthChemHerbicides*	29	1.00	0.00	57	0.64	0.25	**<0.001**
233	*NoUseSynthChemFungicides*	29	1.00	0.00	57	0.85	0.19	**<0.001**
234	*NoUseSynthChemInsecticides*	29	1.00	0.00	57	0.95	0.13	**0.002**
237.1	*AgriculturalLandShareMulching*	27	0.03	0.10	54	0.04	0.19	0.993
253	*PermanentGrasslandsExtensivelyManaged*	26	0.46	0.41	55	0.21	0.32	**0.003**
285	*HumusFormationCatchCrops*	26	0.27	0.22	54	0.26	0.21	0.865
289.1	*HumusFormationCropResidues*	27	0.08	0.21	54	0.05	0.17	0.871
290.1	*SoilAnalysisFertilizerRequirements*	29	0.45	0.28	57	0.42	0.17	0.721
323.1	*NFromFertilizers_Calc*	29	0.64	0.33	57	0.19	0.28	**<0.001**
332	*ElectricityConsumption*	29	0.55	0.29	58	0.42	0.24	**0.017**
345	*IrrigationLowEnergyTechnologyPumps*	29	0.86	0.35	57	1.00	0.00	**0.004**
368	*StockingDensity*	25	1.00	0.00	52	0.81	0.40	**0.020**
370.5	*DailyOutdoorAccess*	24	0.17	0.38	53	0.06	0.23	0.125
371	*AccessToPasture*	23	0.63	0.40	49	0.33	0.41	**0.005**
372	*OutdoorAccesPigs*	5	1.00	0.00	4	0.00	0.00	**0.007**
377.75	*PesticidesAcuteToxicityInhalation*	29	0.97	0.14	58	0.20	0.37	**<0.001**
380	*NutrientsPollutantsSourcesOnFarm*	29	0.17	0.38	58	0.17	0.38	1.000
517	*FeedNoFoodGrazingLivestock*	23	0.32	0.40	49	0.05	0.20	**<0.001**
521	*ProductionBioenergyCrops*	29	0.03	0.19	57	0.04	0.18	0.208
620	*PermanentGrasslandMowingFrequency*	25	0.14	0.23	55	0.28	0.25	**0.020**
737	*UseSyntheticAggregatesForSoilSubstrate*	8	1.00	0.00	4	0.50	0.58	**0.049**
740	*GrowthRegulation*	26	1.00	0.00	54	0.26	0.44	**<0.001**

* rating scale from 0 -1; 0 being the lowest rating and 1 the highest rating

Notes: The *p*-values for the impact of management are given (using independent two sample t-test or Wilcoxon rank sum test).

As discussed above, significant differences were observed in the sub-theme *Profitability*, with organic farms and farms with focus on ruminant meat production realising significantly lower goal achievement. To understand the observed differences the related indicators were also assessed. A total of 46 indicators were used to assess the goal achievement in *Profitability*; a selection of the results for management is shown in Table 12. Significant differences were observed in indicators related to the use of pesticides (e.g., *use of chemical synthetic herbicides* (ID 231) or *insecticides* (ID 234), *use of growth regulation products* (ID 740)). Their use is rated positive for this sub-theme as it lowers the risk for crop loss due to outside influence of weeds and pests. Significant differences were also observed in indicators that assess the intensity of the system, such as *ID00128 – Yield Level* and *ID00620- Permanent Grassland Mowing Frequency*. These are all indicators that negatively impacted sub-themes in the Environmental Integrity dimension, but positively influence Profitability, as the tool deems the risk to income loss lower with higher intensity systems. However, when looking at the two indicators that were income related, no significant differences were observed for management systems and for focus of ruminant husbandry: *ID00099 – Profit Stability* and *ID00804 - Farm Net Income*.

Table 13: Sample size (n), mean indicator rating and the standard deviation (sd) of selected indicators related to the sub-the *Profitability* are shown for management.

ID	Indicators	Organic			Conventional			
		n	Mean*	sd	n	Mean*	sd	*p* - value
0	*ProfessionalAgriculturalAccounts*	29	0.84	0.30	58	0.94	0.21	0.054
73	*LongTermInvestments*	29	0.97	0.19	58	0.95	0.22	0.728
88	*FarmInputsSecureSupply*	28	0.75	0.44	58	0.93	0.26	**0.020**
95.1	*YieldLoss_Calc*	29	0.21	0.41	57	0.25	0.43	0.694
99	*ProfitStability*	28	0.21	0.26	58	0.25	0.30	0.450
128	*YieldTendency*	29	0.75	0.28	58	0.74	0.28	0.791
128	*YieldLevel_Calc*	28	0.09	0.20	57	0.42	0.25	**<0.001**
136	*ClimateChangeAdaptationMeasures*	29	0.86	0.35	58	0.74	0.44	0.204
161	*ProducerPriceVsMarketPriceLevel*	29	0.78	0.28	58	0.55	0.15	**<0.001**
215	*ArableLandShareTemporaryGrassland_Calculated*	25	0.60	0.33	54	0.36	0.38	**0.006**
231	*NoUseSynthChemHerbicides*	29	1.00	0.00	57	0.64	0.25	**<0.001**
234	*NoUseSynthChemInsecticides*	29	1.00	0.00	57	0.95	0.13	**0.002**
247	*HybridCultivars*	29	0.53	0.38	56	0.08	0.23	**<0.001**
257	*ArableLandAveragePlotSize_Calculated*	26	0.74	0.15	54	0.70	0.15	0.311
612	*LamenessAnimals*	23	0.85	0.13	52	0.69	0.24	**0.002**
620	*PermanentGrasslandMowingFrequency*	25	0.14	0.23	55	0.28	0.25	**0.020**
740	*GrowthRegulation*	26	1.00	0.00	54	0.26	0.44	**<0.001**
804	*FarmNetIncome*	29	0.74	0.36	58	0.76	0.35	0.759

* rating scale from 0 -1; 0 being the lowest rating and 1 the highest rating

Notes: The *p*-values for the impact of management are given (using independent two sample t-test or Wilcoxon rank sum test).

Table 14: Sample size (n), mean indicator rating and the standard deviation (sd) of the selected indicators are shown for ruminant husbandry.

ID	Indicators	Dairy				Meat				Both				*p* - value
		n	Mean*		sd	n	Mean*		sd	n	Mean*		sd	
182.1	*PloughLessSoilManagement*	26	0.11		0.18	20	0.07		0.15	20	0.18		0.25	0.094
198	*DualPurposeBreedsRuminants*	26	0.17	a	0.35	25	0.00	b	0.00	21	0.15	a	0.31	**0.022**
199	*BoughtConcentratedFeed*	26	0.35		0.32	24	0.42		0.43	21	0.37		0.30	0.789
202	*AgroForestrySystems_Calculated*	26	0.00		0.00	25	0.00		0.01	21	0.00		0.00	0.391
206	*ShareLegumesArableLand*	26	0.41		0.37	20	0.48		0.33	21	0.33		0.39	0.409
207	*ArableLandShareDirectSeeding*	26	0.04		0.14	20	0.00		0.01	20	0.06		0.21	0.330
215	*ArableLandShareTemporaryGrassland_Calculated*	26	0.55		0.42	20	0.50		0.35	21	0.40		0.37	0.373
219	*ArableLandUnderSownCrops*	26	0.12		0.23	20	0.10		0.19	21	0.14		0.31	0.991
222	*PermanentGrasslandsShareOfAgriculturalArea_Calculated*	26	0.46	a	0.22	25	0.70	b	0.23	21	0.57	ab	0.18	**0.003**
225	*ArableLandShareGreenCoverOutsideGrowingPeriod*	26	0.93	ab	0.11	20	0.94	a	0.22	21	0.88	b	0.20	**0.042**
229.1	*BiodivAreaShareOfFarmLand_Calc*	26	0.45		0.34	25	0.54		0.37	21	0.51		0.36	0.671
231	*NoUseSynthChemHerbicides*	26	0.75	ab	0.21	25	0.87	a	0.23	21	0.69	b	0.23	**0.012**
233	*NoUseSynthChemFungicides*	26	0.91		0.13	25	0.94		0.11	21	0.90		0.11	0.096
234	*NoUseSynthChemInsecticides*	26	0.98		0.06	25	0.98		0.07	21	0.98		0.05	0.552
237.1	*AgriculturalLandShareMulching*	26	0.01		0.03	20	0.00		0.01	21	0.00		0.01	0.856
253	*PermanentGrasslandsExtensivelyManaged*	26	0.12	a	0.21	25	0.43	b	0.39	21	0.07	a	0.08	**<0.001**
285	*HumusFormationCatchCrops*	26	0.24		0.20	20	0.24		0.21	21	0.30		0.20	0.182
289.1	*HumusFormationCropResidues*	26	0.01		0.03	20	0.02		0.03	21	0.04		0.17	0.838
290.1	*SoilAnalysisFertilizerRequirements*	26	0.42		0.17	25	0.41		0.20	21	0.37		0.13	0.527
323.1	*NFromFertilizers_Calc*	26	0.27	a	0.32	25	0.50	b	0.38	21	0.16	a	0.30	**0.002**
332	*ElectricityConsumption*	26	0.38	a	0.15	25	0.66	b	0.19	21	0.46	a	0.23	**<0.001**
370.5	*DailyOutdoorAccess*	26	0.08		0.27	25	0.12		0.33	21	0.10		0.30	0.875
371	*AccessToPasture*	26	0.43	a	0.38	25	0.63	b	0.45	21	0.18	c	0.33	**<0.001**
377.75	*PesticidesAcuteToxicityInhalation*	26	0.33	a	0.46	25	0.72	b	0.42	21	0.24	a	0.41	**<0.001**
380	*NutrientsPollutantsSourcesOnFarm*	26	0.08		0.27	25	0.12		0.33	21	0.00		0.00	0.281
517	*FeedNoFoodGrazingLivestock*	26	0.00	a	0.00	25	0.38	b	0.42	21	0.01	a	0.05	**<0.001**
521	*ProductionBioenergyCrops*	26	0.01		0.05	25	0.00		0.01	21	0.00		0.01	0.664
620	*PermanentGrasslandMowingFrequency*	26	0.40	a	0.20	25	0.06	b	0.17	21	0.31	a	0.25	**<0.001**
740	*GrowthRegulation*	26	0.42		0.50	20	0.70		0.47	21	0.33		0.48	0.051

* rating scale from 0 -1; 0 being the lowest rating and 1 the highest rating

Notes: The *p*-values for the impact of ruminant husbandry are given (using one-way ANOVA and Kruskal-Wallis test). Significant differences between treatment levels identified by the post-hoc pairwise comparison tests are indicated by different letters in column “Mean”.

2.2.6 Regression Analysis

Correlations were calculated between various characteristics of the farms (e.g. area of arable land and grassland, livestock units or livestock units per hectare) and the sustainability performance achieved. No strong correlations were found. Even after classifying the farms according to farm management type or the type of ruminant husbandry, the correlation analysis did not reveal any strong correlations (correlation coefficient $r > \pm 0.6$; results not shown).

Linear correlations between farm characteristics and the sub-themes of *Environmental Integrity* almost showed negative correlations: with increasing farm size, i.e. a larger area, regardless of whether it is arable land or permanent grassland, the sustainability performance for the environmental dimension decreases. This is the same for the number of livestock units: the more livestock units, the lower the sustainability performance. The highest linear correlations were calculated for farm size and *Water Quality* (r = -0.533; Figure 11) and *Species Diversity* (r= 0.504). Correlation between the number of livestock units on a farm and *Water Quality* (r =-0.517; Figure 11), *Ecosystem Diversity* (r = -0.553), *Species Diversity* (r = -0.550), *Genetic Diversity* (r = -0.596), *Material Use* (r = -0.514), and *Energy Use* (r = -0.532) exceeded the threshold of $r > \pm 0.5$, too. All other correlation coefficients were below the threshold.

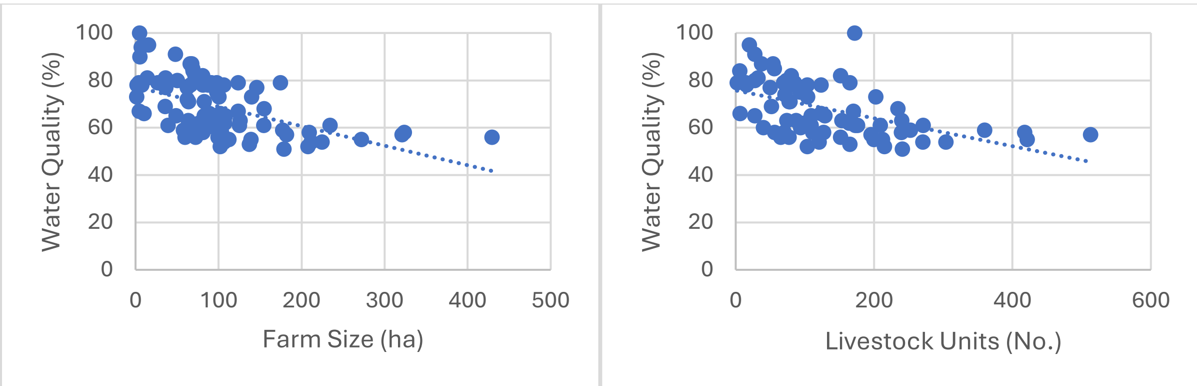

Figure 11: Farm size (ha; left) and number of livestock units (No.; right) and their influence on the goal achievement of the sub-theme Water Quality.

2.3 Discussion

The 87 farms that participated in the study represented 4.5 % of all agriculture holdings in Luxembourg in 2017. The agricultural land laboured by these 87 farms was on average split nearly equally between arable land and permanent grassland. These proportions were comparable to the overall share between arable land and permanent grassland of the whole agricultural land of Luxembourg (Ministère de l'Agriculture, de la Viticulture et du Développement rural, 2023). According to European Farm Typology classification (European Commission, 2014), ruminant husbandry was the most important husbandry type in Luxembourg (with 63.9 %) which was also the case in the study sample with 82.8 %. The slight overrepresentation of ruminant husbandry in the study sample also explained the overall larger average farm size of the sample (99.6 ha) compared to the average farms size of the whole Luxembourgish agricultural sector (67.5 ha) (Ministère de l'Agriculture, de la Viticulture et du Développement rural, 2023).. In terms of management, organic farms were overrepresented in the sample with 33.3 % compared to a share of 5 % organic agriculture in the whole of Luxembourg in 2017 (Ministère de l'Agriculture, de la Viticulture et du Développement rural, 2023). Furthermore, it needs to be noted, that due to the nature of the project and the formulation and framework of the call for participation, it can be expected that the sample was biased towards organic farms and farms that already operated more sustainably or had taken an interest in the topic of sustainability and the implementation of sustainable farming practices on their farm.

While the SMART-Farm Tool has been widely used on a global scale (see Bandanaa et al., 2021; Blockeel et al., 2023; Curran et al., 2020; Kamau et al., 2022; Ssebunya et al., 2019; Winter et al., 2020), there are only a few studies published where it was used in the European context (Curran et al., 2020; Landert et al., 2020). Results presented in Landert et al. (2020) showed from 30 to 80 % goal achievement (ranging from 20-100 %) for the median for *Environmental Integrity* across all case studies of French farms at different stages of transition towards agro-ecological agriculture, while Curran et al. (2020) reported results of 62 % (s.d. = 17 %) goal achievement (depending on farm type) for the dimensions *Good Governance,* 77 % (s.d. = 9.6 %) for *Environmental* Integrity, 70 % (s.d. = 7 %) for *Economic* Resilience and 87 % (s.d. = 6 %) for *Social Well*-being for Bio-Suisse organic farms in Switzerland. At sub-theme level, a moderate to good (50% - 80%) goal achievement for the sub-themes in the environmental dimension were observed in Hungary, where 25 organic and 25 conventional farms (with both animal husbandry and crop production) were analysed using the SMART-Farm Tool (Mészaros, 2017). The goal achievements in the study by Mészaros, (2017) were higher for organic farms for all sub-themes of all dimensions except for *Commodity Investment, Profitability* and *Liquidity,* even if these differences were not significant. The findings for *Profitability* and *Liquidity* showing slightly lower goal achievements for organic farms were also found in Luxembourg, with the difference in Profitability being significant.

In a study comparing organic and conventional wheat producers in France, the goal achievements for *Environmental Integrity* were also in the moderate to good category with significantly higher goal achievements for the organic farms compared to conventional farms except for the sub-themes *Greenhouse Gases, Material Use* and *Wastewater Withdrawal*. In terms of the sub-theme *Profitability*, conventional farms had slightly higher, but not significantly higher goal achievements (Epple, 2018). Thus, the results from the Luxembourgish farms were comparable to those in other European countries. While the Luxembourgish results were in the moderate to good goal achievement brackets, they still indicated a need for further improvement to meet the related sustainability goals. This is especially true when considering the overall overrepresentation of organic farms and the probable bias towards more sustainability affine farms in the sample.

Regarding to the Luxembourgish SMART-Farm results, there were only 4 themes with median goal achievements below 50%: *Corporate Ethics* (44 %), *Accountability* (37 %), *Holistic Management* (44 %) and *Local Economy* (45 %). The first three of this list were in the dimension of *Good Governance*. As was mentioned in Chapter 2.1.1, the SAFA-Guidelines also refer to companies in the food and agriculture sector, and the objectives of some of the themes are therefore only partly achievable or relevant to small- to medium-sized, family run farms (> 95 % in Luxembourg (Ministère de l'Agriculture, de la Viticulture et du Développement rural, 2023)). This applies especially to themes of the dimension *Good Governance*. Due to the informal, family run farming structures predominant in Luxembourg, the holdings often did not have an explicit sustainability plan, did not have any documentation, sustainability reports or written commitments to sustainability publicly available, and external environmental costs were not considered in the accounting of the farms. The below 50 % goal achievement in the theme *Local Economy* could be explained by a generally low number of jobs created, high weekly working hours and low number of apprenticeships offered. Furthermore, especially for organic farms, specific farming material is not always locally available and needs to be bought and imported from further than 150 km away.

Conventional farms showed significantly higher target achievement for *Profitability* in the *Economic Resilience* dimension compared to organic farms. The lower performance of organic farms in *Local Economy* is due to the unavailability of organic raw materials in Luxembourg or within a radius of 150 km. *Product quality and Information* are strongly influenced by the use of pesticides, antibiotics in animal husbandry, the sourcing of inputs from countries with known social problems and the lack of transparent communication of the production system to the consumer.

In terms of *Environmental Integrity*, the goal achievements of conventional farms are consistently lower, mainly due to the use of pesticides and mineral fertilisers. These results are consistent with previous studies (e.g. Reganold and Wachter, 2016; Roychowdhury, 2013; Sanders and Heß, 2019).

Looking at the results at indicator-level, it becomes apparent that part of the significant differences seen between organically and conventionally managed farms are closely related to the inherent differences between these two management systems. For example, some of the indicators for which a significant difference was observed can be connected to practices outlined in the European Regulation (EU) 2018/848 (European Parliament and Council, 2018) on organic production and labelling of organic products.

Many of the indicators showing significant differences for management system could be traced to the underlying concept of closed cycles and cyclical systems. Organically managed farms in the sample showed a lower share of concentrated feedstuff that was bought-in, i.e., they had higher fodder autarky. They also implemented more often than conventionally managed farms crop rotations with a higher share of legumes and a higher share of field fodder on their arable land, and they ensured a higher share of arable land with green cover outside the growing period. Many of the hereabove mentioned indicators for which organic farms achieved a significantly higher indicator rating are related to farming practices that are also easily implementable on conventional farms (e.g., increased share of legumes in the cropping system), meaning that conventionally managed farms do not inherently perform worse compared to organic farms. The likely reason why they are already more widely adopted on organic farms has probably to do with the need to close farm circles to preserve and increase soil fertility, as the use of outside inputs such as mineral fertilizers are not an option.

An urgent cycle that needs closing is the nutrient cycle on the farm, with a focus on nitrogen and phosphorous. Farms have many options to influence and close especially the N-cycle. Reduction in the use of mineral fertilizers, increasing the share of legumes in the crop rotation (grain legumes, clover-grass leys, clover share in permanent grassland communities), and increasing the share of temporary grasslands in the form of clover-grass leys (De Notaris et al., 2021; Mahmud et al., 2021). These practices help increase the overall fodder autarky of the farm, and, introduce atmospheric nitrogen through biotic nitrogen fixation into the farming system, increasing soil fertility and reducing the need for other N-fertilizer sources from outside the farming system (Peoples et al., 2009). Closing the nutrient cycle from converting grass leys to grass-legume mixtures can also reduce carbon losses and increase carbon sequestration in the farming system (Soussana et al., 2010).

To close the nutrient cycle, a reduced and more efficient nutrient input is needed as well as the prevention of nutrient losses from the system. The latter involves a higher implementation of practices such as cover crops and reduced tillage and increasing the share of arable land with green cover outside the growing period. The former involves a reduction in the nutrient surpluses and improving the fertilization plans on each farm (Mahmud et al., 2021). The indicator analysis showed that farms only relied in part on soil analysis information for their fertilization plans. Most farms only took soil samples every 5 years for basic analysis (pH, phosphor, potassium, magnesium, and sodium) that are required in the framework of the landscape conservation payments and are used for basic nutrient fertilisation plans. N fertilisation, in contrast, is governed by the national nitrogen regulation (Règlement grand-ducal du 28 février 2014 concernant l'utilisation de fertilisants azotés dans l'agriculture) (Gouvernement du Grand-Duché de Luxembourg, 2014) based on the European nitrate directive (European Council, 1991) and is based mainly on theoretical data (e.g., theoretical values for crop N-needs based on site and crop specific yield expectations and theoretical values for subsequent nutrient release dynamics from crop residues, the applied organic fertilizers and the soil).

A large issue in the SMART-Farm assessments was the feeding of sources of concentrated energy (e.g., cereals and maize silage), which then needed to be balanced out by concentrated protein sources (e.g., soybean meal from overseas) (Zimmer et al., 2021; Resare Sablin et al., 2022). A better valorisation of the permanent grasslands, which constitutes approx. 50 % of the agricultural area in Luxembourg, could already significantly decrease the need for concentrate feedstuff in ruminant feeding rations (Zimmer et al., 2021). This would also require the adjustment of the yields of the animals in terms of milk and meat, and thus also the market demand for e.g. fattening animals from grassland-based fattening.

Some practices that are beneficial for environmental protection were only implemented by a few farmers and on low shares of land, no matter the management system, such as reduced tillage/no till practices, direct seeding practices, the use of undersown crops and agroforestry systems (Łuczka and Kalinowski, 2020; Rosário et al., 2022). These practices can be difficult to implement consequently across the whole crop rotation and farm management. While reduced tillage or direct seeding methods are often used before maize is sown on conventionally managed farms in Luxembourg, both methods, however, are very difficult to implement for other crops and/or on organically managed farms due to weed control issues (Almoussawi et al., 2020). More research in direct collaboration with farmers is needed on how to put these methods into practise across cropping elements and management systems.

For the correlation analysis, it was expected that the goal achievements in the *Environmental Integrity* dimension would improve with a lower livestock density. The reduction of methane and nitrous oxide emissions with a lower livestock density has been described by Gerber and Food and Agriculture Organization of the United Nations (2013) and Röös et al. (2017). Regarding to *Air quality* ($r = -0.441$) and *Greenhouse Gases* ($r = -0.351$) slight negative correlations were found, supporting the positive effect of a lower number of livestock on the sustainability performance of the farms. The correlation between livestock units and the sub-theme water quality achieved an r of -0.517, meaning that an improvement in water quality can be expected with decreasing livestock density. Teague et al. (2016) described that biodiversity is promoted through lower livestock numbers due to diversification of land use. This positive effect of reduced livestock on biodiversity was also found in the SMART-Farm results with a correlation of $r = -0.553$ for *Ecosystem Diversity* and $r = -0.550$ for *Species Diversity.*

The sustainability assessment using the SMART-Farm tool was useful to gather first insights into the sustainability performance of Luxembourgish farms and identify strengths and weaknesses in the different sustainability dimensions. The results provide starting points on how to increase the sustainability performance at farm-level. Holistic strategies that can be deduced from the results are:

- Closing of farm (nutrient) cycles: reduction in the use of mineral fertilizers, increase in legumes in the crop rotations, higher share of legume-grass leys in the crop rotations, higher share of catch crops and undersown crops, higher fodder autarky
- Reduction in feeding concentrate feedstuff, especially in ruminant husbandry, thus inherently also reducing the number of animals that can be kept.
- Organic agriculture: organic agriculture, as was seen in the results, already inherently implements at a higher rate many of the practices above; thus, encouraging and promoting organic agriculture can intrinsically promote the implementation of these sustainable farming practices.

These results and strategies were further used in the following food system analysis using the SOL (sustainable and organic livestock) model and influenced the future scenarios analysed.

3 Food System-level Sustainability Assessment:

3.1 Material and Methods

3.1.1 General model description

The SOL model (Sustainable and Organic Livestock model, SOLm) is a bottom-up mass flow model that depicts agricultural production and the food sector. It is suitable for capturing all agronomic and mass and nutrient flow related aspects of drastic changes in agriculture and food systems. SOLm maps all mass and nutrient flows in agricultural production that are relevant for the calculation of resource consumption and emissions. SOLm provides detailed results on production patterns and a range of environmental and some socio-economic impacts (Figure 12) (Muller et al., 2020, 2017).

The model is based on FAOSTAT data, in particular the food balance sheets, and covers all countries and geographical areas as well as the commodities covered by FAOSTAT. In addition, it is consistent with national greenhouse gas inventories and N and P balances (Administration de l'Environnement, 2024). In total, SOLm covers 192 countries, 180 primary crop activities and 22 primary animal activities as defined in FAOSTAT. It is based on FAOSTAT commodity tree data covering around 700 intermediate products (Frehner et al., 2022). Only the most important aspects and general features of SOLm are presented below; a detailed description can be found in (Muller et al. (2020, 2017) and Schader et al. (2015).

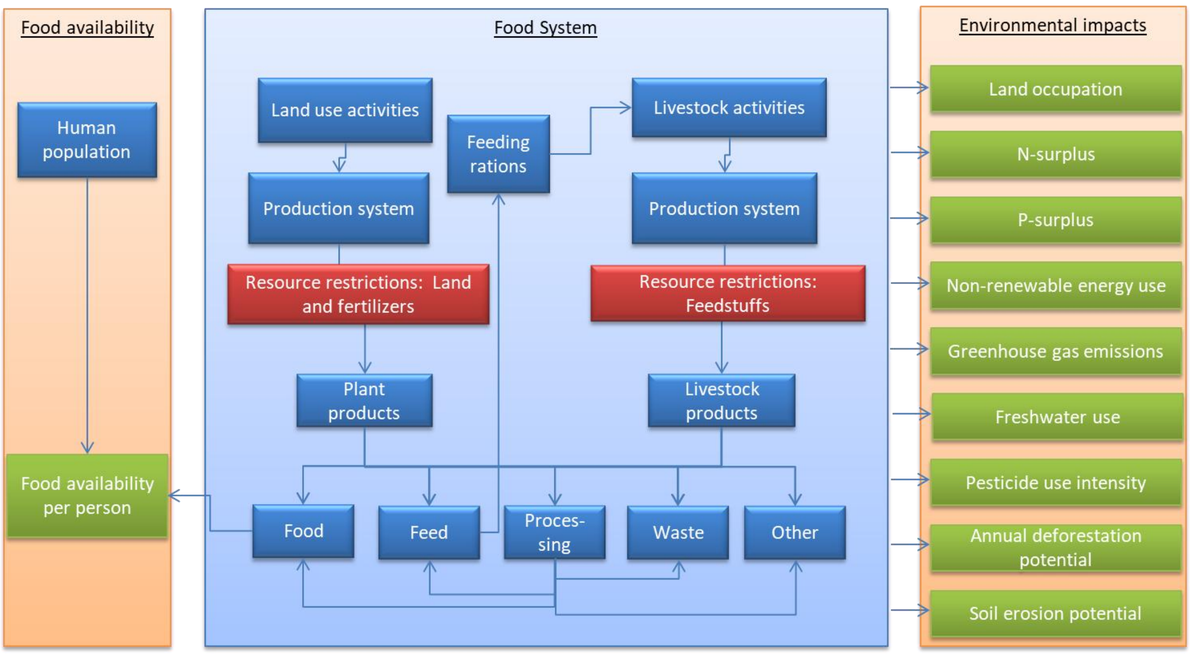

Figure 12: Structure of the food system in the Sustainable and Organic Livestock model (SOLm) (Muller et al., 2017).

Each plant and animal activity in SOLm is characterized by a set of inputs and outputs, i.e. all physical quantity and nutrient flows associated with each activity. For plant activities, the following inputs are included: Land area (differentiated by cropland and grassland), mineral and organic fertilizers (manure, crop residues), nitrogen fixation, pesticides, management practices and processing. Yields include crop yields (main products and by-products) and residues as well as N and P losses. Greenhouse gas emissions from crop production include emissions during production, processing, and transportation (Frehner et al., 2022; Muller et al., 2017).

For livestock farming, the inputs of feed and energy consumption for stables and fences were included. Inputs for livestock farming are animal feed, energy for buildings, processes in stables (cleaning, feeding) and fences. Outputs include products edible for humans (meat, milk, eggs) and products inedible for humans (hides, skins, bones, etc.), manure excretion, nutrient losses (N and P) and greenhouse gas (CO_2, CH_4, N_2O) as well as nitric oxides (NOx) and ammonia (NH_3) emissions (enteric fermentation, manure management) (Muller et al., 2017).

Feedstuffs are divided into four categories: (a) fodder crops grown on arable land, (b) concentrates from food edible for humans (e.g. cereals, legumes) grown on arable land, (c) grassland fodder and (d) fodder from agricultural/agro-industrial by-products. Feed grown on arable land (a and b) competes with food production (referred to as "feed competing with food"), while grassland feed and by-products do not compete (c and d) (Muller et al., 2017).

The country-specific herd structures are calculated for cattle, pigs and chickens. This is used to derive the most likely distribution of age classes within the reported number of live and producing animals and the reported import and export numbers of live animals and allows a more detailed assessment of feed and other input requirements and environmental impacts (Muller et al., 2017).

SOLm captures biomass and nutrient fluxes to assess the physical feasibility of different scenarios. Each animal and plant activity are associated with a range of environmental impacts (land use, N and P surplus, non-renewable energy use, greenhouse gas emissions, water use, pesticide use, deforestation, soil erosion). It does not take into account economic constraints and market effects that relate quantity changes to price changes. Economics are central to the social viability of these scenarios, but their inclusion would come at the expense of detailed differentiation by commodity and country and would require many additional assumptions about price and cross-price elasticities (Muller et al., 2017).

3.1.2 Data Sources and adaptations for Luxembourg

The model is based on FAOSTAT data, in particular the food balance sheets, and covers all countries and geographical areas as well as the commodities covered by FAOSTAT. Data from 2016 to 2020 has been used to set up the model. To adapt the model to Luxembourg, some changes had to be made. Some assumptions, some of them global, had to be adjusted for Luxembourg to correspond to the emissions reported in the GHG inventory report that was used to calibrate the model. In general Luxembourg specific data in FAOSTAT was cross-checked with nationally available data to see if more specific data was available. In most cases, the data in FAOSTAT corresponded with the national data (as was expected as national data is reported to FAOSTAT). Thus, for example, agricultural land area data (and share cropland/grassland) used in the model from FAOSTAT corresponds to the data reported in the national statistics on agriculture (e.g. in MAVDR, 2022).

Considering the focus on Luxembourg in this study, we used the Luxembourgish National Inventory Report (Administration de l’Environnement, 2024), which is based on data up to 2020, to adjust the model to Luxembourg. Moreover, the Rapport d’Activité (Ministère de l’Agriculture, de la Viticulture et du Développement rural, 2023) was used to implement the animal numbers and herd structure to SOLm. This data was the basis to estimate together with Marita Hoffmann from Lycée Technique Agricole the herd structure in Luxembourg and to adapt it to the given categories in SOLm. Feeding ratios of different food groups were adapted according to Zimmer et al. (2021), and to the results from the SMART assessments.

In addition, the following adjustments were made:

- Quantity shares on what is done with crop residues, based on data from SMART assessments.
- Irrigation was adjusted to meet national regulations, as it is only allowed in vegetable production. Irrigation amounts were adjusted according to irrigation practices recorded during the SMART assessments.

- 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.

After having made these adaptations for Luxembourg, the baseline scenario for 2016-2020 was finished and several scenarios for 2050 were calculated.

3.1.3 Scenario description

Besides the baseline and reference scenario, a set of other scenarios comprising the reduction of food waste, the transition to 100 % organic agriculture and the maxim of "feed no food" were developed. The following description was taken from Muller et al. (2017)and information on the Luxembourg scenarios was added.

(i) A baseline scenario ('base year') based on data for 2016 to 2020 as provided by FAOSTAT, additional data from Luxembourg as explained in Chapter 3.1.2 and on the results from the farm-level sustainability assessment using the SMART-Farm Tool (Chapter 2) and herein identified current farming practices in regard to crop production (fertilization, crop protection, crop rotation, etc.) and animal husbandry (productivity, feed, etc.) was adapted in SOLm.

(ii) Afterwards, a reference scenario for the Luxembourgish food system for 2050 based on "business as usual (BAU)" was extrapolated, serving as a reference for comparison with other future scenarios. The reference scenario is also based on the FAO BAU-scenario as described in Alexandratos and Bruinsma (2012) and Muller et al., (2017). This scenario was concretized by projections for Luxembourg such as from ECO2050 Vision by Ministère de l'Economie (2023) and Fondation IDEA (2023). It was assumed that Luxembourg will have 1,000,000 inhabitants in 2050. A projection on land-use change was made, using data from Service d'Economie Rurale (2023) and (Statec, 2023), assuming a slight decline by 2050 of the agricultural area from 132,850 ha to 127,142 ha, with 51.4 % being 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 a 10 % yield gap and slight differences in the feeding rations (based on Zimmer et al., 2019; as described above). There were more differences implemented for crop production: no use of synthetic-chemical pesticides, no use of mineral fertilizers, 20 % share of legumes in crop rotation and a conservative yield gap of 25 % were implemented. 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 only little to no role in Luxembourgish organic crop rotations.

(iv) For the scenario 'reduction of food waste', the existing food waste was incrementally reduced by 25 % and 50 % with respect to the regional and commodity group specific values from FAO ((FAO, 2013); the latter value of 50% being among the Sustainable Development Goals for 2030). In other words, the wastage share for each commodity is reduced by 25% or 50% respectively. In the model, this resulted in a corresponding quantity of each commodity not being produced, thus leading to reduced input demand and impacts. Data for food waste in Luxembourg was obtained from Administration de l'Environnement (2023).

(v) For the scenario 'feed no food', the feeding of food-competing feedstuff is reduced progressively by 50 % and 100 % to maximise the production of food directly for human consumption. The 100% reduction assumes entirely grass-fed ruminant production, and monogastric animals fed only on by-products from food production (Muller et al., 2017).

The future scenarios investigated in SOLm took the reference scenario as a starting point and made additional assumptions on specific parts of interest (described in Muller et al., 2017). All future scenarios kept the same area of cropland and grassland as the reference scenario. Patterns for the different commodities in the future scenarios remained as close as possible to the patterns observed in the reference scenario (i.e. relative shares between commodity groups and between commodities within these groups). Changes in some of these patterns were, however, unavoidable in several scenarios; for example, if the share of legumes increased and the animal product shares decreased. However, while meat consumption dropped in one scenario, the relative share of chicken to pork was retained on country level, just as the relative shares of different legumes was retained on country levels when the total legume shares increased (Muller et al., 2017).

SOLm then derived the inputs, outputs and environmental impacts for all crop and livestock activities, given these additional assumptions. For all scenarios, food availability (expressed as calorie, fat and protein supply per capita per day.), land occupation, animal numbers and a range of environmental impacts such as N-surplus (i.e. the net difference between N in-flows and out-flows) and its various constituents, and GHG emissions were calculated. All scenarios were then assessed in comparison to the reference scenario.

The scenarios were calculated in two modes each, one with normal trade patterns in place (as present in the reference scenario: as SOLm has 192 countries defined and implemented, normal trade patterns between countries based on FAOSTAT data has also been implemented in the model), only adjusted in consistency with the scenario assumptions (e.g. reducing concentrate feed imports for the scenarios with reduced concentrate feed use), the other with international trade switched off. In the calculations without trade, only the import of production-relevant resources was permitted (mineral fertilisers, pesticides, electricity, fuels), whereas the import of feedstuff and food was artificially switched off, thus providing unbiased results on the production potential of the Luxembourgish agricultural areas. In the scenarios without trade, it was assumed that ruminants were raised mainly 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 in the base year on their 'normal' feeding rations while simultaneously using the full grassland area. The alternative would have been to reduce the area of grasslands in use down to a level consistent with the available remaining concentrate feed in line with the previous feeding rations. However, it was decided to focus on the production potential from the available areas, that allowed to keep all grasslands in production.

After having set-up the baseline scenario for 2020, the scenarios were calculated without trade, as the agronomic, and biophysical performance was of main interest to be able to make statements about nutrient flows and availability and effects on the environment in Luxembourg. These were the basis to develop ideas on how to meet future challenges of the agricultural and food system. This was an important step, as in the scenarios with trade, many of the changes in the future scenarios were offset by more international imports, e.g., reduced production of food competing feedstuff in Luxembourg was offset by higher imports of concentrate feedstuff.

3.2 Results

The results from the food systems calculations are presented below in the form of spider diagrams (Figures 13 - 17). In these spider diagrams, the impact of the different scenarios and their option spaces are shown based on a selection of 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 give insight into the animal production potential, the potential of food sovereignty for Luxembourg and the potential of greenhouse gas and nutrient emission reductions. In each spider 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 were than compared as differences in percentages to the results from the BAU- with trade scenario. For the other future scenarios, the results without trade are displayed to present the consequences of the various scenarios on the national production potential without bias. The full detail of the results is given in the form of tables in Appendix A.3.

Figure 13 displays results of the BAU scenarios with and without trade. As mentioned in Chapter 3.1.3, all exports and imports, except for mineral fertilizer, pesticides and fuel, were artificially switched off, and the ruminants were switched to a grass-fed feeding ration because of reduced concentrate feed availability and to fully exploit the permanent grassland areas. As a result, the number of ruminants decreased drastically from 186442 with trade to 116373 without trade. The number of pigs and chicken, on the other hand, significantly increased 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, fertilizer application (due to reduced manure production) and ammonia emissions. Finally, the BAU without trade scenario showed a stark reduction in food sovereignty by a reduced availability of calories (from 1729 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. This was largely due to the reduction in number of cattle and the inherent reduction in animal products. Just looking at the calories, this means a drop from 73 % self-sufficiency to 32 % self-sufficiency (Appendix A.3).

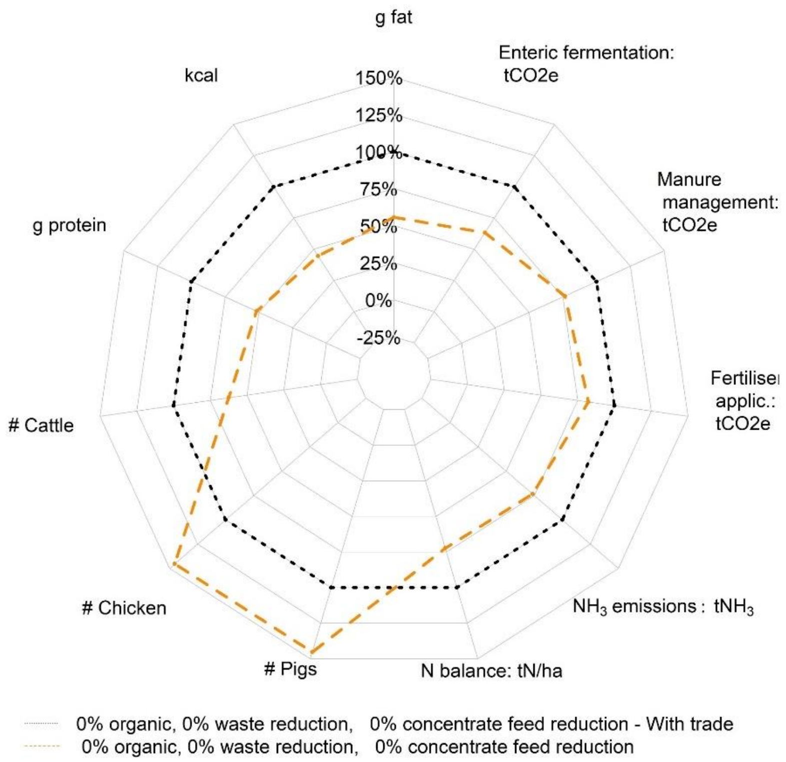

Figure 13: Impact of trade and no trade on the results of the reference scenario 'Business as Usual' (BAU). The dotted black line at 100 % is the BAU situation 2050 with trade. The orange dashed line is the same as the reference scenario, just without trade. Without trade means that except for mineral 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.

Looking at the effect of progressively increasing the share of organic agriculture, the results showed that, 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 **14**). 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 crop rotations assumed in these simulations had less oil crops (mainly less rapeseed) in the crop rotations than in the conventional production systems. In addition, the animal source products with higher shares of fat in relation to calories dropped as well, due to lower animal numbers with increasing organic shares (also because of reduced feed production). The drop 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 were assumed in the organic crop rotations. In terms of food sovereignty, 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 (116 373 at 0 % organic to 93 099 at 100 % organic agriculture) than the number of pigs (114 828 at 0 % organic to 82399 at 100 % organic agriculture) and the number of chicken (178 417 at 0 % organic to 128 029 at 100 % organic agriculture). This was in part due to the fact, that ruminants were by default already grass-fed in the scenarios without trade.

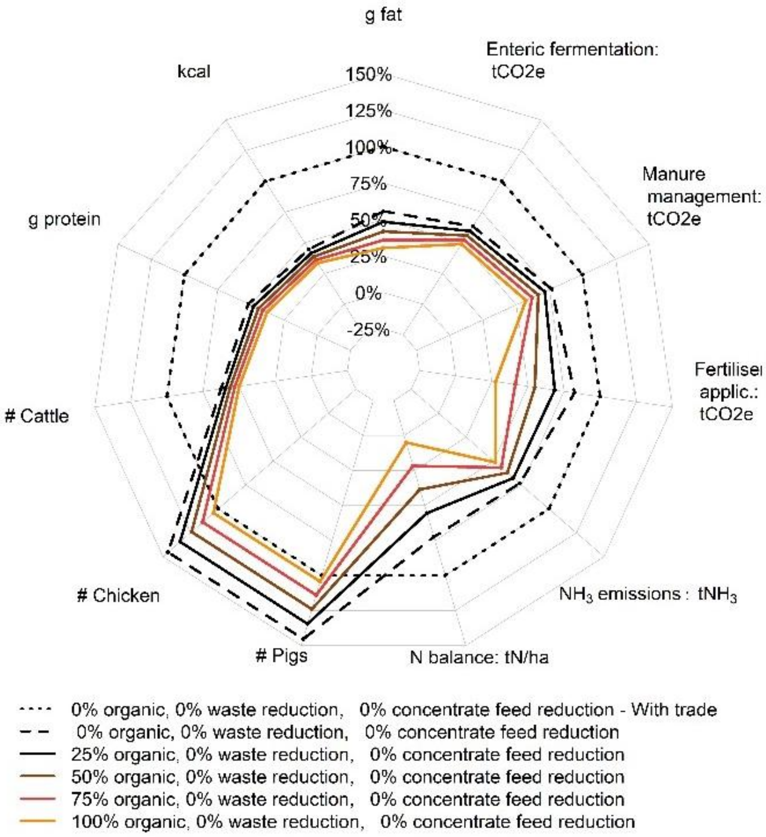

Figure 14: Impacts of an increasing share of organic agriculture. Reference scenario (dotted black line at 100%) is the BAU situation 2050, with trade. The other scenarios are without trade; indicator values given relative to the BAU with trade scenario. Scenarios with 0 % (left), 50% (middle) and 100% (right) food-competing feed reduction, further differentiated by increasing shares of organic production from 0 % to 100%, in steps of 25% steps (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 (cf. above).

Looking at the environmental parameters the reduction in animal numbers with increasing share of organic agriculture did only weakly impact environmental emissions, e.g., emissions from enteric fermentations only dropped slightly as the number of cattle was only marginally reduced (from 248618 tCO_{2eq} at 0 % organic agriculture to 191472 tCO_{2eq} at 100 % organic agriculture). The most significant impact had the reduction in mineral fertilizer application. At 100 % organic agriculture, mineral fertilizer use was naturally reduced to 0 significantly decreasing emissions related to fertilizer application (from 124985 tCO_{2eq} at 0 % organic agriculture to 42026 tCO_{2eq} at 100 % organic agriculture). Ammonia emissions were also significantly lower with increasing share of organic agriculture with a near 30 % reduction when comparing emissions at 100 % organic agriculture to those at 0 % organic agriculture. The nitrogen balance also improved upon with increasing share of organic agriculture. However, at 100 % organic agriculture, the calculated N balance was 0.008 t N/ha. This highlighted a central challenge with increasing the share of organic agriculture, as the possibility exists to drop into a potential nitrogen deficit, risking yield stability. Additional complementary measures would be needed, such as further increase of legumes in crop rotations, e.g. in off-season crops, cover crops and inter crops, or a focus on nutrient recycling, e.g. from municipal organic waste and from sewage plants to maintain soil fertility.

Figure 15 shows the results for scenarios with = %, 50 % and 100 % concentrate feed reduction (FnF) per panel, further differentiated by the increase in the share of organic agriculture (Org) (from 0 % to 100 % in 25 %-steps), while Figure 16 shows the results for scenarios with 0 %, 50 % and 100 % share of organic agriculture per panel, further differentiated by concentrate feed reduction from 0 to 100 %, in steps of 50 %. When the use of concentrate feed was progressively reduced the number of pigs and chickens that could be raised was drastically reduced (chickens: from 178417 in the BAU without trade scenario to 14942 in the 100 % Feed no Food scenario; pigs: from 114828 to 9617 at 100 % concentrate feed reduction). 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 manure management and ammonia emissions (Figure 16, left panel). Interestingly, a 100 % reduction in concentrate feed use resulted in an increase in caloric self-sufficiency (from 32 % to 40 % at 100% FnF). The freed-up area, that was previously used to produce fodder was now used to produce crops for direct human consumption. While the model showed that protein supply could be guaranteed from protein plants (an increase from 34 g of protein/capita/day at 0 % FnF to 45 g/capita/day at 100 % FnF), the results showed that fat supply would significantly decrease by nearly 50 %. Combining Feed no Food with increasing shares of organic agriculture (Figure 16, middle and right panel), it can be observed that with increasing share of organic agriculture, the number of animals that can be kept decreases further and in turn decreasing environmental emissions further, while the food sovereignty parameters are only marginally further impacted. What was notably, however, was the decrease in the N balance. At 100 % FnF and 100 % organic agriculture, the balance became negative (-0.019 tN/ha). Thus, further adjustments in the crop rotations would be needed to maintain soil fertility.

Figure 17 displays in each panel the impact of an increase in the food waste reduction (0 %, 25 % and 50 %), differentiated in each panel by an increasing share of organic agriculture from 0 % to 100 %. Looking at Figure 17, a reduction in food waste did not impact any of the emission parameters, as the full production potential was still exploited from the system. However, the reduction in food waste did impact the food sovereignty parameters with higher levels of calories, protein and far being available 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 seen 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 the GHG emissions from the various sources (see Appendix A.3.: FertilizerLandApplicaton_tCO2e, ManureManagement_tCO2e and EntericFermenation_tCO2e) showed that with the most restricting option space of the scenarios modelled here (100 % Org, 50 % WRed and 100 % FnF), reductions of total GHG emissions by 60 % compared to the reference scenario 2050 with trade were possible, from 632 kt CO_{2eq} to 261 kt CO_{2eq}. The still drastic but less extreme changes of a shift to 50 % Org, 50 % WRed and 50 % FnF still would allow for nearly halving the GHG emissions from the BAU with trade scenario to 346 kt CO_{2eq} (a 45 % reduction).

As seen above, implementing the different scenarios to different extents can significantly improve the different environmental parameters. To be able to know which option might be the best for the Luxembourgish food system, it is important to have clearly defined aims. To this purpose, it was also looked at the 3 most relevant political goals and explored how they might be achieved:

- Main aim - reduction in greenhouse gas emissions. A 50 % or more reduction in greenhouse gas emissions in comparison to the BAU with trade scenario (632 kt CO_{2eq}) was possible under different combinations of the modelled scenarios: 100 % organic agriculture reduced greenhouse gas emissions to 284 kt CO_{2eq} (a 55 % reduction), 75 % organic agriculture combined with 50 % Feed no Food reduced them to 309 kt CO_{2eq} (a 51 % reduction), and 75 % organic agriculture in combination with 50 % reduction in food waste achieved a 49 % reduction (down to 322 kt CO_{2eq}). To achieve these results, the number of cattle would need to be reduced by 48 % in comparison to the 2020 baseline scenario, food sovereignty would be reduced by 69 %, and the ammonia emissions and N balance would be reduced by 45 % and 74 %, respectively.
- Main aim – reduction of ammonia emissions. Again, a 50 % reduction was possible using various combinations of the scenarios: 100 % organic agriculture in combination with 25 % food waste reduction achieved a 49 % reduction (from 4645 t NH_3 in the BAU with trade to 2386 t NH_3); 75 % organic agriculture and 50 % Feed no Food also achieved 49 % reduction (2366 t NH_3); and 50 % organic agriculture combined with 50 % food waste reduction and 100 % Feed no Food achieved 50 % reduction (2299 t NH_3). The number of cattle in comparison to the baseline scenario would need to again be drastically reduced by 45 %. Food sovereignty would decrease by 66 %, greenhouse gas emissions and N balance would also decrease by 46 % and 69 %, respectively.
- Main aim - maintaining and increasing food sovereignty. At 50 % food waste reduction with 50 % feed no food, and at 25 % organic agriculture with 50 % food waste reduction and 100 % Feed no Food, a 42 % caloric self-sufficiency was achieved even with a population increase to 1 000 000 inhabitants. Cattle numbers would need to be reduced by 39 % in comparison to the baseline scenario, while greenhouse gas emissions and ammonia emissions could still be reduced by 34 % and 36 %, respectively. The N balance would be reduced the least, by only 18 % in comparison to the 2020 baseline scenario.

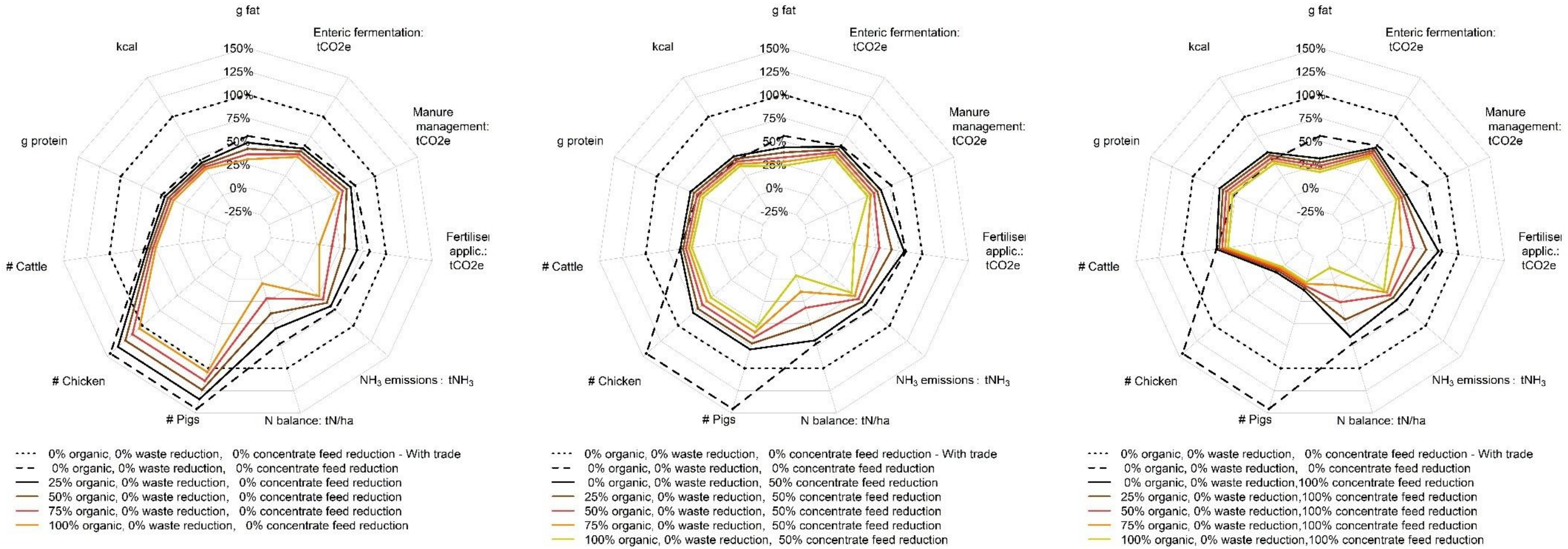

Figure 15: Impacts of organic agriculture at different shares of concentrate feed reduction. Reference scenario (dotted black line at 100%) is the BAU situation 2050, with trade. The other scenarios are without trade; indicator values given relative to the BAU with trade scenario. Scenarios with 0 % (left), 50% (middle) and 100% (right) food-competing feed reduction, further differentiated by increasing shares of organic production from 0 % to 100%, in steps of 25% steps (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 (cf. above).

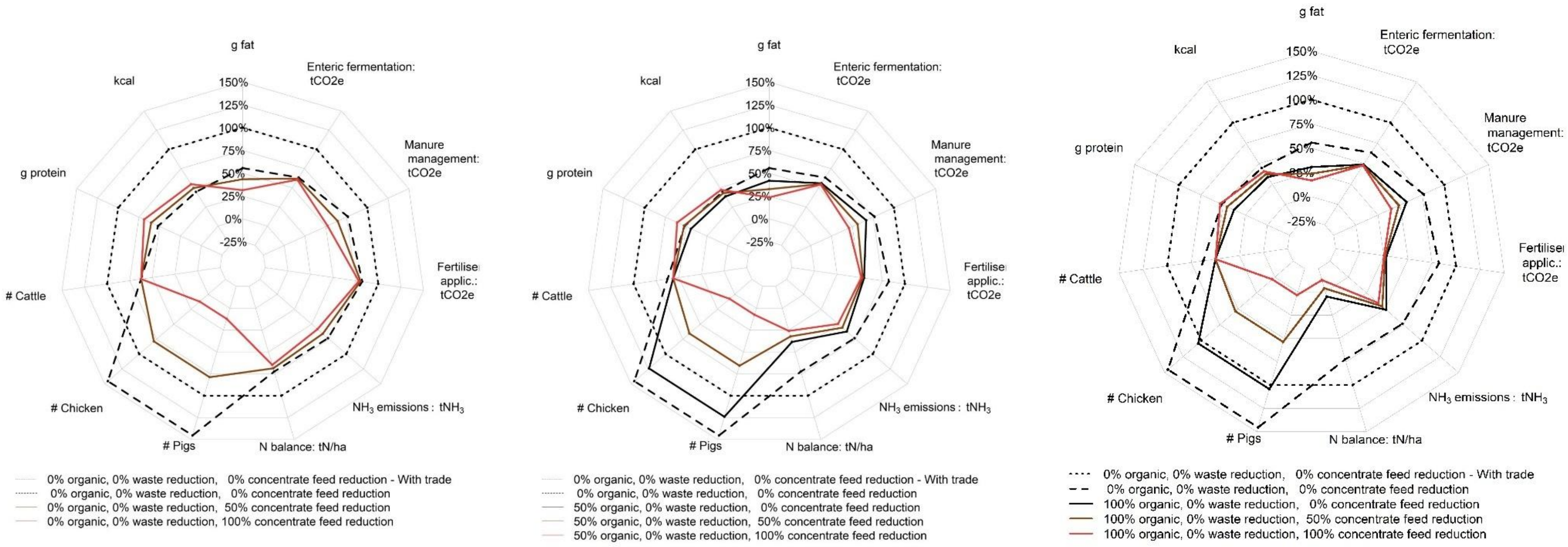

Figure 16: Impacts of Feed no Food at different shares of organic agriculture. Reference scenario (dotted black line at 100 %) is the BAU situation 2050, with trade. The other scenarios are without trade; indicator values given relative to the BAU with trade scenario. Scenarios with 0 % (left), 50 % (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.

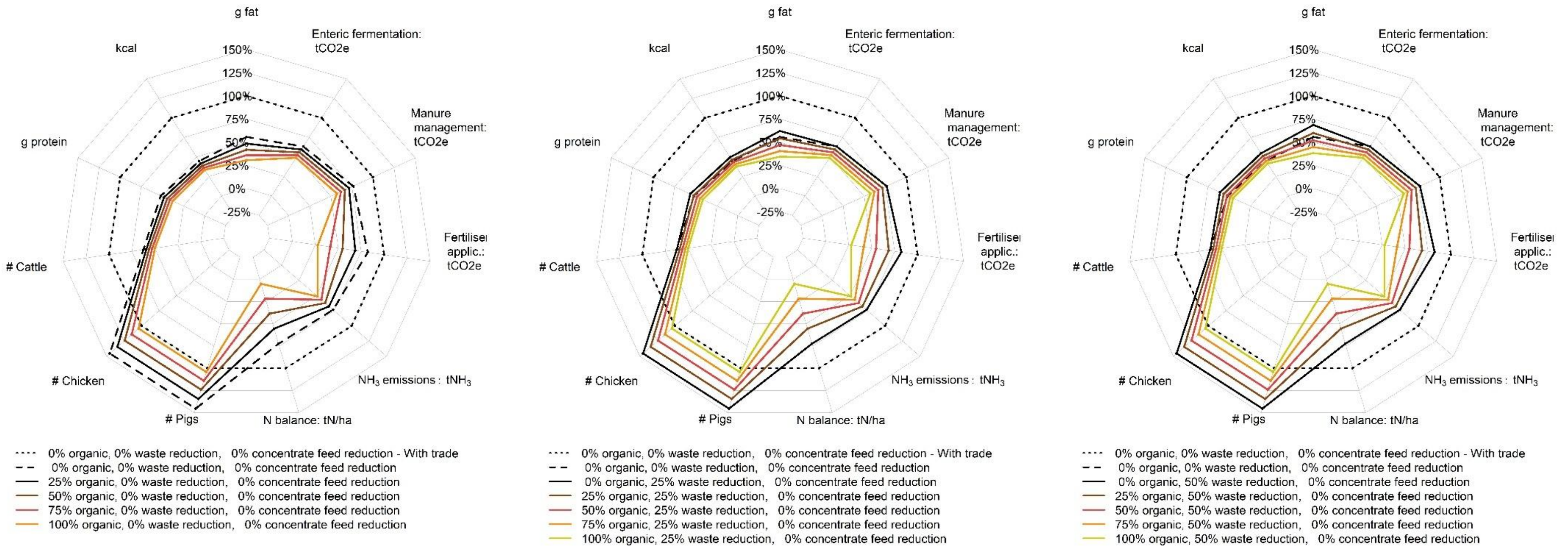

Figure 17: The effect of food waste reduction at different shares of organic agriculture. Reference scenario (dotted black line at 100 %) is the BAU situation 2050, with trade. The other scenarios are without trade; indicator values given relative to the BAU with trade scenario. Scenarios with 0 % (left), 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.

3.3 Discussion

The modelling results provided an option space on how to improve the sustainability of the Luxembourgish food system. They showed that reduction of food waste, organic agriculture and reduction of feeding food-competing feedstuff, with corresponding reduction in animal numbers, can be important levers to significantly decrease various environmental emissions. Thus, a more sustainable management of Luxembourg's agricultural land, with a high proportion of organic farming, would be possible under certain conditions, such as maximising products for human consumption by avoiding food-competing feed production, as well as reducing food waste, and would simultaneously have a positive impact on the environment. The drop in food supply with increased organic 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. This did not fully apply to fats, which strongly reacted to animal numbers and animal source food, if not compensated by specific strategies to increase oil crops in organic rotations. Reducing food-competing feed use had strong impacts particularly on the number of monogastric animals and less so on ruminants, that were already to a large part grass-fed in the scenarios without trade. Nevertheless, the shares of food competing feeds in feeding rations were still relatively high, e.g. for dairy cows, thus also resulting in significant reductions of ruminant numbers when going from the current situation to one with entirely grass-fed ruminants, assuming a constant grass and pasture-based feeding-basis for those. It must be emphasized again that this is not visible in the scenarios without trade, as in those, ruminants were fed without food-competing feedstuff by default as stated above. However, the reduction of food waste would be the most direct action to mitigate the food supply reduction related to increased organic production, cf. Figure 17. To put the results in perspective; currently, only ca. 25 % of the arable land in Luxembourg is used for direct food production, whereas 74 % is used for feed and energy plants (Ministère de l'Agriculture, de la Viticulture et du Développement rural, 2023) and 92,580 t of food waste was produced in 2021, thereof 57,250 t at household level (Administration de l'Environnement, 2023).

Overall, the number of cattle in Luxembourg has fallen from 205,072 in 2000 to 185,105 animals in recent years, while the number of animals slaughtered has remained stable compared to 2000 (24,836 animals; 2021: 28,953 animals), and meat production has remained stable in recent years, totalling 14,644 t of beef in 2021 (Ministère de l'Agriculture, de la Viticulture et du Développement rural, 2023). In recent years, there has been an opposing trend for dairy production: milk yield per cow per year increased from 5441 l in 2000 to 8170 l in 2022 (Ministère de l'Agriculture, de la Viticulture et du Développement rural, 2023). This corresponds to a growth rate of 150 %. The number of dairy cows rose from 43,346 animals in 2000 to 54,971 animals in 2022, while the milk volume increased disproportionately from 264,000 t to 449,000 t in 2022. The associated emissions from milk production have not fallen, even though the emissions per litre of milk have decreased. The study results showed that grassland-based feeding of both meat producing and milk 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 during SMART assessments). For some farmers, the reduction of livestock and change of breed is also only possible to a limited extent due to previous investments (e.g. construction of large-scale new stables).

The scenarios without trade showed the potential of Luxembourg to feed its own population, even with a growing population. This was based on the caloric self-sufficiency calculations. It was assumed that the average adult needs 2350 kilocalories per day. The model then calculated how much of this daily caloric need could be covered from domestic production. The results highlighted the strong dependence of Luxembourg on imports and showed that this dependence will continue till 2050, especially with the estimated population increase to 1 000 000 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 of Luxembourg 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 improve 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 other measures such as 'feed no food' and reduction in food waste are potential pathways towards a more sustainable food system with lower environmental emissions while simultaneously maintaining or increasing food supply. It must be emphasized, though, that the self-sufficiency results of the study at hand did not account for dietary quality (covering all required nutrients), as it was only based on food energy supply. The results presented above did also not look at 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.,136.9 % self-sufficiency for total fresh dairy products in 2022 (Service d'Economy Rural, 2024), while fruit and vegetable self-sufficiency is generally well below 100 % (in 2022: 92.2 % soft wheat, 88.1 % barley; in 2021: 48.5 % potatoes; in 2018: 17.2 % apples, 0.6 % strawberries, 15.6 % lettuce, 10.5 % carrots, 0.1 % tomatoes (Service d'Economy Rural, 2024)).

While such an optimisation was outside the scope if this study, it is of value to look at in further studies. How can the crop rotations be adapted to meet dietary nutrient and calory requirements while simultaneously improving environmental emissions? Are there different crops and thus crop rotations better suited for different regions in Luxembourg regarding pedo-climatic conditions? The latter question needs to be considered especially before the background of climate change: what new crops can be cultivated in Luxembourg with expected rising temperatures and periods of strong rainfall and drought events (as were already observed in recent years (Alharbi and Adhikari, 2020))? The expected influence of climate change up to 2050 is integrated into the model and the expected yield reduction falls above a "default value" implemented in the model. The yield development up to 2050 is still unclear and a fertilisation effect due to rising CO_{2eq} concentrations in the atmosphere cannot be ruled out (Deryng et al., 2014; Rezaei et al., 2023).

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. 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. 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.

Overall, the aim of the scenarios without trade was to determine the production potential and efficiency of Luxembourg's agricultural system based on its natural physical resources. As Luxembourg is and will continue to be highly dependent on food imports, especially with a growing population, the question arises as to what extent Luxembourg's food system should be examined in the context of the EU. In this context, for example, Luxembourg could produce and export animal products such as milk due to its high proportion of grassland, whereas southern European nations produce and export vegetables taking advantage of their warmer climates, with production respecting the national environmental resources and boundaries.

Finally, 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. In the national climate law (Loi du 15 décembre 2020 relative au climat), climate targets for Luxembourg were set: 55 % less CO_{2eq} emissions compared to 2005 by 2003 and climate neutrality by 2050 (Gouvernement du Grand-Duché de Luxembourg, 2020). To achieve these climate targets, the government has set sectoral emission reduction targets. In agriculture and forestry, emissions of greenhouse gases are to be reduced by 20 % by 2030 compared to 2005 and 27 % compared to 2019 (Gouvernement du Grand-Duché de Luxembourg, 2022, 2020). Luxembourg's National Inventory Report (Administration de l'Environnement, 2024) shows 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 by far the largest share of emissions compared to liming, urea application and other carbon-containing fertilisers. 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 NH_3 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 all 75 % Org scenarios, 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. 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 3 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. Dietary 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 (Are there areas in Luxembourg more favourable to growing certain crops, while other areas are better suited for vegetable production? How should these cropping systems look like? What is the production potential when pedo-climatic conditions are respected in the modelling efforts?). A big challenge on the environmental side is 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.

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.

4 Stakeholder involvement

4.1 Farmers

a) Presentation of SMART-Farm results

The results of the surveys using the SMART-Farm Tool were presented to the farmers in a digital format on 22.03.2021. The objectives and background of the project were first explained to the farmers. Then, it was explained how to read the individual farm reports, and the significance of the ranking was explained (Figure 3). In the further course of the event, results of the overarching farm analysis were presented, and the farmers were given the opportunity to place their own sustainability performance in the Luxembourg context. This was followed by a discussion on the opportunities and limitations of implementing measures to promote the sustainability of farms.

b) Perspectives of agriculture by 2050

In another workshop on 1st March 2023, farmers were asked for their perspective on a resilient agricultural system in Luxembourg, what their wishes and visions for the future were and how farmers imagined their profession in an ideal world: what projects would they like to tackle on the farm (e.g. agroforestry, agriPV, fostering biodiversity)? What is the situation with employees? How will they manage their farm and how does this affect arable farming and animal husbandry? The diagrams of the SMART-Farm Tool (Figure 5, Figure 7) were presented and the farmers were asked on their perspectives for the different sub-themes. The resulting flipchart papers are presented in Annex A.1, an overview of the discussed topics is given in the following.

Consumers. Food quality and food safety are of crucial social importance for farmers. It is essential that food quality meets the demands of consumers. One advantage of community supported agriculture in this aspect is the direct customer feedback, which guarantees a constant assurance of quality and customer satisfaction. However, customers must not be released from their responsibility.

Sales. To secure sales, the monopole of the wholesale trade must be counteracted. Support from third parties and employees on the farms are important for direct marketing. Stable sales are directly linked to customer awareness of the origin of food and agriculture. A price must be defined for the products to be able to cope with competition from wholesalers and monopolies.

Sustainable investments. The marketing of food is made easier for producers through non-profit investments. Sustainable investments require staggered subsidies on all investments. Farmers would be in favour of half of the investments being financed by income.

Income. A basic income would be a great support for farmers. The farmer's profit must be in line with the average of the Luxembourg population. Balanced liquidity is crucial to ensure positive development in the future and to overcome economic challenges. One difficulty is the constant self-administration. Farmers strive for independence from subsidies. Some farms invest part of their income in apprentices.

Expenditure. Employee salaries, which are a specific cost item, are the most important expenditure item.

Insurance. Farmers would like better protection in the event of accidents and employee illness. They currently feel dependent on the political context, such as the coronavirus crisis. There is often no consistency in their businesses, so they have to recruit members every year. Constant suppliers are needed to ensure better sales.

Regionality. Regionality should maximize value creation in the region. The most effective regional economy is achieved through business cycles and marketing. Good cooperation with contractors from the region promotes the sale of regional products. The purchase of young plants and regional vegetables can encourage customers to buy at markets.

Promote soil quality. Optimal soil quality can be achieved through adapted crop rotation, tillage and adequate nutrient management. A better soil structure and greater shading also promote soil quality. Very good results have already been achieved with the no tillage/plough less method. Farmers indicated that this method should be given more attention. In addition, the water retention capacity of the soil must be improved. Humus build-up through the application of compost and suitable crop rotation can support this.

Promoting biodiversity. There is a need for greater diversity of arable crops and vegetables in Luxembourg. The genetic diversity of plants and animals must be preserved and promoted. Adapted crop rotation and the cultivation of hedges can contribute to the promotion of biodiversity.

Framework conditions. Politicians are called upon to strengthen local organic seed cultivation. It is criticized that farmers are downright punished for their efforts, while intensive cultivation takes place on small areas. The topic of nutrition and agriculture should be increasingly addressed and integrated into society.

Time. Farmers complain that they usually have to spend their free time on further training. However, there is also a lack of such further training and general information for farmers. There is also a lack of exchange with other farmers. Many farmers would be in favour of meetings of self-managing farms.

Fair income. Farmers would like to see a basic income to ensure a fair income. There should be no compulsion to grow. A farm should have enough income so that a community can be formed among the farms and the work can therefore be easily managed.

Structure. Farmers would like to see less dialog with interest groups and a better work-life balance instead. The focus should be on professionalizing the structure and framework conditions.

Recognition The work of farmers can be better recognized with "true cost" billing of agricultural services. The services should also be recognized by the municipalities and the community.

Paperwork. Farmers want less bureaucracy and clear legal requirements.

Circular economy. Resources must be circulated regionally. This requires a basic understanding of the interrelationships in nature. The circular economy also includes the increasing number of animals and the compost produced.

Security. A good pension scheme is essential for security. Furthermore, a transparent supply chain law would ensure a sales market.

Supply chains/ origin of inputs. Farmers lack local and fair means of production.

Social responsibility. Farmers would like their profession to be portrayed fairly in society and the population to be more aware of food sovereignty. Responsible purchasing brings with it a relationship with this production. It is pointed out that public health starts with healthy food. Politicians are called upon to create more awareness among consumers.

4.2 Advisory Board

a) Workshop on visions of a sustainable agriculture and food system

The workshop with the Advisory Board on visions of a sustainable agricultural and food system took place digitally on 28.06.2022. A total of 13 people took part in the workshop. Norry Schneider (CELL) was recruited to support the moderation of the various working groups and supported the preparation of the workshop in terms of methodology. In breakout sessions for storyline elaboration of scenarios, three different scenarios were developed with the participants, which were specified by the respective working group itself. One narrative developed around the topic of food sovereignty, one dealt with regional cultivation in combination with a vegetarian diet and a third with regenerative agriculture and food sovereignty in Luxembourg.

Food sovereignty

The chosen narrative from group 1 envisions a future where Luxembourg has a high food sovereignty. This means that the food system is as ethically correct as possible with fair pay to farmers and actors along the food supply chain, and equitable access to quality food for everyone, while involving professional stakeholders, civil society organisations, research and citizens into collective and participative decision processes. A sovereign food system is also a food system, that is as self-sufficient as is clever. This means that food, that we aim to produce as much and varied quality food in Luxembourg as possible, but that strategic imports of some foods is given (e.g., bananas). The importance with these imports is to also favour ethically correct and sustainable production systems in the production countries. In this scenario, the well-being of farmers is considered with a solidarity-based distribution of risks along the food supply chain and the valorisation of the food production process. Farmland is also protected: land grabbing and land speculation of agricultural land is prohibited, and access to land for food producers is facilitated. When we look at how this translates to the production side of the food system, the aim is to meaningfully combine water, energy and diversified food production on the available agricultural land, while we simultaneously enhance valorised local ecosystem services.

This is only possible when the small integrated farming systems work together. Monocropping is a thing of the past. Extensive crop rotations are implemented, different crops are grown together per field using the principles of agroecology, permaculture and agroforestry to achieve a maximum of variety per field. Reduced tillage practices are implemented more and more, where possible, to preserve and increase soil carbon content. Fields will again be lined with hedges and the high diversity of crops increases the resilience of the system, reducing the need for chemical inputs. The available arable land is used mainly to produce crops directly usable for human consumption. As such, the feeding practices of livestock need to change (maxim: feed no food) and the animal numbers, especially of poultry and pigs, will decrease. Thus, fewer animals can be kept, which in turn, will entail a change in eating habits with reduced animal protein sources in our diet. As a result, protein crops become an important focus of crop production to provide alternative sources to animal protein. This will also help maintain and increase soil fertility as with reduced animal numbers, less animal manure is available as organic fertilizers. Further changes in agricultural land use will be seen with the incorporation of water capture and energy production systems, such as agro-voltaic systems. In combination with these high-tech solutions, low tech options, such as animal powered machinery for certain works, will be explored to further reduce our dependency on the oil and gas industry.

Regional and vegetarian diet

The chosen narrative of group 2 envisions a future where eating habits have changed to focus on a maximally regional and vegetarian diet. This was made possible through an intensive effort on dietary re-education of citizens and chefs alike. The change in diet and the resulting changes in food demand entailed changes in the production system. Animal husbandry for meat production crashed and balanced out at a low level (pig husbandry died out; male offspring of dairy cows and chicken were avoided as much as possible through breeding techniques, old cows and chickens were sold off for meat production to other countries). This resulted in a change in the composition of the animals being raised and the overall number of animals was also reduced leading to less organic fertilizer accumulating. This caused issues in nutrient availabilities for crop production that had to be balanced out through higher input of mineral fertilizers and clever crop rotations.

Apart from the possible positive health effects, this change in diet also helped counteract biodiversity losses and reduce greenhouse gas emissions and ammonia emissions (increase in air quality). Some impacts of this change in diet were difficult to foresee. For example, would such a change help preserve our water resources or would they put further pressures on them. This question came about from the changes in crop production that the switch to a vegetarian diet entailed. A stark increase in vegetable production was seen due to the higher demand of regionally grown produce which in turn lead to more irrigation needed. Furthermore, the energy consumption of heated greenhouses also posed a challenge.

Regenerative agriculture and food sovereignty

The goal for the year 2050 is a regenerative agriculture and a food cultivation with food sovereignty and food security for the population. It is essentially based on increasing self-production of food in Luxembourg in order to supply the growing population of a predicted 850,000 to 1.2 million inhabitants under the climate projections for 2050 and to establish food sovereignty in Luxembourg as much as possible. This includes local and regional production on smaller, diversified farms, whereby imports cannot be dispensed with in the future.

To achieve the goal of predominantly regional food production, areas for food production must be protected and expanded. Particular attention is paid to the availability of water and drinking water. Restrictions for increased food production result from the lack of water for vegetable production and the soil quality and fertility along with a water holding capacity that needs to be increased. Furthermore, in addition to their professional activities, people must have the time to cultivate the vegetable gardens (e.g. in gardens, city parks, green corridors, etc.). An increase in biodiversity is sought, whereby the question arises to what extent the current goals of environmental protection regarding species conservation will cover the goals in 2050 and possibly include other species in flora and fauna. The training and sensitization of all actors in the field of agriculture and food production and consumption is fundamental for the implementation of the challenges mentioned.

There are several influences on land use that require the expansion, protection, and conversion of existing areas. In addition to establishing agroforestry systems (with grazing areas; possibly using tree species that are currently not permitted for agroforestry systems in Luxembourg), the expansion of agricultural and vegetable growing areas, the conversion of urban green spaces and green corridors, there will also be a use of roofs and facades to produce food (insofar as they are not already being used for photovoltaics). Due to the phasing out of animal products in the diet and the projected increase in population, areas must be available for additional plant-based foods. The expansion of productive areas, especially regarding vegetable growing, requires the progressive expansion of water protection zones and spring protection. Particular attention is paid to the vegetable growing areas, the need for irrigation of which suggests their proximity to rivers. Experimental rooms are needed that allow ecosystem research to be adapted to the expected climate situation.

About animal husbandry, dual-purpose breeds that have been adapted to changing climatic conditions (e.g. breeds from Mediterranean countries) will be kept in the future. Farm manure should continue to be used to fertilize agricultural land. Migratory herds such as sheep or goats can be kept on extensively used areas. In any case, the number of animals, especially cattle, will be reduced in the future, also in order to reduce GHG and N emissions.

This scenario not only requires a change in agriculture and food production, but also requires social change. A key factor here is the renunciation of certain familiar foods and consumer goods, which last but not least requires a change in values. In addition, a limiting factor for (private) vegetable growing is availability of areas for private/urban gardening and time, because in addition to the current working hours, this is not affordable with the required income, which raises the question of a "welfare system" and a possible basic income. The private cultivation of vegetables raises the question of whether Luxembourg citizens are still pure consumers or whether they are prosumers (producers and consumers).

b) Advisory Board on the results of the SOLm model

In a second workshop with the advisory board, the results of the SOLm model have been presented. In a first phase, the workshop focused on the question what the modelling results (organic agriculture, food waste reduction and feed no food) mean to Luxembourg and its politics. Emphasis was set on “What do the results mean for agriculture, for the food sector, for consumers?”, “What needs to change if lessons are to be learned from the modelling results?”, “How drastic are the changes perceived to be? By those present? How would the change affect society?”. In a second phase, the groups worked on the question “What needs to change politically in Luxembourg to respond to the modelling results and prevent the 'business as usual' scenario?" and more specially on "What could policy programs look like to address the individual points (more organic, feed no food, less food waste)?", "How can political framework conditions incentivise change regarding to consumers and farmers?" and "What is the time horizon in which changes need to be initiated?". The main points of the discussion are described below, an exhaustive list is presented in Appendix A.2.

Phase I: Significance of results from SOLm for Luxembourg

Animal husbandry

Animal husbandry needs to be adapted future needs and to mitigate GHG emissions from the agricultural sector, especially in keeping ruminants. It is necessary to promote dual-purpose breeds and breeds that can utilise grass more efficiently. Consideration should also be given to how the distribution of pasture feed can be improved not only for cattle, but also for pigs and poultry. This supports the reduction of GHG and ammonia emissions. Due to the excessive use of concentrated feed, we achieve a too high performance and have too many animals, resulting in a nitrogen surplus of 130 kg N.

Cultivation system

Alternative food systems require alternative cultivation systems. Wider crop rotations will be established, which will help to prevent erosion, among other favourable environmental influences. Diversification is seen as resilient and adequate remedy to meet climate and environmental challenges. From a self-sufficiency perspective, vegetable cultivation should be promoted on forage areas that become available for other agricultural uses. The use of wood should be reconsidered to use resources efficiently and sustainably.

In this context, it was noted that the conventional system will have a major problem in the "feed-no-food" variant, as the entire system of conventional agriculture is designed to achieve high outputs. In the 100 % feed-no-food scenario, conventional agriculture would no longer be feasible without using concentrated feed.

Nutrition/Consumption

The production and consumption of healthy, sustainable food should be considered together. The results emphasise the importance of involving consumers, citizens, civil society organisations and research to reduce food waste and promote more sustainable food production. How to better inform and support consumers was discussed, e.g. through awareness campaigns, sustainability labelling on packaging and education about sustainable diets in schools. In future, more emphasis must be set on plant-based proteins for human nutrition. Which crops will be in the foreground in the future? And what can be grown in the future despite/due to climate change?

The role of politics was also discussed, with incentives such as higher taxes on unsustainable food instead of bans. The question of whether the food system should be considered at national or EU level was also raised, as Luxembourg is embedded in the Greater Region. It was also noted that higher energy prices could benefit farmers by making it more expensive to transport food over long distances. However, economics must be considered as more sustainable farms may perform worse economically. It is important to consider the cost and availability of labour in fruit and vegetable production when changing the food system.

Phase II: Policy recommendations

Raising awareness among consumers and farmers

As the discrepancy between knowledge and action is very large and knowledge is sometimes lacking, consumers need to be sensitized. It should be communicated that nutrition has a major influence on sustainability and that the consumer can play a significant role here. Information can be provided in many different ways: Ideas that were put forward by the workshop participants range from a new school subject "sustainable nutrition", package labelling and the establishment of a participatory food policy council that bring together the food sector, civil society, research and citizens to set up projects enhancing food sovereignty collectively.

Diets should be shifted to more plant-based proteins. However, there is also a need for regulatory instruments on the part of politicians. A possibility might be that sustainable products are taxed differently, not only on a national but on an EU level. Different taxation of conventional and organic products could otherwise result in consumers moving abroad and buying food in neighbouring countries. True cost accounting is a good instrument for setting the right course.

Awareness should also be raised among farmers. Cultivation systems must be changed, less livestock kept, and more protein crops grown for human consumption. It is essential that this change to a higher share of protein crops must be framed by policy so that it remains economically viable for farms. There needs to be a balance between push and pull on the part of politicians.

Economic viability of agricultural production

The economic sustainability of agricultural businesses must be ensured. Instruments should be created to promote sustainable farming systems. This raises the question of which approach should be chosen: if control is not to be achieved through stricter rules, then change must be channelled through financial support for implementation. Sustainably produced products must be attractively priced for both consumers and farmers. Clear criteria for imported products should be defined. As more plant proteins are to be cultivated for human nutrition, it is important to expand these value chains in Luxembourg and the Greater Region. Community supported agriculture (CSA) should also receive more support in the future.

5 Synthesis of Results

5.1 Conclusions

Luxembourg is a comparatively small country with a high population density and limited resources for agricultural production and is therefore dependent 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. The transition to a sustainable agriculture and food sector requires systemic changes, as the sustainability assessments with the SMART-Farm Tool and modelling with SOLm have shown.

The SMART analyses showed that Luxemburgish agriculture is already well on the way to achieving a transition towards a sustainable agriculture and the sustainability ratings for many of the themes and subthemes analysed were above 60 % goal achievement, which is classified as within the ‘good’ range. This is due, among other things, to the farms' own initiative, the legal framework and the high share of organic farms in the sample. Favourable agricultural practices were identified and strategies for a more sustainable agricultural production in Luxembourg were identified: a reduction in concentrated feed and fostering a higher protein autarky, the closing of agricultural cycles and organic farming. In addition, there are some starting points that can be considered in organic and conventional farms including agroforestry systems, sustainable soil cultivation, the valorisation of grassland and the adaptation of crop rotations for efficient nitrogen management. Promoting these measures or farming methods would increase the sustainability performance of the agricultural system in the medium term.

SOLm was then used to model the agronomic feasibility of three main scenarios for 2050, considering the physical boundary conditions of Luxembourg: transition toward 100 % organic agriculture, reduction in food waste and reduction in concentrate feedstuff (‘Feed no Food’). The option spaces were modelled in coarse grading (organic farming: 0 %, 25 %, 50 %, 75 % and 100%, Feed no Food: 0 %, 50 % and 100 %, food waste reduction: 0 % 25 and 50 %), as the aim was to determine trends, not precise estimates.

SOLm showed that within the option space of the three modelled scenarios a significant increase in the sustainability of the Luxembourgish food systems is possible and that the 3 modelled scenarios provide strong levers to implement change and reduce environmental emissions. The extent of the reduction in emissions and the amount of food produced depends on the combination of the three scenarios, and different combinations within the option space of the three scenarios may be more adapt at reaching the different environmental and food system related objectives:

- A 50 % or more **reduction in greenhouse gas emissions** in comparison to the BAU with trade scenario (632 kt CO_{2eq}) was possible under different combinations of the modelled scenarios: 100 % organic agriculture reduced greenhouse gas emissions to 284 kt CO_{2eq} (a 55 % reduction), 75 % organic agriculture combined with 50 % Feed no Food reduced them to 309 kt CO_{2eq} (a 51 % reduction), and 75 % organic agriculture in combination with 50 % reduction in food waste achieved a 49 % reduction (down to 322 kt CO_{2eq}).
- A 50 % **reduction in ammonia emissions** was possible using various combinations of the scenarios: 100 % organic agriculture in combination with 25 % food waste reduction achieved a 49 % reduction (from 4645 t NH_3 in the BAU with trade to 2386 t NH_3); 75 % organic agriculture and 50 % Feed no Food also achieved 49 % reduction (2366 t NH_3); and 50 % organic agriculture combined with 50 % food waste reduction and 100 % Feed no Food achieved 50 % reduction (2299 t NH_3).
- For **increase in food sovereignty**, a 42 % caloric self-sufficiency was achieved (even with a population increase to 1 000 000 inhabitants), at 50 % food waste reduction with 50 % feed no food, and at 25 % organic agriculture with 50 % food waste reduction and 100 % Feed no Food.

It is important to note that at 100 % organic agriculture, the nitrogen balance turned negative and nitrogen supply could not be ensured to maintain crop yields. An N surplus, however, could still be assumed with 75 % organic agriculture, if the cultivation of legumes were consistently implemented on arable lands and closed nutrient cycles were implemented not only on farms but also in the entire food and waste sector. A clear prioritization of environmental and food system related objectives would be needed to be able to calculate how best to achieve that objective. Is it more important to reduce greenhouse gas emissions compared to increasing food production and food sovereignty?

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

5.2 Recommendations for action

A clear vision for Luxembourg and its food system 2050, with clear definitions of objectives and their prioritization, is needed to make impactful target-group specific recommendations, especially in regard to environmental problems, such as climate change, biodiversity loss, drinking water quality, etc.: What are the aims? Where and how do we want to reach them? What are the priorities? The results showed that drastic and holistic approaches for a systemic change are needed. The results provide an option space within which concrete solutions must now be found. In general, as was also seen during the farm-level sustainability assessments, there are already many efforts and steps taken in the right direction. However, even larger and more drastic strides are needed to achieve the necessary changes. Overall, a holistic approach is needed to start the transition towards a more sustainable food system. As part of the systemic change, it is important to foster collaboration between the different stakeholders, implement a food council, and foster and support transition movements and organizations. It is also of utmost importance to promote and encourage collaboration across different fields in the form of an expert panel, with experts in economy, agriculture, environment, social and research.

From the results presented above it is clear that reduction in food waste, reduction in the use of concentrated feed, the closing of farm cycles and the increase in organic agriculture are powerful tools to increase the sustainability of the food system. The difficulty is now to identify what is needed to put these into practice. Based on the discussions in the above-described various workshops and the results of the farm-level and food system-level sustainability assessments, the following recommendations can be put together:

a) Farmers

- The reduction of concentrated feed use by at least 50 %, especially in ruminant husbandry: This can be achieved through the efficient use and valorisation of grassland and the increased cultivation of field fodder such as clover- or alfalfa-gras-mixture to increase fodder autarky. This will, as discussed above, drastically reduce the number of animals that can be raised and lead towards a more area-based animal husbandry.
- Closing of farm nutrient cycles: This can be done by reducing in the use of mineral fertilizers, increasing legumes in the crop rotations, growing a higher share of legume-grass leys in the crop rotations, introducing catch crops and undersown crops at higher rates in the crop rotation and increasing fodder autarky. A general increase in legumes in the crop rotation can improve soil fertility and reduce N needs from mineral fertilizers. An increase of legume-grass-mixture as field fodder in the crop rotation would also reduce weed infestation in the following crops, reducing the need for herbicides as well as adding to the basic fodder supply of ruminants.

- Diversification: The cultivation of grain legumes and alternative crops for direct human consumption (such as various oil crops) on the land freed up through the reduction in animal feed production can help diversify farm structures and lead to greater farm resilience.
- Increase in organic agriculture to 75 % of the agricultural area: organic agriculture, as was seen in the results, already inherently implements at a higher rate many of the practices above; thus, encouraging and promoting organic agriculture can intrinsically promote the implementation of these sustainable farming practices. A 75 % organic agriculture share will have positive impacts on many environmental factors, while simultaneously still maintain a net positive N balance to ensure crop yield. The increase in organic agriculture will also have positive impacts on biodiversity through the reduction in pesticide use. Reaching 75 % of organic agriculture will prove a huge challenge seeing as Luxembourg has currently 5.7 % of agricultural area under organic production (Ministère de l'Agriculture, de la Viticulture et du Développement rural, 2023).

Many of these changes in the production system will entail financial risks for the farmers that will need to be offset by actions (some listed below) from the other actors in the food system.

b) Consumers

- Reduction in the consumption of animal proteins: As the reduction in concentrate feed use will lead to fewer animals that can be raised, it is imperative that the demand for animal protein is concomitantly reduced as well.
- Increase in the consumption of plant proteins: Parallel to the reduction in animal protein consumption it is important to switch to plant protein sources to meet human protein needs. This will also ensure a demand for the diversification efforts recommended above to the farmers.
- Reduction in food waste by 25 %: Consumers bear a great deal of responsibility to reduce food waste in their households. This saves a large proportion of resources, which has an impact on Luxembourg's level of food sovereignty and can, as previously discussed, offset lower yields from organic agriculture. Here the AntiGaspi campaign of the Ministry of Agriculture plays already an important role in educating consumers and providing information on available seasonal food, proper food storage at home and ideas for using up leftovers (Ministère de l'Agriculture, de l'Alimentation et de la Viticulture, 2025).
- Shift in preference towards sustainably and/or organically produced food: The way food is produced needs to become a more prominent factor in the decision-making step when food purchases are made. By choosing sustainably and/or organically produced food items, consumers create demand for these foods and their underlying production systems. This will also ensure the profitability of these production systems for the farmers. To avoid putting the main responsibility for the transformation of the food system on individual consumer's decisions, favourable "food environments" need to be fostered by upstream production, processing and retail, in a way that consumers have the choice between different yet always sustainable produce.

The integration of plant proteins into the diet is an important step. Reducing animal products and fats in the diet can lead to a healthier lifestyle due to the healthier profile of unsaturated fatty acids, the absence of high concentrations of iron, and the association with higher amounts of dietary fibre. The calories produced in Luxembourg is largely based on animal products. A more sustainable food production, which would lead to fewer animal products, would also be conducive to a healthier diet for consumers and possibly increase overall population health.

c) Policy makers

- Using direct policy instruments to (continue to) promote sustainable agricultural practices: This would include the above-mentioned farming practices, e.g. promotion of legume and alternative crop cultivation, promotion of area-based animal husbandry with reduced concentrate feed use, promotion of organic agriculture, etc.
- Support for the development of marketing structures and value chains: Especially organic and niche products are often more expensive because they are sold in smaller quantities and the costs incurred for food transformation, packaging, marketing and transportation by food retailers must be spread over fewer products. Both, production costs and smaller quantities foster higher market prices. Furthermore, the value chains for alternative crops in terms of food processing are often missing in Luxembourg and the Greater Region. Support in establishing local value chains could help minimize these costs and reduce market prices for consumers, as well as secure revenue streams for the farmers. A focus should be set on value chains for grain legumes for human consumption.
- Educational campaigns geared towards consumers encouraging healthy and sustainable eating habits: such campaigns are an important step towards changing people's eating habits, ideally by involving communities in convivial and participative projects that engage citizens and bring about a change in routines and habits. This includes, for example, the promotion of (educational) programs on farms through to the support for community supported agriculture or community gardens. Nutrition can already be integrated into urban and spatial planning by planning of food belts in green spaces or the creation of community gardens.
- Healthy and sustainable diets as part of the school curriculum: healthy and sustainable lifestyle and food production should be included into the school curriculums. This could be coupled with school gardens for hands-on experience in growing food and cooking lessons, whenever and wherever possible.
- Financial incentives for choosing healthy and sustainable food items: This might be done by lowering taxes for healthy and sustainable food items (of local production).
- A front-of-the-pack label supporting sustainable products: similar to the Nutri-Score (Santé publique France, 2024), a front-of-the-pack label to help consumers navigate the foodscape in supermarkets could help shift their buying behaviours towards choosing more often sustainably produced food items.
- Nutritional and sustainability-related guidelines for public canteens and cafeterias: While efforts have already been made in Luxembourg to increase seasonal, locally produced and organic food items on the menu of public canteens and cafeterias, these efforts could be expanded (e.g. fewer meat-options, higher shares of sustainably and/or organically produced food items, etc.).
- Establishment of a national Food Policy Council: The establishment of a nation-wide Food Policy Council and the creation of discussion forums can promote dialogue between all involved actors. Food Policy Councils aim to promote exchange and collaboration among actors and to provide a platform to start innovative pilot projects between actors in the agricultural and food sectors.
- Funding research and development: As was seen in the farm-level sustainability assessments, many of the known environmentally friendly farming practices are only implemented at a small number of farms or on a small share of agricultural land (e.g. direct seeding, agroforestry, reduced tillage, etc.). Applied research in the agricultural sector are needed to study, among other topics, how the implementation rate of such methods can be improved. Parallel to the more applied research in the agricultural sector, social science research on societal acceptance and appropriation of transition processes is needed.

In the long term, there will need to be systemic change that involves citizens, farmers, food producers, policy makers and all other stakeholders in the food system. The scattergun approach with various individual measures will not be sufficient in view of the immense political challenges associated with reducing greenhouse gas emissions in accordance with the Paris Agreement, reducing ammonia emissions and nitrogen losses, increasing biodiversity, safe-guarding water quality and increasing the level of food sovereignty in Luxembourg.

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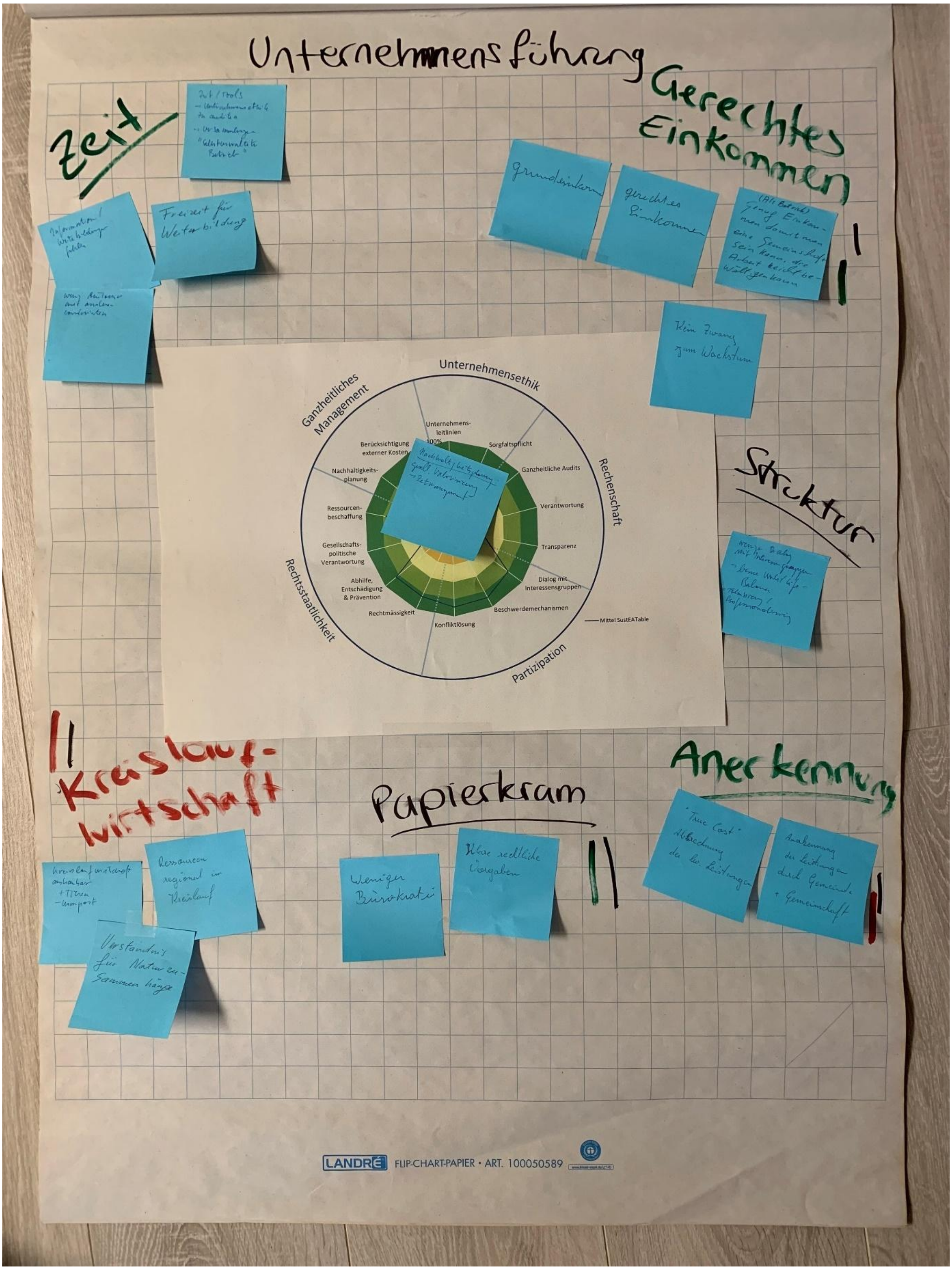
Appendix

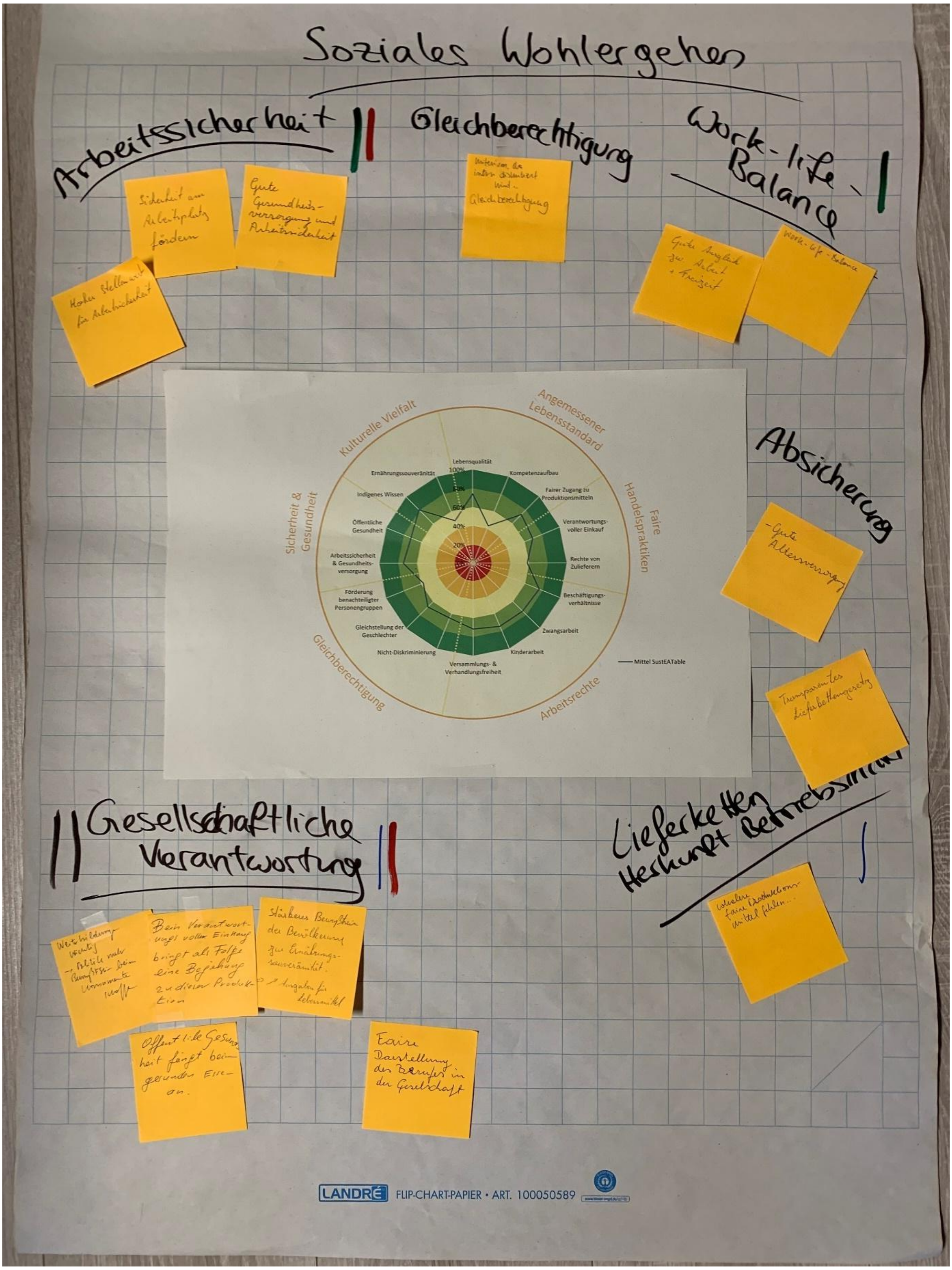
A.1. Farmer's Workshop

a) Good Governance



b) Environmental Integrity

c) Social Well-being



d) Economic Resilience

A.2. Scientific Advisory Board on the results of the SOLm modelling

a) Significance of results from SOLm for Luxembourg

Produktion + Konsum gesunde Ernährung, zusammendenken	Waste Reduction gains 2x so significant as bio losses	Konsument wie diesen mit ins Boot bekom-men? Wie Impact vermitteln? Wie viel Wissen? Front of package labelling Waste Vermeidung -> Aufklärung
ungesättigte tierische Fette?	Bio führt nicht zu Versorgungsmangel (in kcal + Fett)	Kuh als CO2 Sequestierer
Nährstoffe aus Kläranlagen, Bioabfall	Grünland als Hemmschuh oder Chance?	Zweinutzungskuh?
alternative pflanzliche Proteine? Aus Luxemburg	food competing feed reduction Ziel sollte 1 sein für Empfehlung an Politik	Grasland -> politisch unterstützen
neue Kulturen Klimawandel	Welche Ernährungsart ist das Ziel? --> wichtig für Empfehlung an Politik	Bildung -> Wissen mit in die Schule nehmen
alternative pflanzliche Proteine? Aus Luxemburg	effiziente Grünlandnutzung	Verantwortungsbereich Politik
alternative ... Kulturen in Lux anbauen	N/ha 130 kg -> 40 kg	Energiepreis -> Transport reduz-ieren
Unterschied Bio/Konv.		LU ≠ EU in europäischm Kontext
Wenn es kein Feed no Food mehr gibt -> Problem konv		Politische incentives -> evtl über Besteuerungssystem
Weidefutterverteilung auf Kühe, Schweine, Hühner		Obst/Gemüse -> Arbeitskraft, Kosten
Alternative Nahrungssysteme: Gemüseanbau; Diversifizierung ist resilient		Wirtschaftlichkeit der Ergebnisse mit Beschreibung
Alternative Biomasseproduktion: Gehölznutzung		
transnationale Kooperation -> Niveau Großregion		
Rassen, die besser Gras verwerten können Verfütterung & Kraftfutter -> zu hohe Leistungen zwei Nutzungsrassen Rinder 130 kg/N Überschuss zu hohe Leistung zu viele Tiere und zu viel N weniger THG + Ammoniak		
Nutzung Food Waste andere Produkte aus Food Waste andere Fruchtfolgen Strukturelemente Erosion vermeiden durch Fruchtfolgen Lux Insel wenn wir weniger produzieren wird mehr produziert? Sensibilisierung Konsument + LW Fatalismus vermeiden ... Food Veredlung		
Nährstofftransfers innerhalb LW Flä-chen Naturschutzsynergien verbesserte Landnutzung (Biodiv.)		

b) Political recommendations

Nachhaltigkeit	**Solawi**	**Forschung und Beratung**	**Konsument /Aufklärung**	**Ernährungsrat**	**finanzielle Unterstützung**	**Wirtschaft(lichkeit)**	**Regelungen Politik**
Diversifizierung Landwirtschaft	Urbanplanung -> schon Gemenschaftsgärten in neue cités einplanen	Förderung von Forschungsprojekten -> Nachhaltigkeit	Aufklärungskampagne starten für Konsument	Ernährungsrat !partizipativ!	finanzielle Förderung LW Betriebe fianzielle Förderung Aternativen (Fruchtfolgen ..)	Alternative Proteinquellen muss wirtschaftlich sein	AROMA Projekt politische & landwirtschaftliche Kooperation Großregion --> Selbstversorgung --> weg vom Export, hin zur regionalen Versorgung
Ernährung nachhaltiger gestalten	Solawi mehr fördern	mehr angewandte Forschung mit Beratung + LW Politik soll mit Forschung kommunizieren	Konsumenten lenken: Food Waste, Ernährung	Diskussionsforen für alle Stakeholder um Projekte ongoing anzupassen = Ernährungsräte Rückkopplung Probleme <-> Ernährungsrat !zusammen!	push/pull finanzielle Unterstützung für nachhaltige "Praxen" wenn nicht über Regeln, dann braucht es finanzielle Anreize	wirtschaftlich sinnvolle Absatzmöglichkeiten für LW	Interministuelle Zusammenarbeit
Nachhaltigkeitsscore True Cost Accounting		auch Beratung einbinden	Sensibilisierung Konsument Konsequenz Ernährungsart -> Nachhaltigkeit Ernährung umstellen, mehr pflanzliche Proteine	Lux keine Insel -> Konsument geht ins Ausland, wenn hier zu teuer		Marktpreise angehen, nicht von Regierung beeinflussen, Landwirte gemeinsam	Selbstversorgung für Lux angestrebt?
nachhaltig Arbeiten = wirtschaftlich bestraft		Sensibilisierung LW Betriebe	Schulpersonal/Schulkantinen schulen Schulfach healthy lifestyle/sustainability/kochen/Landwirtschaft			Monopolstellung der Handelsketten	Regelung auf EU Ebene
Abfallreduzierung als Priorität		Diskepont Wissen - Handeln				Großverteiler als Logistik nutzen aber durch politische Auflagen gemeinnütziger orientieren	was hätte die Politik gerne? Einsparpotenzial klar darstellen herausfiltern, was am einfachsten ist, umzusetzen
besseres N-Management						Businesspläne auf veränderte Produktion anpassen	Kriterien Importprodukte
Großhandel in die Pflicht nehmen: Nachhaltigkeitsnarrative						Besteuerung nachhaltige Produkte weniger	

Wertschöpfungsketten fördern und aufbauen-> Produkte in Region verkaufen						regionale Transformation für lokale Absätze	
preisliche Attraktivität nachhaltige Produkte							
Mandatory front of Package Labelling für sustainability & health							
Politische Ziele -> Produkte fördern, die nachhaltig produziert werden							
Ammoniak 6kT -> 5,2 kT 2030 (alle) LW 2,5 -> 1,2 mit bisherigen Maßnahmen Hälfte erreicht							

A.3. SOLm results without trade

All scenarios (be-sides the baseline scenario) WITH-OUT trade		Base-lineScenario	Org_0 __WRed_0__FnF_0_With-Trade	Org_0 __WRed_0 __FnF_0	Org_0.25 __WRed_0 __FnF_0	Org_0.5 __WRed_0 __FnF_0	Org_0.75 __WRed_0 __FnF_0	Org_1 __WRed_0 __FnF_0	Org_0 __WRed_0.25__FnF_0	Org_0.25 __WRed_0.25__FnF_0	Org_0.5 __WRed_0.25__FnF_0	Org_0.75 __WRed_0.25__FnF_0	Org_1 __WRed_0.25__FnF_0
	Organic share		0	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
	Waste reduc-tion		0	0	0	0	0	0	0.25	0.25	0.25	0.25	0.25
	food-compet-ing feed red.		0	0	0	0	0	0	0	0	0	0	0
g fat/cap	in relation to the population today	118	116	65	56	49	42	35	72	63	54	47	40
kcal/cap		2758	2703	1203	1121	1044	972	904	1339	1250	1166	1088	1014
g protein/cap		104	103	53	49	45	42	39	58	54	50	46	43
SelfSuff_kcal		1.16	1.14	0.51	0.47	0.44	0.41	0.38	0.56	0.53	0.49	0.46	0.43
g fat/cap	in relation to the population 2050	76	74	41	36	31	27	23	46	40	35	30	26
kcal/cap		1764	1729	769	717	668	621	578	857	800	746	696	648
g protein/cap		67	66	34	31	29	27	25	37	34	32	29	27
SelfSuff_kcal		0.74	0.73	0.32	0.30	0.28	0.26	0.24	0.36	0.34	0.31	0.29	0.27
Nr of Cattle		189282	186442	116373	110555	104736	98917	93099	116373	110555	104736	98917	93099
Nr of Chicken		129598	122774	178417	165130	152304	139936	128029	178417	165130	152304	139936	128029
Nr of Pigs		83409	79017	114828	106277	98022	90063	82399	114828	106277	98022	90063	82399
MineralFertilizer tN		13300	12342	12342	9257	6171	3086	0	12342	9257	6171	3086	0
NExcretion_tN		15183	14920	10146	9541	8949	8371	7805	10146	9541	8949	8371	7805
Biological_NFixa-tion_tN		1780	1729	1795	1880	1966	2051	2136	1795	1880	1966	2051	2136
NDeposition_tN		2322	2290	1717	1645	1574	1505	1437	1717	1645	1574	1505	1437
N_HarvestedBio-mass_tN		15792	12167	12167	11730	11293	10856	10419	12167	11730	11293	10856	10419
TotalAgricultur-alArea_ha		132850	127142	127142	127142	127142	127142	127142	127142	127142	127142	127142	127142
NBal-ance_tN_per_ha		0.126	0.150	0.109	0.083	0.058	0.033	0.008	0.109	0.083	0.058	0.033	0.008
AmmoniaEmis-sions_Total_tNH3		4752	4645	3414	3149	2890	2636	2386	3414	3149	2890	2636	2386
FertilizerLandAp-plication_tCO2e		158940	152072	124985	104159	83392	62682	42026	124985	104159	83392	62682	42026
ManureManage-ment_tCO2e		89949	87716	67166	62738	58452	54302	50283	67166	62738	58452	54302	50283
EntericFermenta-tion_tCO2e		385248	392680	248618	233791	219338	205238	191472	248618	233791	219338	205238	191472

All scenarios (besides the baseline scenario) WITHOUT trade		BaselineScenario	Org_0__WRed_0__FnF_0_WithTrade	Org_0__WRed_0.5__FnF_0	Org_0.25__WRed_0.5__FnF_0	Org_0.5__WRed_0.5__FnF_0	Org_0.75__WRed_0.5__FnF_0	Org_1__WRed_0.5__FnF_0	Org_0__WRed_0__FnF_0.5	Org_0.25__WRed_0__FnF_0.5	Org_0.5__WRed_0__FnF_0.5	Org_0.75__WRed_0__FnF_0.5	Org_1__WRed_0__FnF_0.5
	Organic share		0	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
	Waste reduction		0	0.5	0.5	0.5	0.5	0.5	0	0	0	0	0
	food-competing feed red.		0	0	0	0	0	0	0.5	0.5	0.5	0.5	0.5
g fat/cap	in relation to the population today	118	116	80	69	60	52	44	50	44	38	32	27
kcal/cap		2758	2703	1475	1379	1289	1204	1124	1340	1249	1162	1079	999
g protein/cap		104	103	62	58	54	50	46	62	58	54	50	47
SelfSuff_kcal		1.16	1.14	0.62	0.58	0.54	0.51	0.47	0.56	0.53	0.49	0.45	0.42
g fat/cap	in relation to the population 2050	76	74	51	44	39	33	28	32	28	24	21	18
kcal/cap		1764	1729	944	882	825	770	719	857	799	743	690	639
g protein/cap		67	66	40	37	34	32	30	40	37	34	32	30
SelfSuff_kcal		0.74	0.73	0.40	0.37	0.35	0.32	0.30	0.36	0.34	0.31	0.29	0.27
Nr_of_Cattle		189282	186442	116373	110555	104736	98917	93099	116373	110555	104736	98917	93099
Nr_of_Chicken		129598	122774	178417	165130	152304	139936	128029	96680	88477	80629	73135	65996
Nr_of_Pigs		83409	79017	114828	106277	98022	90063	82399	62223	56943	51892	47069	42475
MineralFertilizer tN		13300	12342	12342	9257	6171	3086	0	12342	9257	6171	3086	0
NExcretion_tN		15183	14920	10146	9541	8949	8371	7805	9436	8896	8366	7844	7330
Biological_NFixation_tN		1780	1729	1795	1880	1966	2051	2136	2150	2193	2235	2278	2321
NDeposition_tN		2322	2290	1717	1645	1574	1505	1437	1632	1568	1504	1441	1380
N_HarvestedBiomass_tN		15792	12167	12167	11730	11293	10856	10419	12448	12278	12108	11938	11768
TotalAgriculturalArea_ha		132850	127142	127142	127142	127142	127142	127142	127142	127142	127142	127142	127142
NBalance_tN_per_ha		0.126	0.150	0.109	0.083	0.058	0.033	0.008	0.103	0.076	0.049	0.021	-0.006
AmmoniaEmissions_Total_tNH3		4752	4645	3414	3149	2890	2636	2386	3062	2826	2594	2366	2140
FertilizerLandApplication_tCO2e		158940	152072	124985	104159	83392	62682	42026	122198	101641	81122	60640	40193
ManureManagement_tCO2e		89949	87716	67166	62738	58452	54302	50283	56421	52840	49352	45956	42651
EntericFermentation_tCO2e		385248	392680	248618	233791	219338	205238	191472	243075	229345	215842	202555	189474

All scenarios (besides the baseline scenario) WITHOUT trade		BaselineScenario	Org_0__WRed_0__FnF_0_WithTrade	Org_0__WRed_0.25__FnF_0.5	Org_0.25__WRed_0.25__FnF_0.5	Org_0.5__WRed_0.25__FnF_0.5	Org_0.75__WRed_0.25__FnF_0.5	Org_1__WRed_0.25__FnF_0.5	Org_0__WRed_0.5__FnF_0.5	Org_0.25__WRed_0.5__FnF_0.5	Org_0.5__WRed_0.5__FnF_0.5	Org_0.75__WRed_0.5__FnF_0.5	Org_1__WRed_0.5__FnF_0.5
	Organic share		0	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
	Waste reduction		0	0.25	0.25	0.25	0.25	0.25	0.5	0.5	0.5	0.5	0.5
	food-competing feed red.		0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
g fat/cap	in relation to the population today	118	116	55	48	42	36	30	60	53	46	39	33
kcal/cap		2758	2703	1456	1358	1265	1176	1091	1572	1468	1369	1274	1183
g protein/cap		104	103	66	62	58	54	50	71	67	62	58	54
SelfSuff_kcal		1.16	1.14	0.61	0.57	0.53	0.50	0.46	0.66	0.62	0.58	0.54	0.50
g fat/cap	in relation to the population 2050	76	74	35	31	27	23	19	39	34	29	25	21
kcal/cap		1764	1729	931	869	809	752	698	1006	939	876	815	757
g protein/cap		67	66	42	40	37	35	32	45	43	40	37	35
SelfSuff_kcal		0.74	0.73	0.39	0.37	0.34	0.32	0.29	0.42	0.40	0.37	0.34	0.32
Nr_of_Cattle		189282	186442	116373	110555	104736	98917	93099	116373	110555	104736	98917	93099
Nr_of_Chicken		129598	122774	96680	88477	80629	73135	65996	96680	88477	80629	73135	65996
Nr_of_Pigs		83409	79017	62223	56943	51892	47069	42475	62223	56943	51892	47069	42475
MineralFertilizer_tN		13300	12342	12342	9257	6171	3086	0	12342	9257	6171	3086	0
NExcretion_tN		15183	14920	9436	8896	8366	7844	7330	9436	8896	8366	7844	7330
Biological_NFixation_tN		1780	1729	2150	2193	2235	2278	2321	2150	2193	2235	2278	2321
NDeposition_tN		2322	2290	1632	1568	1504	1441	1380	1632	1568	1504	1441	1380
N_HarvestedBiomass_tN		15792	12167	12448	12278	12108	11938	11768	12448	12278	12108	11938	11768
TotalAgriculturalArea_ha		132850	127142	127142	127142	127142	127142	127142	127142	127142	127142	127142	127142
NBalance_tN_per_ha		0.126	0.150	0.103	0.076	0.049	0.021	-0.006	0.103	0.076	0.049	0.021	-0.006
AmmoniaEmissions_Total_tNH3		4752	4645	3062	2826	2594	2366	2140	3062	2826	2594	2366	2140
FertilizerLandApplication_tCO2e		158940	152072	122198	101641	81122	60640	40193	122198	101641	81122	60640	40193
ManureManagement_tCO2e		89949	87716	56421	52840	49352	45956	42651	56421	52840	49352	45956	42651
EntericFermentation_tCO2e		385248	392680	243075	229345	215842	202555	189474	243075	229345	215842	202555	189474

All scenarios (besides the baseline scenario) WITHOUT trade		BaselineScenario	Org_0__WRed_0__FnF_0_WithTrade	Org_0__WRed_0__FnF_1	Org_0.25__WRed_0__FnF_1	Org_0.5__WRed_0__FnF_1	Org_0.75__WRed_0__FnF_1	Org_1__WRed_0__FnF_1	Org_0__WRed_0.25__FnF_1	Org_0.25__WRed_0.25__FnF_1	Org_0.5__WRed_0.25__FnF_1	Org_0.75__WRed_0.25__FnF_1	Org_1__WRed_0.25__FnF_1
	Organic share		0	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
	Waste reduction		0	0	0	0	0	0	0.25	0.25	0.25	0.25	0.25
	food-competing feed red.		0	1	1	1	1	1	1	1	1	1	1
g fat/cap	in relation to the population today	118	116	36	32	27	23	19	39	34	29	25	21
kcal/cap		2758	2703	1477	1376	1279	1185	1093	1573	1467	1363	1264	1167
g protein/cap		104	103	70	66	62	58	55	75	71	66	62	58
SelfSuff_kcal		1.16	1.14	0.62	0.58	0.54	0.50	0.46	0.66	0.62	0.57	0.53	0.49
g fat/cap	in relation to the population 2050	76	74	23	20	17	15	12	25	22	19	16	13
kcal/cap		1764	1729	945	880	818	758	699	1006	938	872	808	746
g protein/cap		67	66	45	42	40	37	35	48	45	43	40	37
SelfSuff_kcal		0.74	0.73	0.40	0.37	0.34	0.32	0.29	0.42	0.39	0.37	0.34	0.31
Nr_of_Cattle		189282	186442	116373	110555	104736	98917	93099	116373	110555	104736	98917	93099
Nr_of_Chicken		129598	122774	14942	11937	9169	6639	4347	14942	11937	9169	6639	4347
Nr_of_Pigs		83409	79017	9617	7683	5901	4273	2798	9617	7683	5901	4273	2798
MineralFertilizer_tN		13300	12342	12342	9257	6171	3086	0	12342	9257	6171	3086	0
NExcretion_tN		15183	14920	8726	8253	7784	7318	6857	8726	8253	7784	7318	6857
Biological_NFixation_tN		1780	1729	2505	2505	2505	2505	2505	2505	2505	2505	2505	2505
NDeposition_tN		2322	2290	1547	1490	1434	1378	1323	1547	1490	1434	1378	1323
N_HarvestedBiomass_tN		15792	12167	12728	12825	12923	13020	13118	12728	12825	12923	13020	13118
TotalAgriculturalArea_ha		132850	127142	127142	127142	127142	127142	127142	127142	127142	127142	127142	127142
NBalance_tN_per_ha		0.126	0.150	0.097	0.068	0.039	0.010	-0.019	0.097	0.068	0.039	0.010	-0.019
AmmoniaEmissions_Total_tNH3		4752	4645	2710	2504	2299	2096	1895	2710	2504	2299	2096	1895
FertilizerLandApplication_tCO2e		158940	152072	119411	99127	78858	58606	38370	119411	99127	78858	58606	38370
ManureManagement_tCO2e		89949	87716	45677	42955	40278	37648	35064	45677	42955	40278	37648	35064
EntericFermentation_tCO2e		385248	392680	237533	224901	212350	199877	187484	237533	224901	212350	199877	187484

All scenarios (besides the baseline scenario) WITHOUT trade		Base-lineScenario	Org_0__WRed_0__FnF_0_WithTrade	Org_0__WRed_0.5__FnF_1	Org_0.25__WRed_0.5__FnF_1	Org_0.5__WRed_0.5__FnF_1	Org_0.75__WRed_0.5__FnF_1	Org_1__WRed_0.5__FnF_1
	Organic share		0	0	0.25	0.5	0.75	1
	Waste reduction		0	0.5	0.5	0.5	0.5	0.5
	food-competing feed red.		0	1	1	1	1	1
g fat/cap	in relation to the population today	118	116	41	36	31	26	22
kcal/cap		2758	2703	1669	1557	1448	1343	1241
g protein/cap		104	103	80	75	71	66	62
SelfSuff_kcal		1.16	1.14	0.70	0.66	0.61	0.57	0.52
g fat/cap	in relation to the population 2050	76	74	26	23	20	17	14
kcal/cap		1764	1729	1068	996	926	859	793
g protein/cap		67	66	51	48	45	42	40
SelfSuff_kcal		0.74	0.73	0.45	0.42	0.39	0.36	0.33
Nr_of_Cattle		189282	186442	116373	110555	104736	98917	93099
Nr_of_Chicken		129598	122774	14942	11937	9169	6639	4347
Nr_of_Pigs		83409	79017	9617	7683	5901	4273	2798
MineralFertilizer_tN		13300	12342	12342	9257	6171	3086	0
NExcretion_tN		15183	14920	8726	8253	7784	7318	6857
Biological_NFixation_tN		1780	1729	2505	2505	2505	2505	2505
NDeposition_tN		2322	2290	1547	1490	1434	1378	1323
N_HarvestedBiomass_tN		15792	12167	12728	12825	12923	13020	13118
TotalAgriculturalArea_ha		132850	127142	127142	127142	127142	127142	127142
NBalance_tN_per_ha		0.126	0.150	0.097	0.068	0.039	0.010	-0.019
AmmoniaEmissions_Total_tNH3		4752	4645	2710	2504	2299	2096	1895
FertilizerLandApplication_tCO2e		158940	152072	119411	99127	78858	58606	38370
ManureManagement_tCO2e		89949	87716	45677	42955	40278	37648	35064
EntericFermentation_tCO2e		385248	392680	237533	224901	212350	199877	187484

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