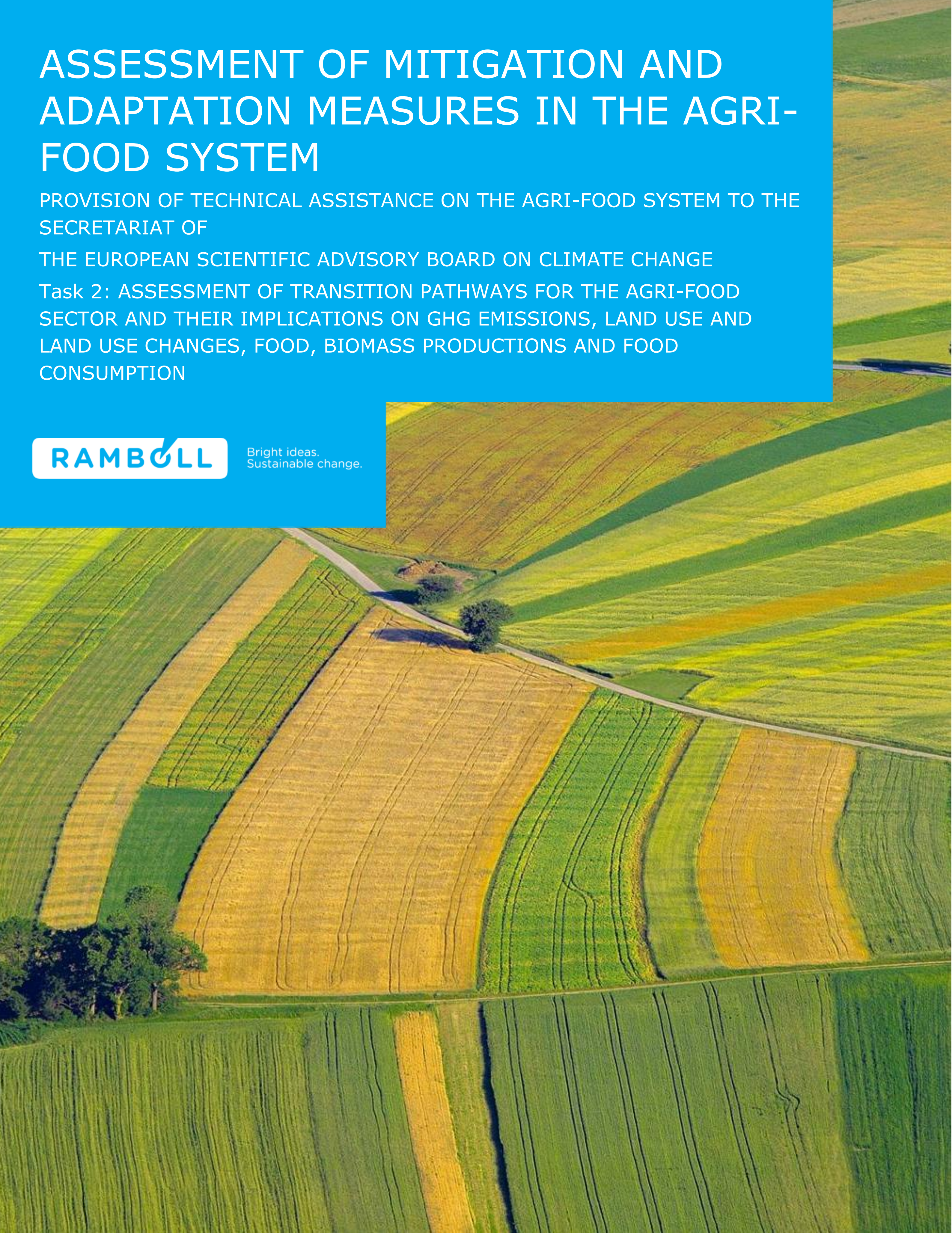

ASSESSMENT OF MITIGATION AND ADAPTATION MEASURES IN THE AGRI-FOOD SYSTEM

PROVISION OF TECHNICAL ASSISTANCE ON THE AGRI-FOOD SYSTEM TO THE SECRETARIAT OF

THE EUROPEAN SCIENTIFIC ADVISORY BOARD ON CLIMATE CHANGE

Task 2: ASSESSMENT OF TRANSITION PATHWAYS FOR THE AGRI-FOOD SECTOR AND THEIR IMPLICATIONS ON GHG EMISSIONS, LAND USE AND LAND USE CHANGES, FOOD, BIOMASS PRODUCTIONS AND FOOD CONSUMPTION

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11.03.2026

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1. INTRODUCTION

Agriculture plays a key role in tackling climate change. Agricultural activities are a source of emissions while they can also enhance carbon sequestration on agricultural land. At the same time, the agricultural sector is closely linked to the climate impact of other sectors as it provides renewable raw materials and bioenergy as input to industrial production processes and energy supply. The sector accounts for more than 10% of the EU's total GHG emissions and action to reduce its climate impact is urgently needed.

This report aims at assessing and comparing different transition pathways for the agri-food sector regarding their assumptions and results for GHG emissions and removals, the role of technical mitigation options, demand-side options, the development of livestock farming, changes in land use and crop production, trade, and income effects as well as adaptation effects.

The study reviews various scenario studies on the development of the agri-food sector for target years under different assumptions. The selection of studies is based on ESABCC Board preferences; the criteria for selection included EU data availability, climate protection focus, long-term perspective (2040, 2050), diverse methodologies, and storylines. Nine studies were chosen, using five different models. Six studies used CAPRI or MAGNET models (André et al. 2024; Rieger et al. 2023; Frank et al. 2019; European Commission (EC) 2024b; Pérez Domínguez et al. 2020) or MAGNET models (Rieger et al. 2023 (only 2050); Frank et al. 2019; Boysen-Urban et al. 2022), while the other three applied biophysical models focusing on physical and biological aspects without integrating economic information (Billen et al. 2024; Poux und Aubert 2018; Röös et al. 2022).

Additionally, key grey literature on the transformation of the agri-food sector suggested by the ESABCC was reviewed and analysed to prepare this report. This literature includes reports by major European and international organisations and think tanks like the FAO, JRC or WRI that provide visions, strategies, and policy recommendations for this transformation. The different narratives and suggested policy options of these studies were examined and are included in the analysis of key drivers for transformation in chapter 4 of this report. Furthermore, scientific literature on specific issues was consulted where necessary to support the arguments for specific strategies to reduce emissions from the agricultural sector and make it climate-resilient.

Chapter 2 provides key messages resulting from the analysis. In chapter 3, the scenarios included in selected studies are described regarding their main contents and methodology and scenario results are compared. Chapter 4 outlines key drivers for transforming the agricultural sector and includes focused comparisons of specific aspects from the quantitative scenarios complemented by policy considerations from additional literature.

2. KEY MESSAGES

- **The transformation of the agriculture and food system is 'an agenda for society as a whole.'** As a vision for the future, agriculture will serve biodiversity conservation and positively impact the climate. The macroeconomic costs of agriculture are transformed into economic benefits for farms which enable sustainable and ethical farming practices (including animal welfare) (ZKL 2021).
- Summarising the findings from stakeholder processes, official EU and international organisations, think tanks and scientific research, the vision for the future of the agri-food sector seems to be largely aligned:
    - **Firstly, all studies and stakeholder processes emphasise the role of agriculture in achieving climate neutrality by reducing emissions.**
        - **Yet, the precise level of emission reductions is not clearly defined** as it largely depends on the level of animal production and the implementation of technical mitigation measures.
        - The scenarios depict a wide range of emission reductions, from -5% to -60%, depending on the underlying model assumptions. While it is impossible to achieve complete emission reductions in the agricultural sector, the extent of residual emissions is influenced by the development of key drivers. The main drivers identified through scenario analysis include livestock numbers and animal product production, adoption of technical mitigation options, and the intensity of agricultural land use. The studies show that a mitigation potential between **-40% up to -60%** compared to 2020 is achievable, if technical mitigation options and measures that change the demand side and ultimately lead to a reduction in animal product production are considered (see EC 2024, S2/S3 and LIFE). If more ambitious assumptions are made regarding dietary changes, such as Agora Agriculture halving the consumption of animal products, reductions of up to 60% are achievable.
        - **The mitigation potential of technical measures in livestock farming is limited, ranging from 14% to a maximum of 39% of total emissions.** This variation is influenced by different assumptions regarding greenhouse gas (GHG) prices, adoption rates, and the set of mitigation measures included. The most relevant mitigation technologies include anaerobic digestion of manure and enhancing nitrogen efficiency by minimising nitrogen losses during storage and application. Additionally, breeding for feed efficiency can help reduce emissions. Furthermore, using additives to lower CH_4 emissions from enteric fermentation and manure management, as well as employing nitrification inhibitors, can significantly reduce N_2O emissions from soils. These figures reflect only the technical mitigation potential known today. The case of the 3-nitrooxypropanol feed additive (e.g. Bovaer) demonstrates that new mitigation technologies can significantly alter the landscape. However, due to the complexity of biological processes, uncertainties remain regarding their impact on animal welfare, long-term greenhouse gas (GHG) mitigation, and effects on other environmental media (IPCC 2022).
    - **Secondly, dietary change and the corresponding reduction of animal production is recognised as a key factor in climate protection and essential for adhering to planetary boundaries**.
        - **Shifting to more sustainable diets and reducing pressure on land presents the largest opportunity to significantly cut the climate impact of the agricultural sector.**
        - In stakeholder processes such as the EU Strategic Dialogue (European Commission (EC) 2024a) and the German Commission on the Future of Agriculture (Commission on the

        Future of Agriculture (ZKL) 2021), dietary change is highlighted as essential for transforming the agri-food sector. The Planetary Health Diet, published by the Eat Lancet Commission (Willett et al. 2019), forms the basis for numerous quantitative studies assessing the impact of dietary changes. Official bodies, including the Joint Research Centre and the European Commission, also release studies featuring scenarios with dietary changes and reduced animal product production (e.g. European Commission (EC) 2024b LIFE; Boysen-Urban et al. 2022).
        - **Making a significant contribution to the creation of new carbon sinks necessitates reducing animal production, as the large land use for animal feed limits the potential for alternative uses.** A significant contribution to creating new carbon sinks on agricultural land is primarily analysed in studies with reduced animal production. Without reducing the demand for animal feed and freeing up land, the potential for additional carbon sinks is limited. In the LIFE scenario of the EU Impact Assessment (EC 2024b), dietary changes lead to emission savings in the agricultural sector and an expansion of the carbon sink, improving the GHG balance of the LULUCF and agricultural sector by 111 Mt CO_2e compared to the other scenario results (S2/S3) without dietary changes.
        - Frank et al. (2019) emphasise that while technical and structural options are key for initial emission reductions, production cuts become more important at higher carbon prices in the carbon price scenarios without dietary changes. The primary driver for production cuts is the increased cost of production due to high carbon prices. If high prices are passed on to consumers, it could affect demand, but this scenario does not take that into account. Other scenarios by Frank et al. (2019) incorporate exogenous assumptions about dietary changes, leading to a reduction in animal product production in response to these changes. These scenarios highlight the significant mitigation potential of shifting diets. The models show significant mitigation potential, but the balance between production cuts and other measures depends on carbon price and regional responses. This highlights the complexity of agricultural mitigation strategies and the need for a balanced approach considering both supply-side and demand-side measures. Shifting to less meat-intensive diets in developed and emerging countries can enhance mitigation potential and improve food security in developing countries.
- Key conclusions regarding implications of and conditions for dietary changes and reducing animal production include the following:
    - **Studies generally agree that efforts to reduce GHG emissions from livestock farming and decreased livestock numbers should consider the transformation towards increased animal welfare, grassland-based feeding, and a reduction in the regional concentration of livestock farms.**
    - Rieger et al. (2023) conclude that dietary changes lead to decreased production and prices for animal-based products, while fruits and vegetables see sharp increases. International trade helps buffer these impacts. The agricultural sector in the EU-27 could benefit overall, but results vary by country, region, and farm type. In Germany, farms specialising in animal products may face income losses, while those focusing on vegetables could see gains.
    - **Therefore, a transformation in animal husbandry is feasible only if it is economically sustainable and farms have access to alternative income sources.** Economic viability is a key focus in stakeholder processes. For instance, the EU strategic dialogue mentions the establishment of buy-out schemes (EC 2024a). Most quantitative studies have not yet detailed the economic impact of reducing livestock production. Rieger et al. (2023) explore the effects of reduced demand on farms. Future sources of income for agricultural businesses are discussed qualitatively in Agora Agriculture 2024.
- **Against this background, future climate targets for the agricultural sector should prioritise both the implementation of technical measures and the reduction of animal**

product production in line with demand-side changes. This approach will help to adhere to planetary boundaries, support animal welfare, and decrease the use of human-edible agricultural products for livestock feed.

- **To design policy measures to achieve sustainable agriculture, a comprehensive approach must be taken involving regulatory changes, economic incentives, market-based instruments, and education.** Key measures include improving animal welfare, revising EU legislation, introducing consumer-side measures like mandatory labels and excise duties, developing self-sufficient farming practices, providing economic incentives for extensive farming, conditional CAP funding, and supporting alternative income sources. Additionally, it emphasises the importance of market-based instruments, education, capacity building, harmonised sustainability standards, and financing mechanisms such as an Agri-food Just Transition Fund to support the transition. **Some aspects are not sufficiently addressed in the literature. The following gaps were identified in the studies reviewed:**
  - **Emission pathways**: Only the EC's impact assessment (European Commission (EC) 2024b) and the Frank et al. (2019) study provides emission pathways extending to 2050. All other scenarios focus solely on a target year.
  - **Economic implications**: Few studies address the economic implications of transforming the agri-food sector, both on farms and throughout the value chain. Only Rieger et al. (2023) and Boysen-Urban et al. (Boysen-Urban et al. 2022) offer detailed analyses of these economic impacts.
  - **Climate change effects and adaptation**: The effects of climate change and adaptation strategies are not the primary focus of the studies considered. Most studies do not even mention these aspects. While the Agora Agriculture study discusses climate adaptation, it is not comprehensively integrated into the scenario. However, while most studies do not explicitly identify practices as adaptation measures, they are often included within the context of agro-ecology or climate mitigation strategies.
  - **Peatlands**: Peatlands are not prominently featured in the quantitative scenarios or stakeholder processes. Only Agora Agriculture (2024), the EC's impact assessment (European Commission (EC) 2024b), and the Pérez Domínguez et al. (2020) highlight the significant potential for emission reductions through peatland rewetting.

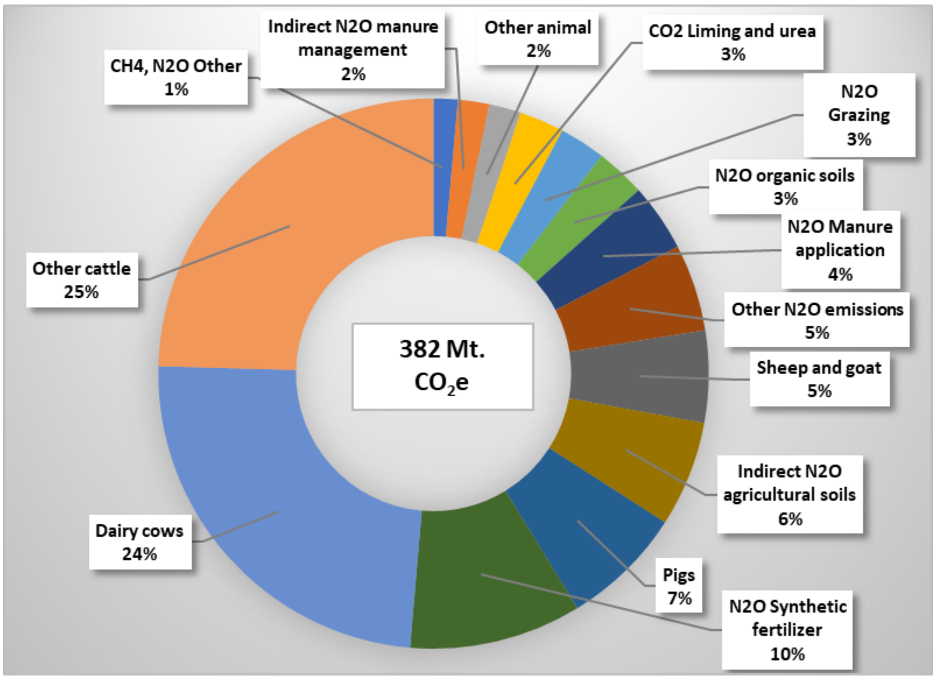
3. SCENARIOS FOR THE DEVELOPMENT OF THE AGRI-FOOD SECTOR UNTIL 2050

3.1 GHG emissions of the agri-food sector in the EU (scope)

In the Common Reporting Format (CRF) for the EU Greenhouse Gas Emission Inventory, agricultural emissions are grouped in CRF category 3. This category encompasses CH_4 and N_2O emissions from livestock farming, nitrogen input to agricultural soils, CO_2 emissions from urea application and liming, along with several other emission sources. CO_2 emissions from energy consumption in agriculture are reported under the energy sector, while emissions from fertilizer and pesticide production fall under the industry sector. CO_2 emissions and carbon sinks associated with land use and land use changes are reported in the LULUCF sector.

Nearly half of the total agricultural emissions are direct emissions of methane (CH_4) from enteric fermentation and methane (CH_4) and nitrous oxide (N_2O) from manure management in stables and storage, primarily from dairy cows and other cattle. Direct emissions from other animals, such as pigs, sheep, and goats, account for 14% of the total agricultural emissions. Nitrous oxide (N_2O) emissions from fodder production are included under various N_2O categories from agricultural soils, such as synthetic fertilizer application, manure application, and indirect N_2O emissions. N_2O emissions from agricultural soils constitute 31% of total agricultural emissions, with the largest share coming from synthetic fertilizer application, followed by indirect N_2O emissions from atmospheric deposition and nitrogen leaching into soils. Carbon dioxide (CO_2) emissions from liming and urea application, along with CH_4 and N_2O emissions from other sources, account for only 4% of total agricultural emissions. Figure 1 provides an overview of the GHG emissions reported in the CRF category 3.

Figure 1: GHG emissions of the agricultural sector in 2020

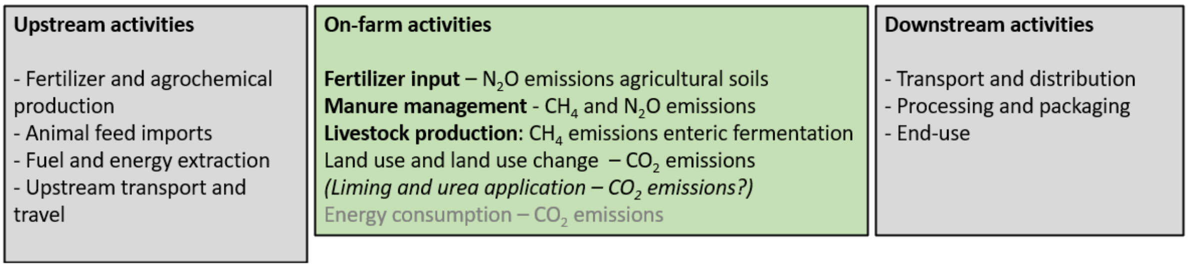


Note: Emissions from livestock include CH_4 from enteric fermentation and CH_4 and N_2O from manure management; 'CH4, N2O, Other' includes emissions from field burning, rice cultivation and other. 'Other cattle' includes also breeding of dairy cows such as calves and heifers.

Source: European Environment Agency (EEA) 2023

Figure 2 gives an overview of the agricultural supply chain and the system boundaries of the analysis.

Figure 2: System boundaries and scope of study focus



Source: Authors' own overview (Oeko-Institut)

The analysis concentrates on agricultural emissions at the farm gate level. Most studies do not include CO_2 emissions from land use and land use changes; if available, these are outlined separately (see Chapter 4.4.5). Emissions from both upstream and downstream activities are also excluded from the analysis. Some studies highlight the impact of animal feed imports or virtual land trade in various scenarios (see Chapter 4.5.2). Reducing feed purchases abroad or achieving positive land trade effects could lead to sustainability benefits abroad.

3.2 Overview of studies and methodology

The study evaluates various scenario studies that describe the development of the agri-food sector for a target year under different assumptions. These studies, published between 2018 and 2024, were selected based on a list of literature references provided by the ESABCC Board. The selection criteria included the following:

- availability of EU data,
- a focus on climate protection,
- a long-term perspective (2040, 2050),
- different methodological approaches, and
- diverse storylines.

As a result, nine studies were selected, modelling different scenarios using five different models. Six of these studies use general equilibrium models (CGE) such as the CAPRI model (André et al. 2024; Rieger et al. 2023; Frank et al. 2019; European Commission (EC) 2024b; Pérez Domínguez et al. 2020) or MAGNET model (Rieger et al. 2023 (only 2050); Frank et al. 2019; Boysen-Urban et al. 2022). The other studies (Billen et al. 2024; Poux und Aubert 2018; Röös et al. 2022) apply agro-ecological models with a focus on the physical and biological aspects of agricultural systems, such as crop growth, soil health, and environmental impacts. They are not integrated with economic models to include economic information.

The CAPRI and MAGNET model are used at EU level for policy analysis, climate change mitigation, economic forecasting, and integrated analyses. The CAPRI model is a global partial equilibrium model for assessing agricultural, environmental, and trade policies, focusing on the EU. It integrates regional supply models for 280 European regions and a global market model for 44 trade regions, analysing policy impacts on markets, production, and the environment. The MAGNET model is a global computable general equilibrium model. Its agricultural component analyses policy and market impacts, representing various sectors, tracking resource use, and assessing environmental impacts. It models international trade flows and addresses bioeconomy and sustainability, aiding in understanding policy and market responses. General equilibrium models are economic models that analyse the economy-wide impacts of policies and changes, considering multiple markets and sectors. The development of livestock numbers and production of animal products in these models is typically driven by market dynamics, prices, and economic policies, rather than detailed ecological interactions. The impact of dietary changes on production can be incorporated into these models by introducing preference shocks caused by dietary shifts, which modify agricultural prices and, in turn, affect production.

Three different agro-ecological models are utilised in the studies included in this analysis (Billen et al. 2024; Poux und Aubert 2018; Röös et al. 2022). These agro-ecological models consider not only biophysical processes but also the interactions between various components of the agroecosystem, such as biodiversity, crop rotation and other environmental effects. The development of livestock numbers and the production of animal products often rely on a combination of exogenous assumptions about dietary changes and the availability of land and feed resources for livestock production.

Most studies vary in the questions that they address, the modelling approaches that they use, and the design of their scenarios. For the scenario outcome, assumptions on demand-side changes and their impact on the production of animal products are relevant.

- **Agora Agriculture (2024):** The Agora Agriculture study titled 'Agriculture, Forestry and Food in a Climate Neutral EU' explores pathways for the land use sectors to contribute to a climate-neutral EU by mid-century. It uses the CAPRI (Common Agricultural Policy Regionalised Impact) model. This model is employed to ensure the consistency of assumptions and to derive economic and environmental results for the agriculture and food demand sectors. The study's modelling approach aims to assess the potential of the agriculture, forestry, and food sectors to achieve climate neutrality, enhance biodiversity, and improve human health and other societal sustainability objectives. Assumptions on demand-side changes, share of semi-natural landscapes, rewetted agricultural land on organic soils, growing of lignocellulose crops and nitrogen standards are pre-defined and exogenous scenario inputs. Production changes and reduction in livestock numbers are a consequence of such external assumptions (e.g. nitrogen standards).
- **Billen et al. (2024):** The study titled 'Beyond the Farm to Fork Strategy' uses the **GRAFS** (Generalized Representation of Agri-Food Systems) model to analyse the European agri-food system. The GRAFS (Generalized Representation of Agri-Food Systems) model describes nitrogen (N) fluxes across cropland, grassland, livestock, and human consumption. It divides Europe into 127 geographical units and quantifies N fluxes based on agricultural activity data. The model is used to explore **three scenarios** for the European agri-food system in 2050: **business-as-usual (BAU), Farm to Fork (F2F), and agro-ecological (AE)**. The scenarios differ in terms of dietary patterns, agricultural practices, and livestock management. The agro-ecology scenario envisions a future European agri-food system that emphasises sustainability and environmental stewardship. The Farm to Fork (F2F) scenario is designed to assess the impact of the measures prescribed in the European Commission's Farm to Fork and Biodiversity Strategies. Livestock populations and production of animal products are based on assumptions about dietary changes, assumptions about feed imports and the limit in terms of feed resources decided in the storylines of the scenario. This methodology ensures that livestock numbers are calculated based on the availability of feed resources and the efficiency of livestock production, taking into account regional variations and specific constraints of each scenario.
- **Boysen-Urban et al.** (Boysen-Urban et al. 2022): This study assesses the impact of behavioural changes in food consumption, focusing on SDG target 12.3 (halve global per capity food waste). It uses the MAGNET model, a global economic simulation tool, to explore

medium- to long-term scenarios. The model examines the sustainability implications of changes in the global food system, considering economic, social, and environmental indicators. The first scenario investigates the impact of reducing global food waste and food loss (FWL) by 2030 and maintaining it until 2050. Additional scenarios explore: (i) food waste and food loss reductions in isolation, (ii) variations in compliance costs, (iii) resilience to rising fossil energy prices, and (iv) a shift to healthier plant-based diets inspired by the EAT-Lancet report.

  - The analysis of this study is not included in the Chapter 3.3 scenario results as information on emission reduction is only available in absolute figures compared to a baseline. A comparison against a historic year or a baseline is not possible as no relevant information is available. Therefore, information is only included in Chapter 4 if available.

- **EC (2024b)**: The aim of the EU Impact Assessment for the 2040 climate targets is to evaluate the potential effects of proposed policies and measures to achieve significant reductions in greenhouse gas emissions. For the EU Impact Assessment on 2040 targets, several modelling tools are used to project the future development of various sectors. For the agricultural sector, the CAPRI model was utilised to evaluate the effects of agricultural, trade, and environmental policies on agriculture, including biodiversity aspects related to agriculture. Technical mitigation measures are implemented through a GHG pricing mechanism, while the production of animal products is driven by consumer demand. There are three representative scenarios (S1, S2, S3) included in the impact assessment. They all achieve climate neutrality by 2050 but differ in their net GHG levels in 2040. In addition, a LIFE scenario is calculated in which more sustainable lifestyles are assumed. The LIFE variant assesses how societal trends might impact future GHG emissions and opens the debate on their role in achieving climate neutrality by 2050.
- **Frank et al. (2019):** The study assesses the potential for reducing agricultural non-CO_2 emissions to meet the 1.5°C climate target. The study aims to quantify agriculture's contribution to the 1.5°C climate target by decomposing mitigation potentials by emission source, region, and mechanism. It uses four global economic models (CAPRI, GLOBIOM, IMAGE, MAGNET) to assess methane (CH_4) and nitrous oxide (N_2O) emissions. The mitigation mechanisms include technical options, structural changes, and production effects. Eight carbon price trajectories (up to 2500 USD/tCO_2e by 2070) were implemented to estimate cost-efficient mitigation potentials. **Scenarios without dietary changes:** Production changes are a consequence of market developments and GHG pricing. **Scenarios with dietary changes:** Production changes are a consequence of market developments (GHG pricing) and assumptions on dietary changes and a reduction in demand.
  - Only three carbon price scenarios per variant (without/with dietary changes) were considered in this study. The analysis was carried out for a low, a medium and a very high carbon price scenario.
- **Pérez-Domínguez et al. (2020):** The study offers an economic assessment of GHG mitigation policy options for EU agriculture. It focuses on technical mitigation options within the CAPRI model and quantifies the mitigation potential of individual measures.
  - This study does not present a comprehensive scenario for future agriculture but instead focuses on individual mitigation options. The results of this study can be found in sections 4.3.3.2 and 4.4.4.1.
- **IDDRI (Poux und Aubert 2018)**: The IDDRI study evaluates the feasibility and benefits of transitioning to an agro-ecological farming system in Europe by 2050. The TYFA model

treats the EU-28 as a single unit, focusing on balancing production and consumption and managing nitrogen cycles. It incorporates nutritional recommendations, simulates crop and livestock production, differentiates between nitrogen-fixing and non-fixing crops, includes agro-ecological infrastructures, and tracks nitrogen inputs and outputs. The development of animal numbers in the TYFA scenarios is calculated based on a holistic approach that integrates dietary changes, extensive farming practices, local resource use, and nutrient cycling. Livestock numbers are adjusted based on the availability of local feed resources. This means that the number of animals is directly linked to the capacity of the local environment to support them without relying on imported feed.

- **Rieger et al**. (2023): The study uses an agro-economic modelling framework to assess the impacts of dietary changes towards the EAT-Lancet recommendations on the agricultural sector in the EU-27. The study focuses on the years 2030 and 2050. The CAPRI model is used for calculations for 2030, while the MAGNET model is employed for 2050. Additionally, regional results for Germany are derived using the FARMIS model. The study models two scenarios for 2030 and three scenarios for 2050, assuming a partial shift of EU-27 consumption patterns towards the EAT-Lancet diet, and a full adoption of the EAT-Lancet diet by 2050. Dietary changes are modelled as preference shocks, which alter agricultural prices and subsequently influence production.
- **Röös et al. (2022)**: The study assesses the environmental and economic impacts of transitioning to agroecological farming and healthy diets in the EU by 2050. Using two biophysical models, BioBaM and SOLm, the study simulates outcomes related to land use, food production, environmental and social indicators, and regional food self-sufficiency. Scenarios include different dietary patterns, such as the EAT-Lancet diet, and consider yield levels, nitrogen management, and agro-ecological practices. The models track greenhouse gas emissions, nitrogen surplus, water use, pesticide use and energy use. The 'Local-agro-ecological-food-systems' scenario describes a future where local food systems are developed with a strong focus on agro-ecological practices. The 'Localisation-for-sustainability' focuses on creating sustainable and resilient local food systems. Demand-side changes are considered through modifications in dietary patterns and food waste reduction. These changes significantly impact the production of animal products. The development of animal numbers in the Röös et al. scenarios is calculated by integrating livestock diets, productivity improvements, and redistribution of livestock production based on land availability.

Nineteen scenarios were selected from the nine studies for analysis. In addition to the target scenarios, some baseline scenarios are available and described in Chapter 3.3.3. Certain scenarios were excluded because they result in increased emissions (e.g. (Röös et al. 2022)). The following analysis provides information on GHG emissions and all aspects of key drivers for these nineteen scenarios and also information on the baseline scenarios. Unfortunately, not all scenarios include data on the complete set of identified key drivers, resulting in some tables lacking information for certain scenarios.

The analysis also includes information on scenarios achieving emission reductions of up to 20%. These scenarios may not be compatible with achieving climate neutrality by 2050 due to their low emission reductions. However, brief information on these scenarios is included for reference.

Table 1 provides an overview of the scenarios and the key elements included in each. More detailed information on these key drivers can be found in the relevant chapter on key drivers. Additionally, the table indicates whether the scenario or model uses a 'backcasting' approach, where the 2050 outcome (e.g. reductions) is predefined and the model identifies the best way to achieve it, or an approach in which the model introduces incentives (e.g. price signals) that determine the final outcome endogenously. The overview shows that a backcasting approach is applied in almost all scenarios. Only the scenarios in Frank et al. (2019) without dietary changes do not apply a backcasting approach as the results arise from the different GHG prices.

Table 1: Overview of scenarios

Study	Number	Scenario name	Reference compared to	Backcasting approach	Technical mitigation	Dietary changes	Food loss and waste	Extensification (Biodiversity, organic farming)	Reduction in animal product	Rewetting of peatland	Natural carbon sinks
Agora Agriculture 2024	S1	Agora Agriculture	2020	Yes	x	x	x	x	x	x	x
Billen et al. 2024	S2-2	BAU-20%fert.	2014:2019	Yes	n/a	-	-	x	-	n/a	n/a
	S2-4	Farm to fork	2014:2019	Yes	n/a	-	?	X	x	n/a	n/a
	S2-5	Agro-ecology	2014:2019	Yes	n/a	X	x	X	X	n/a	n/a
	S2-6	Agro-ecology current diet (sub-scenario)	2014:2019	Yes	n/a	-	-	x	X	n/a	n/a
EC 2024	S4-2/3	S2/S3	2020	Unclear	x	-	-	-	-	x	x
	S4-4	LIFE	2020	Yes	x	x	x	X	x	x	x
Frank et al. 2019	S5-1	GHG price of 50 USD/tCO_2	Baseline 2050	No	x	-	?	n/a	-	n/a	n/a
	S5-2	GHG price of 125 USD/tCO_2	Baseline 2050	No	x	-	?	n/a	x	n/a	n/a
	S5-3	GHG price of 2500 USD/tCO_2	Baseline 2050	No	X	-	?	n/a	x	n/a	n/a
	S5-1_diet	GHG price of 50 USD/tCO_2_diet changes	Baseline 2050	Partly	x	x	?	n/a	x	n/a	n/a

Study	Number	Scenario name	Reference compared to	Backcasting approach	Technical mitigation	Dietary changes	Food loss and waste	Extensification (Biodiversity, organic farming)	Reduction in animal product	Rewetting of peatland	Natural carbon sinks
	S5-2_diet	GHG price of 125 USD/tCO_2_diet changes	Baseline 2050	Partly	x	x	?	n/a	x	n/a	n/a
	S5-3_diet	GHG price of 2500 USD/tCO_2_diet changes	Baseline 2050	Partly	x	x	?	n/a	x	n/a	n/a
Poux et al. 2018	S7-1	TYFA	2010	Yes	n/a	x	x	x	x	n/a	n/a
Rieger et al. 2023	S8-1	Lancet low	Baseline 2050	Yes	n/a	x	x	n/a	x	n/a	n/a
	S8-2	Lancet high	Baseline 2050	Yes	n/a	x	x	n/a	x	n/a	n/a
	S8-3	Lancet full	Baseline 2050	Yes	n/a	x	x	n/a	x	n/a	n/a
Röös et al. 2022	S9-3	Localisation for sustainability	2012	Yes	n/a	x	x	X	x	n/a	x
	S9-4	Local-agroecological-food-systems	2012	Yes	n/a	x	x	x	x	n/a	x

Note: The abbreviation 'n/a' is used if it is not a focus of the study; '-' is used if it is not part of the scenario.
This table presents all scenarios included in this analysis (except baseline scenarios). The ID used is taken from the Excel database. The Excel database includes all scenarios in the analysed studies. However, as some scenarios result in emission increases or do not provide the appropriate information needed for the analysis, they are not included in this table.
Source: Authors' own compilation, Oeko-Institut

As shown in the Table 1 the agro-ecological scenarios analysed in this study do not incorporate technical mitigation measures such as feed additives, nitrification inhibitors, or anaerobic digestion. Additionally, studies utilising computable general equilibrium (CGE) models, such as those by Rieger et al. and Boysen-Urban et al., do not include these technical mitigation options due to their different focus. However, scenarios that integrate both technical mitigation measures and reductions in animal product production include Agora Agriculture (2024), EC (2024b) LIFE, and those by Frank et al. (2019) with high greenhouse gas (GHG) prices, as well as the scenarios combining dietary changes with GHG pricing.

Most studies provide information only for a target year rather than describing a trajectory towards such a target year. Only the EC's impact assessment (European Commission (EC) 2024b) offers data for both 2040 and 2050. Frank et al. (2019) and Rieger et al. (2023) also provide information for 2030. However, data for 2030 is not included, as the study focuses on 2040 and 2050.

Baseline scenario versus base year

While some studies offer information relative to a historic base year, others compare only to a future baseline scenario. The baseline scenario accounts for developments such as population changes, dietary assumptions, and occasionally includes technical mitigation options.

Illustrating developments against a baseline scenario is sufficient to show the impact of different scenario assumptions. However, if baseline emissions increase due to population growth, rising demand for animal products, and increased trade, a 50% emission reduction in the target scenario compared to the baseline scenario is not equivalent to a 50% reduction compared to a historic base year (e.g. 2020). Therefore, it is unclear whether this emission reduction is sufficient to meet climate targets.

3.3 Scenario results

3.3.1 Emission scope of the scenario results

All models account for (at least) non-CO2 emissions from the agricultural sector at the farm level, except for the Billen et al. (2024) study, which focuses solely on N2O emissions from agriculture and does not consider CH4 and other emission sources. However, for some scenarios, it is unclear whether CO2 emissions from urea and lime application, as well as N2O and CH4 emissions from other sources (e.g. anaerobic digestion of crops and residual material), are included. Furthermore, all scenarios either exclude emissions and sinks from the LULUCF sector or report this information separately to avoid any confusion. The Agora Agriculture scenario (2024) includes CO2 emissions from drained peatlands, but reports these figures separately. The Röös et al. (2022) study also provides information on the GHG balance, including carbon sinks on agricultural land, but this information is also reported separately. The Iddri (2018) study also provides information on the development of emissions from energy consumption and nitrogen production, among other factors. Since emissions are reported separately by category, these emissions are not included in the following analysis. The information contained in Figure 3 includes only GHG emissions from the agricultural sector included in the CRF category 3.

3.3.2 Overview of scenario results

Figure 3 shows the results of the selected studies on GHG emission reductions in the agri-food sector. The scenarios depict a wide range of emission reductions, from -5% to -60% compared to a historic reference year or in comparison to a 2050 baseline, depending on the underlying scenario assumptions. Despite the use of different reference years and baseline scenarios, the comparison of these studies highlights the potential for emission reductions in the agri-food sector. While it is impossible to achieve emission reductions to zero in the agricultural sector, the level of residual emissions is influenced by the development of key drivers. The main drivers identified through scenario analyses include livestock numbers and animal product production, adoption of technical mitigation options, and the intensity of agricultural land use.

There are **four scenarios** (excluding the scenario of the Member States) that fall within the range of **up to -20% emission reductions** compared to a historic reference year or in comparison to a 2050 baseline. These scenarios already exhibit varying assumptions regarding key drivers, including development of animal production, adoption of technical mitigation measures, and use of agricultural land (Billen et al. 2024); (Frank et al. 2019).

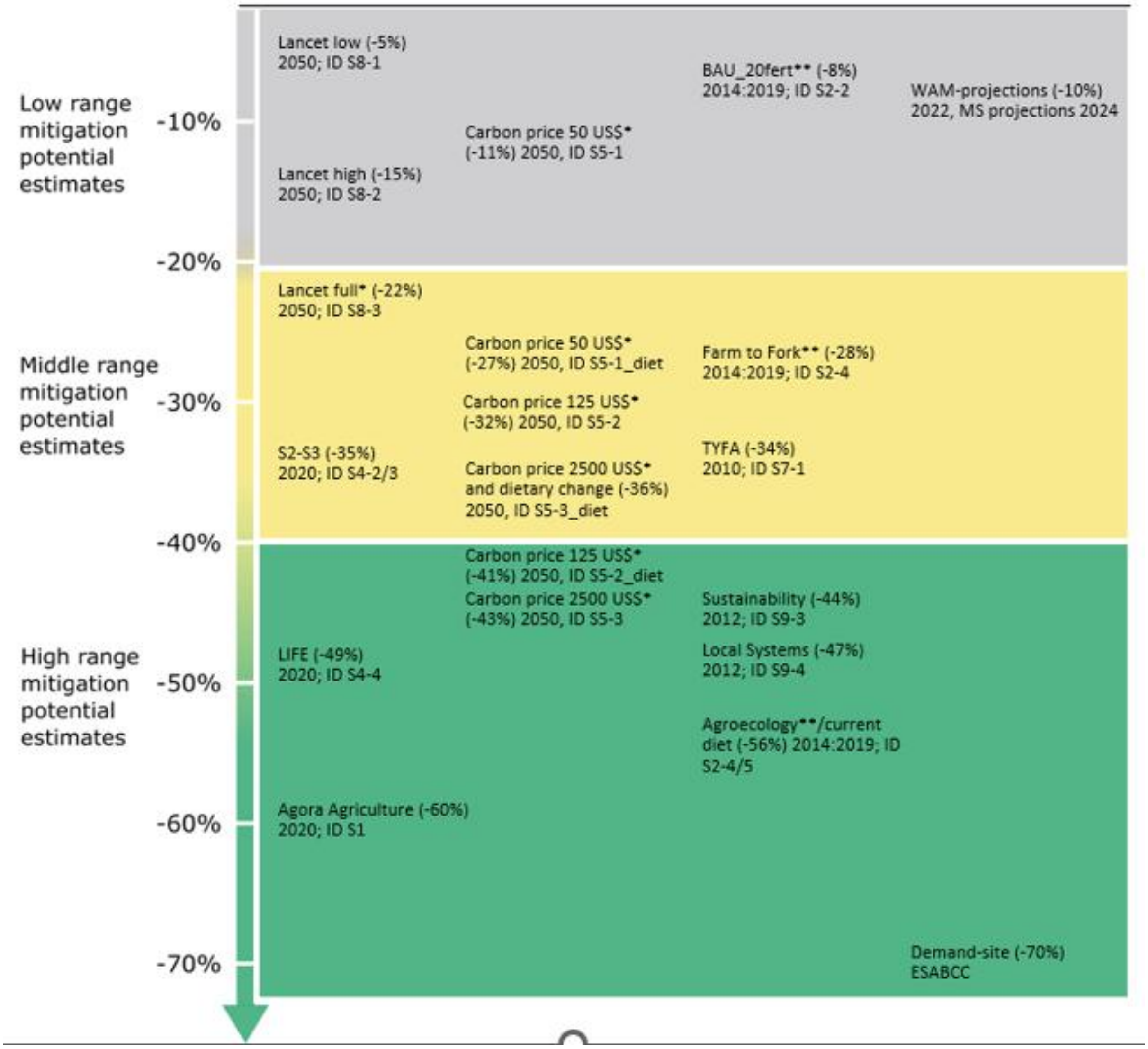
Seven scenarios describe a mid-range mitigation potential of **-20% to -39%** compared to a historic reference year or in comparison to a 2050 baseline. Like the low mitigation potential scenarios, the assumptions regarding key drivers vary. Within this range, there is also a scenario in the EC’s impact assessment (European Commission (EC) 2024b, S2/S3) that slightly increases animal product production, while all other scenarios in this group assume reduced production of animal products. In this S2/S3 scenario, emission reductions are achieved through the adoption of technical mitigation measures.

Eight scenarios form the largest group of scenarios that contain high range mitigation potentials. However, the fact that the highest number of scenarios is found in this range is rather coincidental and due to the selection of studies. All scenarios with more than **40% emission reductions** compared to a historic reference year or in comparison to a 2050 baseline share a common feature: they include **dietary changes** as a key driver in their assumptions. The only exception is the scenario by Frank et al. (2019), which forecasts carbon prices reaching $2,500 by 2070 (and $950 by 2050). In this scenario, dietary changes are not considered as external input assumptions. Instead, the high carbon price drives production changes, resulting in reduced GHG emissions. If high prices are passed on to consumers, it could affect demand. However, this scenario does not take this possibility into account. All scenarios in this group indicate a decline in livestock numbers and a decrease in animal product output. The extent of reduction in animal products varies significantly, ranging from stable dairy production and a 21% decrease in meat production (European Commission (EC) 2024b, LIFE) compared to 2020 to a 69% reduction in dairy and a 76% decrease in meat production (Röös et al. 2022, local system) compared to 2012. In addition to the reduction in animal products, scenarios vary in terms of the assumed implementation of technical mitigation measures and land use. The use of land for increasing carbon removals becomes more relevant in scenarios with more than a 40% emission reduction. Reducing animal products frees up land for other uses as it is no longer required for fodder production.

The contribution of the agri-food sector to achieving climate neutrality remains unclear. Only the scenarios in the EC's impact assessment (European Commission (EC) 2024b) are integrated with other sectors meeting different 2040 targets (S2 = 85% and S3 90% reduction compared to 1990 levels) and achieving climate neutrality by 2050. The scenarios in the EC's impact assessment (European Commission (EC) 2024b) achieving climate neutrality by 2050 show emission reductions in the agricultural sector ranging from 35% (S2/S3) to 49% (LIFE) compared to 2020 levels (see Figure 3)

Figure 3 provides an overview of the scenario results for the year 2050, comparing them either to a historic reference year or a 2050 baseline. The figure specifies whether the comparison is against a reference year or a baseline scenario. Notably, only the carbon price scenarios in Frank et al. (2019) (S5-1 to S5-3_diet) and the scenarios in Rieger et al. (2023) (S8-1 to S8-3) compare emission reductions solely against a 2050 baseline scenario. All other scenarios compare emission reductions against a historic year. The Agora Agriculture study leaves the target year open, mentioning either 2045 or 2050 as a target year. All results include only emissions from the agricultural sector (Inventory Common Reporting Format (CRF) 3) and no emissions from LULUCF or energy consumption.

Figure 3: Overview of scenario results from different studies for the year 2050



*Note: *The carbon prices in Frank et al. (2019) present the name of the scenario and are reached in 2070. For 2050, the carbon prices are different ($2500 in 2070 = $950 in 2050; $125 in 2070 = $100 in 2050; $50 in 2070 = $20 in 2050). Frank et al. (2019) present results for four different models. The results shown here represent the mean value, summarising the outcomes of these models. While this provides only a rough overview due to variations among the models, detailed results for each model are available in the Excel file.*

*** The scenarios in Billen et al. 2024 focus only on N_2O emissions.*

The scenarios of the Member States and the demand-side data from the ESABCC are only included for information purposes only.

Source: Authors' own diagram (Oeko-Institut) based on different studies.

In addition to the studies and scenario results presented in Figure 3, Boysen-Urban et al. (2022) analyse the effects on GHG emissions, water, and land across different scenarios. Since results are only presented as absolute emission reductions, they cannot be compared to relative baselines or historic emissions. Therefore, only specific aspects will be analysed in Chapter 4.

The following chapters provide a detailed description of the scenarios, beginning with the baseline scenarios and followed by the high mitigation range scenarios.

3.3.3 Baseline scenarios

In addition to various GHG mitigation scenarios, some studies also provide information on baseline scenarios, illustrating the development of emissions based on assumptions about population growth and other factors.

Three studies (Billen et al. 2024; Frank et al. 2019; Röös et al. 2022) provide information on baseline GHG reductions compared to a historical reference year. All other studies either compare their results directly to a historic reference year (e.g. André et al. 2024; European Commission (EC) 2024b; Poux und Aubert 2018) or do not include baseline values in comparison to a historic reference year (e.g. Rieger et al. 2023; Boysen-Urban et al. 2022).

Emissions in the baseline scenarios for 2050 range from a 10% reduction compared to 2010 (Frank et al. (2019), dietary changes) to a 13% increase compared to 2012 (Röös et al. 2022). Frank et al. (2019) provide two baseline scenarios: one with a 10% reduction compared to the historic year 2010, assuming dietary changes, and another without dietary changes, resulting in a 12% increase compared to 2010. For the baseline scenario without dietary changes, Frank et al. (2019) assume higher production levels in animal products due to increased demand from a wealthier and larger world population. The baseline scenario continues current agricultural production practices without significant mitigation technologies or sustainable farming practices. Although efficiency gains in livestock and crop production are assumed, they cannot counteract the overall increase in production. Similarly, the baseline scenario in Röös et al. (2022) assumes higher production volumes, particularly for meat, due to rising demand and a limited adoption of sustainable practices, leading to increased emissions. In contrast, the baseline scenario in Billen et al. (2024) shows a slight reduction in emissions by 2050 (compared to a historic base period 2014:2019), assuming no significant population increase and no changes in current agricultural practices. Potential efficiency gains in livestock production are not explicitly considered.

Compared to the other baseline scenarios, the baseline scenario with dietary changes from Frank et al. (2019) explicitly assumes dietary changes, leading to decreased demand for animal products and a reduction in livestock units within the baseline scenario. The 'with existing measures' (WEM) scenario of the EU Member States is considered a reference scenario as it reflects the current status of national and European policies implemented in the agricultural sector, along with further developments. The figures provided for the EU represent the sum of 27 scenarios provided by each Member State. However, there is no additional information available on specific data, such as production development and animal numbers, for the individual Member States (European Environment Agency (EEA) 2023).

Table 2: Overview of different aspects in the baseline scenarios

Study/ scenario	Compared to	GHG mitigation	Technical mitigation	Production	Livestock	Carbon removals	Trade
Chapter link		4.3.3 4.4.4.1	4.3.3.2 4.4.4.1	4.3.2	4.3.2	4.4.5	4.5
Frank et al. 2019 BAU_dietary shift**	Base year 2010	-10%	?	-7% dairy -11% ruminant meat -8% non-ruminant meat	n/a	n/a	n/a

Study/ scenario	Compared to	GHG mitigation	Technical mitigation	Production	Livestock	Carbon removals	Trade
Member States WEM	Base year 2020	-5%	Yes, minimum	n/a	n/a	n/a	n/a
Billen et al. 2024 BAU	Base period 2014-2019	-3%	No	n/a	+7% LSU	n/a	Yes
Billen et al. 2024 BAU_low diet	Base period 2014-2019	0%	No	n/a	+3% LSU	n/a	Yes
Frank et al. 2019 BAU**	Base year 2010	+12%	?	+18% dairy +15% ruminant meat +20% non-ruminant meat	n/a	n/a	n/a
Röös et al. 2022 BAU	Base year 2012	+13%	No	+15% ruminant meat -6% pig and poultry meat -18% dairy	n/a	Carbon sequest-ration on 17% of total agri-cultural land	n/a

*Note: * Figures read from graph; **Only N_2O emissions; ** Frank et al. (2019) present results for four different models. The results shown here represent the mean value, summarising the outcomes of these models. While this provides only a rough overview due to variations among the models, detailed results for each model are available in the Excel file.*
Source: Authors' own compilation (Oeko-Institut).

3.3.4 Scenarios achieving high reduction in GHG emissions (more than a 40% reduction)

Eight scenarios in five different studies show reductions of more than 40% compared to reference levels. All scenarios that achieve emission reductions of more than 35% assume dietary changes that reduce the demand for animal products. Reducing the production of animal products – for example as a change in demand – frees up land for other purposes, as less agricultural area is needed for livestock feeding. This outcome is reflected in four of the eight scenarios. These scenarios link the freed-up land to increased carbon removals on agricultural land.

Further emission reductions can be achieved by implementing technical mitigation options. However, only four of eight scenarios reflect the potential of these options to further reduce agricultural emissions.

Achieving emission reductions of more than 35% necessitates a decrease in livestock numbers. Scenarios with reductions exceeding 40% consistently show significant declines in livestock populations, leading to lower production of animal products. The Agora Agriculture study (André et al. 2024) shows the highest mitigation percentage at -60% relative to the 2020 base year.

Despite achieving similar emission reductions, the production levels of animal products can vary greatly. Without the use of technical measures, a significantly larger reduction in livestock numbers is necessary. This is clearly illustrated when comparing the LIFE scenario in the EC's impact assessment (European Commission (EC) 2024b) to the Local System scenario (Röös et al. 2022). The EC LIFE scenario achieves a reduction of 49% compared to the reference year[1], while the Local System scenario in Röös et al. (2022) achieves a 47% reduction. However, in the LIFE scenario, dairy production remains constant at 2020 levels, and meat production decreases by 21%. In contrast, the Local System scenario shows a 69% reduction in dairy production and a 76% reduction in meat production. The LIFE scenario incorporates technical mitigation options and efficiency improvements in livestock farming, such as increasing milk yields. In contrast, the Local System scenario focuses on extensive agricultural production. Efficiency is even reduced, for example, by 10% for monogastric, and there is a 50% yield gap in crop production compared to the reference scenario. Additionally, 50% of cropland is managed with strong agro-ecological practices, producing for local markets with short supply chains. Animal welfare has been enhanced for all animal categories, with ruminant production being grass-based and adjusted to local land availability. Billen et al. (2024) also present an agro-ecology scenario that does not include increased efficiency or technical mitigation measures. In the agro-ecology scenario by Billen et al. (2024), livestock numbers are reduced by 41% compared to the historic base period 2014:2019, and emissions (specifically N_2O emissions) are reduced by 56%.

Frank et al. (2019) present two scenarios achieving approximately 40% emission reductions at varying carbon prices. In the scenario without dietary changes, a 43% reduction is attained at a carbon price of $950 in 2050 ($2500 in 2070). This reduction is driven by the implementation of technical and structural measures, as well as production cuts induced by the high carbon price. Conversely, the dietary changes scenario achieves a similar 41% reduction (compared to the baseline) at carbon prices of around $50 in 2050 ($125 in 2070). In this scenario, production changes are driven by demand changes which are based on external assumptions and are independent of the carbon price. Additional emission reductions are realised through technical and structural measures prompted by the carbon price.

Land freed from fodder production is repurposed for extensification production (Billen et al. 2024; Poux und Aubert 2018; André et al. 2024; European Commission (EC) 2024b) and boosting carbon removals (André et al. 2024; European Commission (EC) 2024b; Röös et al. 2022). This aspect of changes in land use is not addressed in Frank et al. (2019). Various measures are implemented in the scenarios to enhance carbon removals. In the scenarios included in Röös et al. (2022), all freed land is allocated to natural revegetation. The significant reduction in livestock numbers frees up a large amount of land, which is then used for natural revegetation, creating substantial carbon sinks (see chapter 4.4.2 and 4.4.5). In the scenarios in Agora Agriculture (2024) and the LIFE scenarios in the EC's impact assessment (2024b), land is allocated for afforestation (both scenarios) and for growing lignocellulose crops (André et al. 2024). Additionally, it is used to enhance biodiversity areas.

Trade is only reflected in the study by Agora Agriculture (2024) and Billen et al. (2024). In the study by Agora Agriculture (2024), trade balances improve with increased exports, particularly for dairy products, while remaining constant for meat and cereal products. However, trade balances shift to net imports for vegetables and show increased net imports for fruits due to the high demand associated with changing diets. In the agro-ecology scenario in Billen et al. (2024), imports of livestock feed are not permitted. There is still a net export of vegetable food and animal products, but at a lower level than in the reference year due to changes in demand and reduced production.

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[1] The studies show different reference years. LIFE = 2020, Local Systems = 2012. However, the differences in emissions between 2012 and 2020 amount to only 1.7% as emissions did not change drastically over this time.

Table 3: Overview of different aspects for scenarios achieving an emission reduction of more than -40%

Study/ scenario	Compared to	GHG mitigation	Technical mitigation	Production	Livestock	Carbon removal	Trade
Chapter link		4.3.3 4.4.4.1	4.3.3.2 4.4.4.1	4.3.2	4.3.2	4.4.5	4.5
Agora Agriculture 2024	Base year 2020	-60%	Yes	-27% dairy -49% meat	- 52% cattle	12.7 million ha of ligno-cellulosic crops	Yes
Billen et al. 2024 Agro-Ecology /Agro-Ecology current diet	Base period 2014-2019	-56%*	No	n/a	-41% LSU	No	Yes
EC 2024b LIFE	Base year 2020	-49%	Yes	0% dairy -21% meat	-28%	+ 6.9 million ha high diversity land-scape (hedges, buffer strip etc.) 8.9 million ha afforestation	n/a
Röös et al. 2022 Local systems	Base year 2012	-47%	No	-69% dairy -76% meat	n/a	Carbon sequest-ration on 23% of total agri-cultural land	n/a
Röös et al. 2022 Sustain-ability	Base year 2012	-44%	No	-63% dairy -72% meat	n/a	Carbon sequest-ration on 48% of total agri-cultural land	n/a

Study/ scenario	Compared to	GHG mitigation	Technical mitigation	Production	Livestock	Carbon removal	Trade
Frank et al. 2019 Carbon price $2500 **	Baseline 2050	-43%	Yes	-12% dairy -20% ruminant meat -23% non-ruminant meat	n/a	No	n/a
Frank et al. 2019 Diet changes Carbon price $125**	Baseline 2050	-41%	Yes	-22% dairy -22% ruminant meat -24% non-ruminant meat	n/a	No	n/a

*Note: Only N_2O emissions; ** Frank et al. (2019) present results for four different models. The results shown here represent the mean value, summarising the outcomes of these models. While this provides only a rough overview due to variations among the models, detailed results for each model are available in the Excel file. The name of the scenarios reflects the carbon prices in 2070, while the results are presented for 2050. As a rough estimate, carbon prices of $2,500 in 2050 represent a carbon price of $950 in 2050, carbon prices of $125 in 2070 represent a carbon price of about $50 in 2050.*
Source: Authors' own compilation (Öeko-Institut)

Scenarios emphasising extensive agro-ecological production, such as those by Billen et al. (2024), and Röös et al. (2022), demonstrate a reduction in animal numbers of about 40% (Billen et al. 2024) or a reduction in animal production of more than 60% (Röös et al. 2022), achieving emission reductions of 40% to 56% compared to reference levels. Conversely, studies that incorporate technical mitigation measures, like those by Agora Agriculture (2024), the LIFE scenario in the EU's impact assessment (European Commission (EC) 2024b), and Frank et al. (2019), attain higher emission reductions with a smaller decrease in animal products.

3.3.5 Scenarios achieving moderate reduction in GHG emissions (-20% up to -40%)

Seven of nineteen scenarios show moderate emission reductions, achieving reductions between 22% and 36% compared to a reference. These seven scenarios are derived from five distinct studies.

Determining the key drivers for scenarios with moderate GHG emission reductions is difficult due to their limited similarities. While some scenarios involve changes in demand and production (Rieger et al. 2023), others focus solely on technical mitigation options (European Commission (EC) 2024b, S2/S3). Only the EU impact assessment study considers increased carbon sinks by increasing the afforestation area (European Commission (EC) 2024b). In the TYFA scenario in IDDRI (2018), freed-up land is utilised for increasing cereal production and maintaining grasslands, which leads to increased milk production for export.

The scenarios included in the range of moderate GHG emission reductions of between -20% up to -40% vary considerably with regard to the level of production of animal products. In the S2 and S3 scenarios in the EC's impact assessment, there is a strong GHG emission reduction of -35% compared to 2020 (European Commission (EC) 2024b). In this scenario, the production of animal products increases, while there is a small decrease in livestock numbers. Emission reductions in this scenario are reached by improving efficiency in the livestock sector and by implementing technical mitigation options. A similar level of emission reduction (-36 % compared to the baseline scenario 2050) can be found in the 'Dietary change and carbon price $2500' scenario by Frank et al. (2019). Compared to the S2/S3 scenario, this scenario includes a reduction in animal products. However, as this reduction is measured against a 2050 baseline scenario, it is not fully comparable with the results of S2/S3.

Unlike the EC scenarios, the Lancet_full scenario in Rieger et al. (2023) features substantial reductions in beef (-74%), pork (-57%), and dairy (-42.6%) production compared to a baseline 2050 scenario. However, these significant cuts only result in moderate emission reductions of -22% compared to the 2050 baseline. Emission reductions from meat and dairy production amount to -126 million t CO_2e. These are similar to reductions from livestock in the Agora Agriculture (2024) scenario (-152 million t CO_2e, see Table 9), though the latter achieves a much higher overall reduction of -60%. This discrepancy can partly be explained by increased emissions from vegetable and fruit production (+15 million t CO_2e) and the absence of technical mitigation options.

The scenario results in Frank et al. (2019) show that a 32% reduction in emissions by 2050 is possible with a carbon price of around $50 in 2050 (equivalent to $125 in 2070). The production of animal products shows only a slight decrease compared to the baseline scenario in 2050, indicating that technical and structural measures are the main drivers of greenhouse gas mitigation. In an alternative scenario, they show that implementing dietary changes through sufficient demand-side measures can achieve a 27% reduction in emissions with a greenhouse gas price of just $20 in 2050 (equivalent to $50 in 2070). In this scenario, the production of animal products decreases by about 20% due to external assumptions on demand changes, while technical and structural measures are not fully implemented because of the low carbon prices. Without dietary changes, this carbon price achieves only an 11% reduction (see Table 5). Contrary to expectations, the 'Dietary changes and carbon price $2500' scenario shows that as carbon prices rise, production increases again in scenarios with dietary changes. This is likely because higher carbon prices lead to a reallocation of agricultural resources towards more efficient production systems, boosting overall production, especially in the EU where technological and efficiency improvements are substantial. This becomes particularly evident when comparing production in this scenario to the 'Dietary changes and carbon price $50' scenario.

Table 4: Overview of different aspects for scenarios reaching emission reductions of between -20% up to -40%

Study/ scenario	Compared to	GHG mitigation	Technical mitigation	Production	Livestock	Carbon removals	Trade
Chapter link		4.3.3 4.4.4.1	4.3.3.2 4.4.4.1	4.3.2	4.3.2	4.4.5	4.5
Frank et al. (2019) Dietary changes and carbon price $2500**	Baseline 2050	-36%	Yes	-3 % dairy -5% ruminant meat -7% non-ruminant meat	n/a	n/a	n/a
EC 2024b S2, S3	Base year 2020	-35%	Yes	+10% dairy +5% meat	-3.4%	4.9 million ha afforestation	n/a

Study/ scenario	Compared to	GHG mitigation	Technical mitigation	Production	Livestock	Carbon removals	Trade
Frank et al. (2019) Carbon price $125**	Baseline 2050	-32%	Yes	0% dairy -3% ruminant meat -5% non-ruminant meat	n/a	n/a	n/a
Billen et al. (2024)* Farm to Fork	Base period 2014-2019	-28%	No	n/a	-22%	n/a	Yes
Frank et al. (2019) Dietary changes $50**	Baseline 2050	-27%	Yes	-22% dairy -22% ruminant meat -23% non-ruminant meat	n/a	n/a	n/a
Rieger et al. (2023) Lancet_full	Baseline 2050	-22%	No	-74.1% beef - 57.2% pork -42.6% dairy + 100% vegetables and fruits	n/a	n/a	Yes
IDDRI 2018 TYFA	Base year 2010	-34%	No	-31% dairy -9% beef -65% non-ruminant	-40%	No	Yes

*Note: *Only N_2O emissions; ** Frank et al. (2019) present results for four different models. The results shown here represent the mean value, summarising the outcomes of these models. While this provides only a rough overview due to variations among the models, detailed results for each model are available in the Excel file. The name of the scenarios represents the carbon prices in 2070, while the results are presented for 2050. As a rough estimate, carbon prices of $2,500 in 2050 represent a carbon price of $950 in 2050, carbon prices of $125 in 2070 represent a carbon price of about $50 in 2050, carbon prices of $50 in 2070 represent a carbon price of $20 in 2050.*
Source: Authors' own compilation (Öeko-Institut).

3.3.6 Scenarios achieving low reductions in GHG emissions (a reduction of up to 20%)

Four of the nineteen scenarios show emission reductions of between -5% and -15% compared to a historic reference year or a baseline 2050 scenario. These four scenarios are derived from three different studies. Most of them do not implement technical mitigation options, or only with a limited adoption rate. Only two of the scenarios implement technical mitigation options, and even then, only with a limited adoption rate. The Rieger et al. (2023) scenarios assume a reduced production of animal products with varying degrees of implementation of the planetary health diet. However, despite the moderate to high reductions in animal product production, the resulting emission reductions are relatively low. Billen et al. (2024) show an 8% emission reduction if fertiliser application is reduced by 20% compared to the historic base period 2014:2019, while livestock numbers increase by 2%. However, this results in a 6% reduction in cropland production and a 2% reduction in grassland production.

Table 5: Overview of distinct aspects for scenario reaching emission reduction of up to -20%

Study/ scenario	Compared to	GHG mitigation	Technical mitigation	Production	Livestock	Carbon removals	Trade
Chapter link		4.3.3 4.4.4.1	4.3.3.2 4.4.4.1	4.3.2	4.3.2	4.4.5	4.5
Rieger et al. (2023) Lancet_high	Baseline 2050	-15%	No	-47% beef* -39% pork* -27% dairy* +69.6% veg./fruits	n/a	n/a	Yes
Frank et al. (2019) Carbon price $50* **	Baseline 2050	-11%	Yes	0% +1% ruminant meat -1% non-ruminant meat	n/a	n/a	n/a
Billen et al. (2024) BAU-20fert.	Base period 2014-2019	-8%	No	n/a	+2% LSU	n/a	Yes
Rieger et al. (2023) Lancet_Low	Baseline 2050	-5%	No	-15.9% beef -13.4% pork -9.1% dairy +27.5% veg./fruits	n/a	n/a	Yes

*Note: * Figures read from graph; **Only N_2O emissions; *** Frank et al. (2019) present results for four different models. The results shown here represent the mean value, summarising the outcomes of these models. While this provides only a rough overview due to variations among the models, detailed results for each model are available in the Excel file. The name of the scenarios refers to the carbon prices in 2070, while the results are presented for 2050. As a rough estimate, carbon prices of $50 in 2070 equate to a carbon price of $20 in 2050.*

Source: Authors' own compilation (Öeko-Institut)

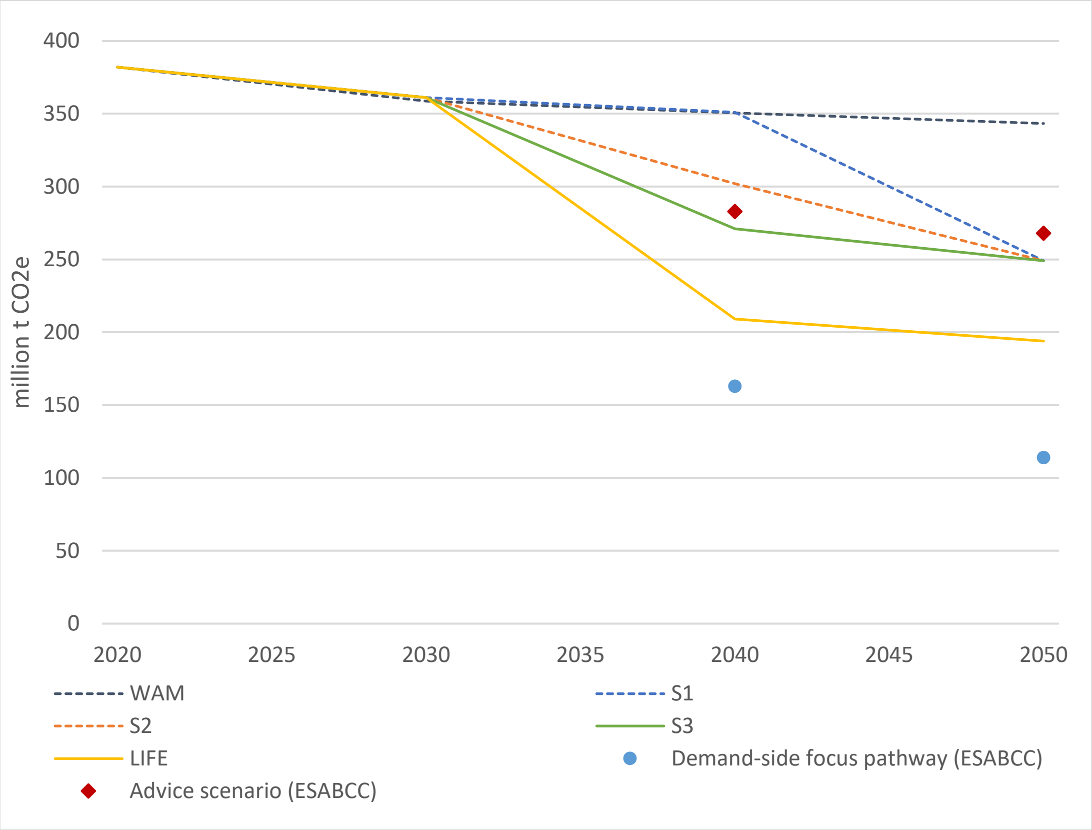
It is not clear whether the scenarios presented in this range are sufficient to contribute to climate neutrality. In the EC (2024b) scenarios, which aim to achieve climate neutrality by 2050, a reduction in emissions between -35% (S2/S3) and -49% (LIFE) is forecast for the agricultural sector by 2050 (see Figure 3). To compensate for higher emissions, further negative emissions from natural or technical sinks would be required. The creation of additional natural sinks on agricultural land requires changes in production, such as a reduction in animal feed production, in order to free up land for this purpose. The development of natural sinks is generally subject to great uncertainty, and technical sinks are associated with high costs. Ambitious emission reductions in the agricultural sector are therefore essential.

3.4 Emissions pathways of the scenarios

In addition to the 2050 target, the pathway leading up to 2050 is also important. While the 2030 target is indirectly covered under the Effort Sharing Regulation, the 2040 target remains particularly relevant. Yet, most studies do not outline a pathway for reaching the 2050 (and 2040) target and focus solely on a target year rather than modelling different years on the way to this target year. The only study providing information on an emission pathway is the EC's impact assessment (EC 2024b), which includes four different emission pathways up to 2050. The emission pathways of the reference scenario and S1 do not seem compatible with a 90% reduction target for all sectors by 2040. As a result, the agricultural sector's contribution to a reduction of 85% to 90% in total EU emissions by 2040 compared to 1990 ranges between the S2 and S3 scenarios, with reductions of 21% and 29% respectively compared to 2020 (see Figure 4). The S2 and S3 scenarios differ in their assumptions about the adoption rates of mitigation technologies. In the S3 scenario, adoption rates are higher by 2040 than in the S2 scenario. However, by 2050, both S2 and S3 scenarios reach the same target value. The LIFE scenario projects a steep reduction path until 2040, reaching a reduction of 45 % already in 2040, driven by assumed dietary changes. Assuming a linear reduction pathway between the 2030 and 2050 target values, the 2040 value would correspond to the S3 scenario.

The recommended pathway for the agricultural sector from the ESABCC falls within the range of the S2 and S3 scenarios. The demand-side focus pathways (ESABCC 2024) indicate significantly higher emission reductions, underscoring the vital role of dietary habits in decreasing agricultural emissions.

Figure 4: Emission pathways in different scenarios of the EU impact assessment



Source: Scheffler und Wiegmann 2024

4. KEY DRIVERS FOR TRANSFORMATION

4.1 Introduction

Different approaches can be taken to reduce the climate impact of the agricultural sector. These approaches are interlinked and need to be pursued at the same time:

- The climate impact can be diminished by reducing the production of GHG intensive agricultural commodities. To achieve this and avoid carbon leakage to non-EU countries, dietary habits need to be changed to reduce the consumption of meat and dairy products. This in turn would lead to reducing overall livestock production as well as the production of animal feed, thus lowering total emissions and reducing the agricultural land required for producing fodder.
- Additionally, reducing food waste and food loss reduces the climate impact of the agricultural sector. The loss of edible food and food waste along the supply chain mean that higher levels of agricultural production are required than are actually necessary to provide people with nutrition. By tackling food waste and loss, the related GHG emissions and pressure on land can be reduced (Hiç et al. 2016).
- The way in which agricultural commodities are produced can be changed to decrease the GHG emissions per unit of output (increase GHG efficiency), for example by using technical mitigation measures (e.g. anaerobic digestion of manure) to reduce emissions from livestock and increasing nitrogen efficiency.
- Increasing carbon sequestration on agricultural land can reduce net climate impacts from agricultural production. This can be achieved by removing and storing carbon in soil and biomass, e.g. by shifting to agroforestry, changing tillage practices, protecting organic soils or converting croplands to grass lands (Lóránt und Allan 2019).

The Institut for European Environmental Policy (IEEP) suggests a hierarchy for action to reduce the climate impact of the agricultural sector: firstly, emissions should be avoided by changing the types of commodities produced, reducing the consumption of livestock and other carbon-intensive products, and eliminating food waste. Secondly, any unavoidable emissions should be reduced by increasing resource efficiency, lowering the per-unit GHG emissions of a commodity, producing seasonally and in the most optimal conditions in Europe and reducing harvesting waste. At the same time, where possible, carbon sequestration on land should be enhanced and nutrients recovered, energy and materials as inputs to the sector to promote circular use of biomass (Lóránt und Allan 2019).

Benton and Harwatt (2022) differentiate between two ‘versions’ or paradigms for shifting to sustainable food systems: Version 1 focuses on intensifying agricultural production in order to increase yields per unit of area. By making agricultural production more efficient while minimising environmental impacts, land can be “spared” from agriculture (**land sparing**). Version 2 focuses on enhancing agro-ecological practices that are nature-friendly. Such approaches produce lower yields and thus require more land for the same level of agricultural output but also entail lower environmental impacts (**land sharing**). The two versions mainly differ in terms of the underlying assumptions about future demand for agricultural products, i.e. whether demand can be changed to shift to more sustainable diets or whether demand is exogeneous and will necessarily increase with population size and wealth increase. Accordingly, version 1 relies on technological approaches to achieve an intensification of agriculture through efficiency gains while version 2 emphasises that sufficient food can be produced through agro-ecological, more extensive agricultural practices if demand patterns change.

These two versions constitute two diverse ways of thinking about changing agricultural production patterns that serve as important references in the following. The subsequent chapters discuss five aspects that are key drivers in the transformation of the agricultural sector: changes on the demand side including dietary changes, food waste reduction (section 4.2), livestock farming (section 4.3), land use and crop production (section 4.4), trade (section 4.5), other economic effects (section 4.6) and briefly describes other relevant drivers (section **Fehler! Verweisquelle konnte nicht gefunden werden.**). The chapters provide a brief introduction to the relevance of the topics, summarise results from the selected quantitative scenarios regarding future developments on the issues and provide additional references to arguments made in qualitative studies.

4.2 Demand side

4.2.1 Introduction

The transition towards a sustainable food system relies on transforming not only the production side but also the dynamics of the demand side, as shifting consumer behaviour is essential to effectively influencing and reshaping production practices. As emphasised in the EU Strategic Dialogue (European Commission (EC) 2024a), there is an intrinsic interdependence between production and consumption, whereby consumer choices and behaviour can act as a powerful driver of systemic change. Demand is covered by domestic production and net imports. By adopting responsible consumption patterns, consumers could reshape production patterns. For example, shifting consumer demand towards more sustainable diets could significantly alleviate the pressure on agricultural land by reducing the need for intensive farming practices (Benton und Harwatt 2022).

Demand-side policies at EU level should therefore address agri-food systems as a whole with the goal of less resource-intensive, healthy diets as well as reducing food waste (European Commission (EC) 2024a). The implications of demand-side dynamics are far-reaching. By steering consumer preferences toward sustainable options, the cumulative effect can result in reduced resource-intensive practices and a reorientation of agricultural priorities. In doing so, the interdependence between production and consumption can be leveraged to drive systemic change, advancing the dual objectives of environmental sustainability and public health (European Commission (EC) 2024a; Publications Office of the European Union 2020).

4.2.2 Role of dietary changes for changing demand

4.2.2.1 Qualitative views on dietary changes

Food systems, alongside energy and transportation, play a vital role in cutting emissions. This sector is responsible for an estimated 34% of global GHG emissions (Crippa et al. 2021). Clark et al. (2020) demonstrate that even if fossil fuel emissions were eliminated immediately, emissions from the food system alone would prevent achieving the 1.5°C warming target, and severely challenge the 2°C goal. A significant share of emissions originates from animal product production, which has a significantly greater environmental impact compared to plant-based alternatives (Poore und Nemecek 2018; Clark et al. 2022). Therefore, sustainable food consumption is essential for meeting climate targets (Springmann et al. 2018).

The need for dietary changes is widely acknowledged as a crucial component of achieving sustainable agri-food systems. The EU Strategic Dialogue highlights that diets need to become less resource-intensive to adequately support this transition (European Commission (EC) 2024a).

The German Commission on the Future of Agriculture (ZKL) further emphasises that technological improvements to enhance production efficiency alone will not be sufficient to keep resource use within planetary boundaries (Commission on the Future of Agriculture (ZKL) 2021). Supporting this view, Poore and Nemecek (2018) find that demand-side dietary changes can deliver environmental benefits on a scale that production-side measures cannot achieve.

To support sustainable food consumption, the EAT-Lancet Commission developed the Planetary Health Diet (PHD) (Willett et al. 2019). This dietary framework promotes both human health while minimising environmental impacts by prioritising plant-based foods and limiting the consumption of animal products and processed foods. The PHD aligns nutritional needs with ecological limits, aiming to reduce environmental impacts such as greenhouse gas emissions, land use, and water consumption.

The importance of dietary changes is also widely recognised, not only for the environment in general and climate change in particular, but also for human health. The EU Strategic Dialogue highlights the importance of responsible consumption of animal products, noting that Europeans currently consume animal-based proteins at levels exceeding those recommended for optimal health (European Commission (EC) 2024a). Likewise, the FAO (2023a) highlights the significant hidden costs of unhealthy diets, which drive malnutrition, obesity, and non-communicable diseases, exacerbate environmental harm, and burden global economies. While the FAO does not prescribe specific food types for a healthy diet, it stresses the importance of providing adequate nutrients within planetary limits.

The World Resources Institute further shows the inefficiency of meat and dairy production in terms of feed and natural resource use, which exacerbates global food inequities; while protein consumption exceeds dietary requirements in some regions, chronic hunger persists in other regions of the world (Searchinger et al. 2019). Likewise, Agora Agriculture (2024) states that increasing the consumption of plant-based foods in relation to animal-based foods supports the goal of poverty reduction. Thus, shifting to more plant-based diets will help provide healthy and sustainable diets for all.

4.2.2.2 *Role of substitutes*

Substitutes for animal products can be categorised into plant-based, cultured, fermented (including fungi- and algae-based), and insect-based alternatives (Onwezen et al. 2021). These options aim to replicate the nutritional, sensory, and functional qualities of animal-based products, such as meat and dairy, thereby supporting a shift toward more sustainable diets. While many reports highlight the importance of reducing the demand for animal products, they also emphasise the need for continuous innovation and improvement in alternative protein development.

For instance, Benton and Harwatt (Benton und Harwatt 2022) argue that advancing plant-based and lab-grown proteins is essential for reducing reliance on animal products while meeting nutritional needs. Similarly, Boysen-Urban et al. (Boysen-Urban et al. 2022) underscore the growing importance of plant-based proteins and meat alternatives in shifting consumption patterns, emphasising that progress in this area is key to achieving a broader transition away from animal-based products. Supporting this view, the EC (2024c) highlights the role of innovation in alternative proteins in facilitating sustainable dietary transitions while addressing consumer nutritional requirements and preferences.

However, critical perspectives exist. For example, the FAO (2023b) observes that alternative products cannot entirely replicate the nutritional composition of animal-based foods. This aligns with Houzer and Scoones (2021), who caution against overestimating the potential of plant-based and industrial protein substitutes to replace animal-source foods in all contexts. They emphasise the continued importance of animal-source foods for nutrition, particularly in vulnerable populations, advocating for a balanced perspective on livestock’s role in sustainable food systems. While recent findings by, for example, Siegrist et al. (2024) and ProVeg International (2024) suggest that while plant-based substitutes may not perfectly match the nutritional profiles of their animal counterparts, they are not inherently inferior, these studies still reinforce the consensus that further improvements are necessary to make alternatives healthier and unreservedly recommendable options. Broader criticisms, such as those raised by the EC (2020), caution that these substitutes must be produced sustainably, avoiding overreliance on intensive industrial methods that could undermine their environmental benefits.

In summary, while there is widespread agreement on the potential of animal product substitutes to reduce environmental impacts and promote sustainable diets, significant challenges remain. Ensuring nutritional adequacy, fostering genuine sustainability, and addressing socio-cultural considerations are essential to fully realising the potential of these alternatives.

4.2.2.3 Consideration of dietary changes in quantitative studies

Dietary changes play a crucial role in enhancing the mitigation potential of the agri-food sector. This is evident in the quantitative scenario studies. Eleven of the seventeen scenarios include dietary changes as a key factor. Assumptions about dietary changes are considered external drivers in all scenario studies and are not derived from modelling results. Most studies do not provide any information on how dietary changes are implemented. Only the Agora Agriculture (2024) study provides a more detailed description. The implementation of dietary changes is supported by policy measures such as subsidies for plant-based foods, taxes on high-emission foods, and public awareness campaigns to promote sustainable eating habits. The study emphasises the importance of creating fair food environments that support healthier, more plant-rich diets. This includes making plant-based foods more accessible and affordable to encourage their consumption.

Sustainable and healthy diets encompass various dimensions, including basic nutritional benchmarks, deviations from existing dietary practices (as a proxy for cultural considerations), and environmental issues such as biodiversity, land use, and climate change (Poux und Aubert 2018). Many scenarios focus on implementing the planetary health diet from the Eat-Lancet Commission (Willett et al. 2019), which integrates healthy nutrition with planetary boundaries. These scenarios assume varying degrees of implementation, from 25% (European Commission (EC) 2024b, LIFE) to full implementation (Rieger et al. 2023, Lancet_Full and Röös et al. 2022, Local-agroecological-food-systems). The TYFA scenario by IDDRI (2018) and Frank et al. (2019) focus on alternative nutritional recommendations, as the Eat-Lancet diet was not available at the time of their publication.

All scenarios that consider dietary changes indicate a decrease in animal product consumption and an increase in plant-based consumption, particularly fruits and vegetables. In the TYFA and Agora Agriculture scenarios, meat consumption decreases by around 50%, while the Lancet Full scenario in Rieger et al. (2023) shows a 64% reduction compared to a reference scenario (see Table 6). Dairy consumption also declines significantly, though not as sharply as meat. The Agora Agriculture study (André et al. 2024) assumes a 43% decrease in dairy consumption compared to 2020 levels, whereas full implementation of the Eat-Lancet diet (Rieger et al. 2023) results in a 58% reduction compared to the reference scenario.

Table 6: Overview of scenario assumptions on dietary changes

Scenarios	Assumptions on dietary changes	Consumption of meat	Consump-tion of dairy	Consump-tion of fruits and vegetables	Consump-tion of legumes	Share
Agora Agriculture 2024	80% of the Planetary Health Diet and 20% of current consumption patterns of EU Member States	Compared to 2020 Total meat: -51% Beef: -60% Pig meat: -67% Poultry: -18%	Compared to 2020 Dairy (milk eq.): -43%	Compared to 2020 +149%	Compared to 2020 +1025%	Plant based calories: 2020: 30% 2024: 62%
IDDRI 2018 TYFA	The 2050 diet aligns with nutritional criteria, featuring reduced animal proteins, increased vegetable proteins, and higher fruit and vegetable intake.	Compared to 2010 Total meat: -50% Beef: -3% Pork: - 60% Poultry: -66%	n/a	Compared to 2010 +149%	n/a	n/a
Rieger et al. 2023 Lancet Low	Achievement of 10% Eat lancet diet in 2030, linear increase until 2050	Compared to Reference Total meat: -14% Beef: 18-% Pig meat: -16% Poultry: -5%	Compared to Reference -12%	Compared to Reference +105%	n/a	n/a
Rieger et al. 2023 Lancet High	Achievement of 30% Eat lancet diet in 2030, linear increase until 2050	Compared to Reference Total meat: -41% Beef: -55% Pig meat: -49% Poultry: -14%	Compared to reference -36%	Compared to reference +319%	n/a	n/a
Rieger et al. 2023 Lancet full	Full implementation of planetary health diet in 2050	Compared to reference Total meat: -64% Beef: -85% Pig meat: -	Compared to reference -58%	Compared to reference +522%	n/a	n/a

Scenarios	Assumptions on dietary changes	Consumption of meat	Consumption of dairy	Consumption of fruits and vegetables	Consumption of legumes	Share
		74% Poultry: -30%				
Röös et al. 2022 Localisation-for-sustainability Local-agroecological-food-systems	Dietary changes are assumed in the Local-for-sustainability and the Local-agroecological-food-systems scenario. Diets are assumed to drastically change to align with the EAT-Lancet reference diet, which is healthy and environmentally sustainable. The quantity of major food groups remains the same as in EAT-Lancet, but the types of grains and vegetables depend on what was historically grown in the region. The Local-for-sustainability scenario strictly follows EAT-Lancet, while Local-agroecological-food-systems replace 50% of monogastric meat with ruminant meat and dairy to utilise grasslands effectively.					
Billen et al. Agro-ecology scenario	In the agro-ecology scenario, dietary changes are assumed. The change in human diet involves adopting a healthy diet based on the WHO and EAT-Lancet guidelines. A universally adopted diet reduces total protein intake from 6.2 kgN/cap/yr to 5 kgN/cap/yr and decreases animal-based products from 58% to 30% of total protein consumption. No dietary changes are assumed for the Farm to Fork scenario.					
EC 2024b LIFE	The LIFE scenario assumes changes towards more sustainable food diets (25% shift towards optimal sustainable and healthy diet 2040).					
Frank et al. 2019 Dietary changes	The dietary changes scenarios assume a decrease in livestock calorie intake to 430 kcal/capita/day by 2070 in developed and emerging countries. This target is based on recommendations by the United States Department of Agriculture (USDA).					

Note: The colour code indicates the level of the GHG reduction ambition, green=/>40%, yellow= 20% up to 40%, grey = 0% up to 20%, Frank et al. 2019 contains no colour as different scenarios are included with different GHG reduction ambition
Source: Authors' own compilation (Öeko-Institut)

4.2.2.4 *Framework conditions and policy instruments*

Addressing the demand side is essential for advancing the transition to more sustainable agri-food systems. Key priorities include changes in dietary habits and reduction of food waste, requiring a well-coordinated approach that integrates a range of complementary measures and interventions.

In the context of the dietary shift, one commonly discussed option are financial incentives. The German Commission of the Future of Agriculture (Commission on the Future of Agriculture (ZKL) 2021), for example, advocates for excise taxes on unhealthy food components to discourage their consumption. These taxes can be paired with subsidies to make healthier, more sustainable options more affordable. Low-income and vulnerable households could benefit from financial support to compensate for rising food prices, enabling them to adopt healthier and more sustainable diets.

Educational measures are another option that can facilitate long-term behavioural changes. For example, the ZKL (2021) and JRC (2022) recommend targeted education initiatives, including integrating sustainable diet and cooking skills into school and adult programs, to teach the value of and implementation of healthy, sustainable eating habits. Moreover, national dietary guidelines should inform people about healthy and sustainable diets. To achieve this, they should be improved to align with health and environmental goals (FAO 2023a) and be regularly updated based on independent expertise to integrate all sustainability dimensions (Bock et al. 2022).

To complement this, food environments should be designed to promote healthy and sustainable options, making them accessible, affordable, and appealing (European Commission (EC) 2024a). Likewise, Agora Agriculture (2024) underscores the importance of establishing enabling conditions that support consumers in making sustainable choices. This involves fostering equitable food environments where the principles of fairness and accessibility are paramount. The ZKL (2021) underscores that demand must shift toward products that are environmentally and ethically produced. Achieving this requires proactive efforts to shape food environments, i.e., the broader decision-making context in which consumers make food-related choices, including factors like cost, convenience, cultural preferences, and food presentation. Acknowledging this, the EC (2020) advocates for creating food environments that actively facilitate sustainable and healthy decision-making by ensuring that such choices are not only readily accessible but also promoted. Food environments are the consumer interface with the food system, encompassing the availability, affordability, convenience, promotion and quality, and sustainability of foods and beverages within wild, cultivated, and built spaces, shaped by socio-cultural, political, and ecological factors. For example, a built food environment includes supermarkets and restaurants where consumers make purchasing decisions based on factors such as price, accessibility, and marketing, while a cultivated food environment might involve home gardens or small farms where individuals grow their own food (Downs et al. 2020). Similarly, the FAO (2023a) emphasises that overcoming socio-economic hurdles is essential to broadening the reach of demand-side interventions. Without addressing issues such as affordability and availability, the transformative potential of consumer behaviour remains constrained.

Behavioural approaches, such as nudging, can encourage consumers to choose healthier and more sustainable options by making them the easiest or even default option; a promising avenue could be the introduction of mandatory requirements for this in public procurement (BMEL 2020; Commission on the Future of Agriculture (ZKL) 2021). Additionally, third-party certifications, and product labelling can bridge educational and nudging approaches. For instance, a certificate could ensure retail offerings align with the PHD and provide clear information on environmental impacts (Fischer et al. 2021). Bans, minimum requirements, and maximum ceilings can serve as additional regulatory instruments in food safety and public procurement. This can help to promote sustainable production methods. Catering in schools has proven to be an effective lever to change dietary intake of students (Publications Office of the European Union 2020; Howard 2022; Bock et al. 2022).

4.2.3 Role of food loss and food waste reduction

As defined by the WRI (2019), the distinction between food loss and food waste lies in their causes and stages within the food supply chain; food loss occurs between farm and retail due to systemic issues like inadequate storage or poor infrastructure, while food waste happens at retail and consumption stages due to deliberate actions such as neglect or poor stock management.

The need to address inefficiencies caused by loss and waste to achieve more sustainable, equitable, and climate-resilient food system is widely recognised. Both food waste and loss contribute significantly to environmental, social, and economic challenges. They reduce the availability of food for consumption, while also wasting critical resources such as water and land, contributing significantly to environmental and climate pressures (European Commission (EC) 2024a). For instance, food waste alone accounts for approximately 8% of global annual GHG emissions (World Bank 2020). Agora Agrar (2024) underscores that reducing food waste eases the strain on land resources and contributes to lowering greenhouse gas emissions.

Looking at food waste in particular, the Farm to Fork Strategy of the European Commission (2020) sets ambitious goals to halve per capita food waste at the retail and consumer levels by 2030. Yet recent findings from the European Climate Neutrality Observatory (Velten et al. 2024) reveal that instead of moving closer to this target, food waste has increased in recent years. Moreover, according to IPES FOOD (2019), around half of the food waste is produced at the household level, showing the importance of demand-side measures to address consumer behaviour and cultural practices contributing to food waste.

Addressing food loss and waste not only eases environmental strain but also advances social equity. The FAO (2023a) emphasises that minimising waste also reduces economic losses, and promotes a more equitable global food distribution. By tackling food insecurity and fostering sustainable food systems, reductions in food waste align with broader goals of hunger alleviation and economic resilience. However, a study by Jafari et al. (2020) suggests that reducing food waste in Europe has limited impacts on global food availability due to price-driven supply adjustments and the costs associated with waste reduction. While the EU prioritises food waste reduction, this study finds that global trade leakage effects offset most benefits, making it an inefficient strategy for improving global food security or environmental outcomes.

At the same time, reducing food waste in Europe presents economic and social trade-offs, making complete elimination neither feasible nor optimal. While waste reduction can enhance food affordability, environmental sustainability, and efficiency, it also incurs costs for producers, retailers, and consumers. Estimates suggest that reducing food waste can cost between 17 and over 100 EUR per ton, depending on policy ambition, and may lead to labour market shifts, infrastructure investments, and behavioural changes that require time and effort (de Jong et al. 2023). Given these complexities, policymakers must balance the socioeconomic costs with the benefits to determine sustainable and effective reduction strategies.

Achieving the necessary reductions in food loss and waste requires a dual approach that addresses actions on both the production and consumption sides of the food system. Given the complexities of (global) food markets, policymakers must balance the socioeconomic costs with the benefits to determine sustainable and effective reduction strategies. The World Bank (2020) states that the reduction of food loss and waste is essentially a demand-side solution because it decreases the need for food by minimizing losses and improving waste recovery throughout the supply chain. On the production side, systemic issues such as inadequate infrastructure and poor supply chain management must be addressed, while demand-side interventions are vital to fostering awareness and accountability at the household level. Additionally, the issue of packaging waste, which exacerbates environmental harm, must be integrated into broader zero-waste strategies (Schutter et al. 2019).

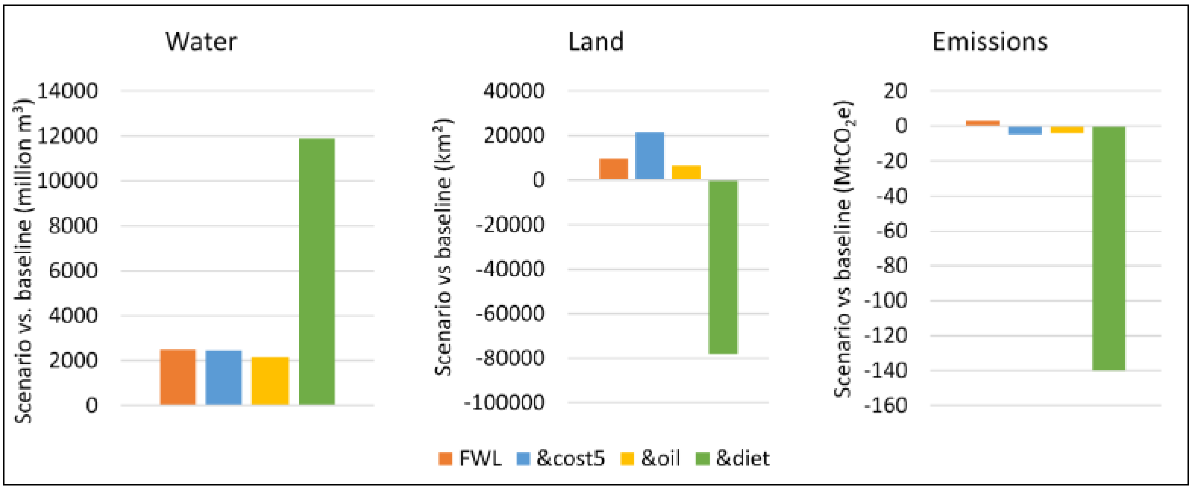
4.2.3.1 *Consideration of food waste reduction in quantitative studies*

Many quantitative scenarios consider the reduction of food loss and waste, with reductions ranging from 20% (Billen et al. 2024; Frank et al. 2019) to 50% (André et al. 2024; Röös et al. 2022) of current levels. Some studies also differentiate the stages at which food loss and waste are reduced (primary agriculture, producer, retail, and consumer) or specify if it refers to avoidable waste. However, detailed quantitative information on the effects of food loss and waste reduction is not provided.

Boysen-Urban et al. (Boysen-Urban et al. 2022) provide more detailed information on the avoidance of food waste and loss. This study models the effects of a 50% reduction in global food loss and waste. The scenario results include impacts on GHG emissions (see Chapter 3.3), virtual land trade (see Chapter 4.5.2), EU market prices (see Chapter 4.6.1), and labour (see Chapter 4.6.3).

The Food Waste and Loss (FWL) scenario in Boysen-Urban et al. (2022) provides insights into the impact of reducing food losses and waste on greenhouse gas emissions. The FWL scenario shows a slight increase in total food consumption-related emissions due to lower market prices and higher consumption (see Figure 5). The effects of reducing FWL on GHG emissions do not always appear to lead to a reduction in emissions, depending on the assumption and modelling approach. However, the impact on GHG emissions seems rather low. The scenarios with rising market and energy prices show a slight decrease in emissions. In line with other scenarios, dietary changes lead to the largest emission reductions.

Figure 5: Results from Boysen-Urban et al. (Boysen-Urban et al. 2022) for GHG emissions, water and land use including food waste and loss



Note: FWL = Food waste and loss,
Source: Boysen-Urban et al. 2022.

4.2.3.2 *Framework conditions and policy instruments*

In contrast to dietary changes, the objective to reduce food loss and waste enjoys broad societal acceptance and support. A key challenge is that food loss and waste arise in small quantities across multiple stakeholders, from production and distribution to individual consumption (Searchinger et al. 2019). While significant food loss occurs earlier in the supply chain, consumer actions at the point of purchase and consumption are crucial in complementing these upstream efforts. Addressing this issue requires a holistic approach that integrates both EU-level policy frameworks and targeted national and local, household level measures.

At the policy level, the EU Strategic Dialogue recommends, for example, fiscal incentives such as zero-rated VAT to promote food donations, and harmonised regulations to support non-profit organisations in managing food surpluses hygienically. These measures aim to ensure that surplus food can be safely redistributed for charitable purposes, including feeding disadvantaged individuals and animals. It has been proposed that a body appointed by the European Commission oversees monitoring and regulatory enforcement to ensure compliance and progress across member states (European Commission (EC) 2024a).

As targeted national measures, the German Commission on the Future of Agriculture (Commission on the Future of Agriculture (ZKL) 2021) highlights the importance of addressing key sectors such as production, industry, and hospitality through data-driven actions and binding targets. These measures should focus on minimising waste at critical points in the supply chain, such as during production and distribution, when inefficiencies often lead to significant losses. Furthermore, Schutter et al. (2019) criticise existing policies for normalising food waste and excessive packaging, calling instead for a broader cultural shift to realign values and address the systemic drivers of waste.

Interventions at the production and distribution levels can further reduce food waste. The WRI (2019) identifies strategies such as improving harvesting techniques and storage technologies to minimise post-harvest losses. Similarly, optimising procurement strategies, improving food date labelling practices can reduce confusion and waste in retail settings. Additionally, the WRI (2019) advocates for facilitating the donation of unsold food.

Consumer-focused strategies are essential for effectively addressing food waste, complementing upstream policy and supply chain interventions. These strategies, such as reducing food waste at home and in retail, are highlighted as pivotal for reducing the environmental footprint of food systems (World Bank 2020). Informational and motivational campaigns can play a pivotal role in raising awareness and encouraging behavioural change among consumers. The German Commission on the Future of Agriculture (Commission on the Future of Agriculture (ZKL) 2021) underscores the importance of reinforcing such strategies to educate consumers about the environmental and social consequences of food waste. A compelling example of this is the German initiative "Zu gut für die Tonne" ("*too good to go*") funded by the German Federal Ministry of Food and Agriculture. This programme aimed to educate consumers about the causes and consequences of food waste while providing practical guidance on how to reduce or prevent it in their daily lives including, for example, knowledge about food preparation and storage techniques. Further, Agora Agriculture (2024) points out that adequate food environments help reduce food waste on the demand side.

The European Policy Centre proposes that policies to reduce food waste should include a ban on destroying unsold food, mandatory surplus food donations, and harmonised food safety standards to expand food banks. Innovations like smart digital tags to monitor real-time food quality should also be explored (Sipka et al. 2024).

Overall, comprehensive strategies that integrate regulatory, financial, educational, and behavioural approaches are crucial to driving the necessary demand-side changes. This requires a proactive approach and the establishment of robust policy frameworks, as voluntary industry and consumer initiatives, while valuable, should not be relied upon as the primary drivers of change (Publications Office of the European Union 2020).

4.3 Livestock farming

4.3.1 Introduction

The EU strategic dialogue draws a clear link between the need of dietary changes and a reduction in animal product production. By 2035/2040, animals are reared according to high animal welfare standards, the weight of livestock clusters as well as antibiotic use have been reduced and meat and dairy consumption as well as third country exports 'ensure sustainability in terms of farmers livelihoods, health, climate, environment, animal welfare and social justice' according to the report (European Commission (EC) 2024a, p. 22). The ZKL (2021) also clearly expresses the need for reduced consumption and the reduced production of animal products (p. 79).

Similar statements are made by the JRC (Bock et al. 2022). The IPES Food (2022) also clearly states that 'intensive livestock systems relying on feed crops must be dramatically scaled back' (p. 76). Increasing quality awareness can also contribute to a reduction in livestock numbers. The transition of animal farming in the European Union must focus on enhancing sustainability through improved practices and scaling, while supporting mixed farming systems and high-welfare farms.

Additionally, it should promote business models that minimise negative externalities and generate positive ones.

Despite clear scientific advice to reduce consumption of animal products[2] and thus livestock numbers, there is a lack of solid majority support in society. A consultation process for the French National Low Carbon Strategy, for example, showed that technical interventions seem to be well accepted while measures leading to a reduction in livestock production have raised concerns, especially among beef and dairy producers (Lóránt und Allan 2019, p. 32).

Clear statements on the necessity to reduce the consumption and production of animal products are only made in reference to the EU and other industrialised parts of the world though. In a global context, different arguments are made without advocating for reducing the production levels of animal products. Taking a focus on food security and healthy nutrition, the FAO (2023b) refers to various studies that argue that the healthy reference diet of the EAT-Lancet Commission ‘may not be available or accessible in certain contexts’. It emphasises the crucial role of livestock in enhancing food security and nutrition ‘of the public at large and the rural and urban poor in particular’ (p. 205). Also, the FAO highlights the economic importance of livestock in supporting the livelihoods of approximately 1.7 billion poor people worldwide (FAO 2023a). For extensive livestock systems in developing countries, the focus on reducing emissions through reduced production levels therefore should not apply (Houzer und Scoones 2021).

Furthermore, the FAO (2023b) states that livestock contribute to agro-ecological transition by enhancing diversity, synergies and recycling on farms as well as contributing to cultural and food traditions, to circular economy and to the overall efficiency and resilience of food systems (p. 205). The OECD-FAO Agricultural Outlook 2023-2032 (OECD und FAO 2024) expects a downward pressure on the growth of meat demand amid high and rising consumer costs and weak income growth.

The IPCC remains vague on this issue. While highlighting the high emission reduction potential in the livestock sector, it vaguely refers to ‘incentive mechanisms and funding [which] can encourage adoption of mitigation strategies’ in countries with export-orientated livestock industries where farmers often control large forest or re-forestable areas (Nabuurs et al. 2022).

4.3.2 Animal numbers and production levels (quantitative studies)

4.3.2.1 Livestock numbers

The development of livestock numbers, combined with changes in milk yields and carcass weights, significantly impacts the evolution of greenhouse gas emissions. Not all studies report on the development of animal numbers. We found information in four studies (André et al. 2024; European Commission (EC) 2024b; Poux und Aubert 2018; Billen et al. 2024) and summarise the results in Table 7.

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[2] Demand is met through domestic production and net imports. If production is reduced without a corresponding decrease in demand, leakage effects may occur, leading to increased net imports of animal products. Conversely, reducing demand without cutting production can result in higher exports, especially when self-sufficiency levels are high.

Table 7: Development of animal numbers in the different scenarios

Study	Data/ scenario	Unit	Year	Total live-stock	Total cattle	Dairy	Other cattle	Pigs	Poultry	Sheep and goats
EC 2024b	Base year	MLSU	2020	111.6	54,4	20,9	33,5	35,4	7,6	13,9
Agora Agriculture (2024)*	Agora Agri-culture -60% GHG	MLSU compared to 2020	2045/ 2050	n/a	-52%	-45%	-71%	-64%	-28%	n/a
Billen et al. 2024**	Base period	MLSU	2014: 2019	111	n/a	n/a	n/a	n/a	n/a	n/a
	Reference S0	MLSU	2014: 2019	137	n/a	n/a	n/a	n/a	n/a	n/a
	BAU -3%	MLSU compared to S0	2050	146 +7%	n/a	n/a	n/a	n/a	n/a	n/a
	BAU-lowdiet 0%	MLSU compared to S0	2050	141 +3%	n/a	n/a	n/a	n/a	n/a	n/a
	BAU-20%fert. -8%	MLSU compared to S0	2050	140 +2%	n/a	n/a	n/a	n/a	n/a	n/a
	Farm to Fork -28%	MLSU compared to S0	2050	107 -22%	n/a	n/a	n/a	n/a	n/a	n/a
	Agro-ecology -56%	MLSU compared to S0	2050	81 -41%	n/a	n/a	n/a	n/a	n/a	n/a
	Agro-ecology_low diet -56%	MLSU compared to S0	2050	87 -36%	n/a	n/a	n/a	n/a	n/a	n/a
EC 2024b	S1, S2, S3 -35% GHG	MLSU Compared to 2020	2040/ 2050	107.8 -3.4%	51,1 -6%	19,2 -8%	34,9 -5%	34,9 -1%	6,8 -11%	15,0 +8%
	LIFE -49% GHG	MLSU Compared to 2020	2040/ 2050	79.9 -28%	37 -32%	17,3 -17%	19,7 -41%	25,5 -28%	5,3 -30%	12,1 -13%
IDRI (2018)	TYFA -40% GHG	Compared to 2010**	2050	-40%	n/a	-27%	-8%	-60%	-66%	-38%

*Note: MLSU = million livestock units; *Data for fatting pigs, breeding sows decrease by 70% compared to 2020; ** Figure was read out by hand; therefore uncertainties are possible.*

***% changes are shown as development in comparison to the S0 Scenario. However, this can be seen as the % changes*

compared to the base year 2014:2019 as this is the result of the mode calibration to meet current statistics.
The colour code indicates the level of the GHG reduction ambition, green=/>40%, yellow= 20% up to 40%, grey = 0% up to 20%
Source: Authors' own compilation (Oeko-Institut), based on different studies.

The Agora Agriculture scenario (André et al. 2024) shows a significant reduction across all livestock categories, with the steepest declines in other cattle (-71%) and pigs (-64%), followed by dairy cattle (-45%), and the smallest reduction in poultry (-28%). In comparison, the LIFE scenario included in the EC's impact assessment (European Commission (EC) 2024b) contains lower reductions in livestock numbers. In the LIFE scenario, total livestock units decrease by 28% compared to 2020. Dairy cattle as well as sheep and goats see smaller reductions of 17% and 12%, respectively, while other cattle experience the largest decline at 41% compared to 2020. The smaller reduction in livestock numbers in the LIFE scenario, compared to the Agora Agriculture scenario, is reflected in lower greenhouse gas emission reductions. The LIFE scenario achieves a 49% reduction in GHG emissions compared to 2020 levels, whereas the Agora Agriculture scenario achieves a 60% reduction.

The TYFA scenario (Poux und Aubert 2018) forecasts a 40% reduction in livestock numbers from 2010 to 2050, with a strong reduction of pigs and poultry. Dairy cow decrease by about 27% and support grassland-based dairy production, though dairy output is expected to drop by 31%. Beef cattle numbers will slightly decrease, with beef production mainly as a by-product of dairy farming. Average milk productivity per cow will be lower, and dairy cows will have a longer lifespan of 9-11 years.

In addition, the development of livestock units in the various scenarios in Billen et al. (2024) is shown in Table 7. Only information on total livestock units is available, and no detailed information per animal category provided. Compared to the reference situation (which is comparable with 2020 levels), the scenarios show an increase in livestock numbers compared to the base year. The Farm to Fork scenario shows a reduction in livestock numbers amounting to 22%, which is in a similar range as the LIFE scenario in the EC's impact assessment (-28%). Agro-ecological practices (AE scenarios) would fundamentally transform the agri-food system by restricting livestock feeding to regional feed production and banning feed imports. This would result in a reduction of livestock populations by approximately 35–45% compared to the current situation. The scenarios included in Billen et al. (2024) focus only on N_2O emissions. Also, N_2O emissions are closely related to livestock numbers, mainly due to the production of animal fodder, manure management and manure spreading.

4.3.2.2 *Production levels*

The production levels of animal products are linked to the demand-side changes. These are based on livestock numbers including optimisation in herd sizes and the development of milk yields and carcass weights. If productivity increases, fewer animals are required to produce the same amount of milk or meat. Information on production volumes is available in almost all studies and are provided in the following sections. However, most studies do not provide detailed information on productivity gains. In the Agora Agriculture (2024) scenario, a 7% increase in milk yield compared to 2020 is assumed. The Frank et al. (2019) study mentions productivity increases but does not include specific details. Röös et al. (2022) assume annual productivity gains of 0.1% for all livestock in the baseline scenario, while other scenarios assume productivity decreases (e.g. -10% for monogastric). Additionally, the assumption of grass-based feeding for ruminants might impact efficiency gains, although this is not explicitly mentioned. Other studies either do not provide explicit information on productivity gains or state that current productivity levels are maintained. For example, the IDDRI (Poux und Aubert 2018) study assumes a decrease in milk yields, particularly due to the increased adoption of organic farming practices.

Meat production

Statistical data indicates a 9% increase in meat production over the last decade (2010 to 2020). While ruminant meat production slightly decreased by 4% in 2020 compared to 2010 levels, pig and poultry meat production increased. The baseline scenario in Frank et al. (2019) projects a 15% increase in ruminant meat production and a 20% increase in non-ruminant meat production by 2050 compared to 2010 (see Table 8). The two scenarios (S2/S3) in the EU impact assessment (European Commission (EC) 2024b) project a 5% increase in meat production by 2040[3] compared to 2020. However, other scenarios indicate a decrease in meat production, demonstrating high variability. The most significant reduction is observed in the sustainability and local system scenarios in Röös et al. (2022), with a decrease of more than 70% in meat production.

In the LIFE scenario in the EC's impact assessment (European Commission (EC) 2024b), meat production decreases by 21%. This scenario represents the highest meat production among the ambitious scenarios, resulting in production rates of 34 million tonnes. The decrease in meat production in the LIFE scenario is driven by a 28% reduction in animal numbers compared to 2020, with approximately 60% of this reduction coming from ruminant livestock (cattle, sheep, goats).

Scenarios with emission reductions exceeding 40% generally show even lower meat production levels. For instance, the Agora scenario (André et al. 2024) projects a 49% decrease in meat production compared to 2020. Similarly, the TYFA scenario in IDDRI (2018) indicates a significant reduction in pig and poultry meat, while beef meat sees only a slight decrease.

Dairy production

Dairy production increased by 18% over the last decade (2010-2020). The EC's impact assessment for scenarios S2 and S3 (European Commission (EC) 2024b) projects a 10% increase in milk production up to 2040 compared to 2020 levels, while the EU LIFE scenarios project stable milk production. However, in all other scenarios, milk production is expected to decrease from the current 146 million tonnes. All scenarios show smaller decreases in dairy production compared to meat production. The reduction levels vary between 27% (Agora Agriculture) compared to 2020 and up to 69% compared to 2012 (Röös et al. 2022, Sustainability). The results of the LIFE scenario (European Commission (EC) 2024b) indicate that emission reductions of over 40% compared to 2020 are possible even if dairy production remains stable at 2020 levels.

Table 8: Production of animal products in different scenarios

Study	Data/ scenario	Year	Dairy (raw milk)	Meat total	Ruminant meat	Pig and poultry meat
			million tonnes or % change to reference			
Statistic	Base year data	2010	124	41	7.8	32.7
	Base year data compared to 2010	2012	127 +3%	40 0%	7,4 -5%	33.0 +1%
	Base year data compared to 2010	2020	146 +18%	44 +9%	7.6 -4%	36.9 +13%
Agora Agrar 2024	Target compared to 2020	2045	106 -27%	22 -49%	n/a	n/a

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[3] There is no information on livestock numbers in 2050 available, but it is assumed that they remain at the 2040 level.

Study	Data/ scenario	Year	Dairy (raw milk)	Meat total	Ruminant meat	Pig and poultry meat
Röös et al. 2022	Sustainability compared to 2012	2050	-69%	-72%’	-66%	-73%
	Local system compared to 2012	2050	-63%	-76%’	-37%	-85%
Rieger et al. 2023	Lancet_Low compared to baseline	2050	-9.1%	n/a	-15.9% beef	-13.4% pork
	Lancet_High compared to baseline	2050	-27%	n/a	-47% beef	-39% pork
	Lancet_Full compared to baseline	2050	-42.6%	n/a	-74.1% beef	-57.2% pork
EC 2024b	S2, S3	2040	161 +10%	45 +5%	n/a	n/a
	LIFE	2040	145 +0%	34 -21%	n/a	n/a
Frank et al. 2019**	Baseline compared to 2010	2050	+18%	n/a	+15%	+20%
	Carbon price $50 compared to baseline	2050	0%	n/a	+1%	-1%
	Carbon price $125 compared to baseline	2050	0%	n/a	-3%	-5%
	Carbon price $2500 compared to baseline	2050	-12%	n/a	-20%	-23%
	Baseline with dietary changes compared to baseline	2050	-22%	n/a	-22%	-23%
	Dietary changes + carbon price $50 compared to baseline	2050	-22%	n/a	-22%	-24%
	Dietary changes + carbon price $125 compared to baseline	2050	-13%	n/a	-19%	-23%
	Dietary changes + carbon price $2500 compared to baseline	2050	-3%	n/a	-5%	-7%

Study	Data/ scenario	Year	Dairy (raw milk)	Meat total	Ruminant meat	Pig and poultry meat
IDDRI 2018	TYFA compared to 2010	2050	-31%	n/a	-9%*	-65%*

*Notes: * Figure was read out by hand; therefore uncertainties remain.*

***% changes are shows as development in comparison to the baseline scenario, the absolute figures provided in the Frank et al. 2019 are not comparable to the statistics. Therefore, only relative changes are shows here. Frank et al. (2019) present results for four different models. The results shown here represent the mean value, summarizing the outcomes of these models. While this provides only a rough overview due to variations among the models, detailed results for each model are available in the Excel file. The name of the scenarios reflects the carbon prices in 2070, while the results are presented for 2050. As a rough estimate, carbon prices of $2,500 in 2050 represent a carbon price of $950 in 2050, carbon prices of $125 in 2070 represent a carbon price of about $50 in 2050.The colour code indicates the level of the GHG reduction ambition, green=/>40%, yellow= 20% up to 40%, grey = 0% up to 20%.*

Source: Authors' own compilation (Oeko-Institut), Statistics (European Commission (EC) 2022) Frank et al. 2018, supplementary material

Frank et al. (2019) modelled a baseline scenario to illustrate the impact of a growing global population and other factors. Compared to 2010, there is an increase in meat production (+15% for ruminants, +20% for non-ruminants) and dairy production (+18%) by 2050. However, compared to current production levels in 2020, milk production remains steady, while the increase in meat production is lower due to significant growth over the past decade.

The results in Frank et al. (2019) indicate that at low carbon prices, production levels remain unchanged as GHG reductions are achieved through technical mitigation measures. However, at carbon prices of $2500 in 2070 (equivalent to $950 in 2050), production levels change. In response to the carbon price, dairy production decreases by 12%, while ruminant and non-ruminant meat production decreases by 20% and 23%, respectively, compared to baseline levels. Reducing the consumption of animal products through consumer-side measures significantly impacts production in the scenarios where dietary changes are considered as external assumptions. Assuming livestock calorie intake decreases to 430 kcal/capita/day by 2070 in developed and emerging countries, with a gradual shift from 2020 to 2070, animal product production drops by about 22% in the EU until 2050 compared to 2010 (Frank et al. 2019). At low carbon prices, production remains unaffected, as in scenarios without carbon pricing. However, as carbon prices rise, production increases again in scenarios with dietary changes. This is likely because higher carbon prices lead to a reallocation of agricultural resources towards more efficient production systems, boosting overall production, especially in the EU where technological and efficiency improvements are substantial.

4.3.3 GHG mitigation potential (quantitative studies)

4.3.3.1 Reduction in production

Reduced production of animal products by reducing livestock numbers has a significant impact on emission reductions. This effect is significantly more pronounced with the reduction of ruminant livestock, such as cattle and dairy cows, which contribute substantially to total emissions (see Figure 1). Only two studies explicitly detail the effects of greenhouse gas (GHG) mitigation resulting from reductions in animal numbers without overlapping technical mitigation measures.

The Agora Agrar Study (André et al. 2024) reports a GHG mitigation of **152 Mt CO_2e** from the reduction of livestock numbers by 2045/2050 compared to 2020. This represents a **54% decrease** in emissions compared to the base year in 2020, CH_4 emissions from enteric fermentation, N_2O and CH_4 emissions from manure management, and N_2O emissions from manure spreading totalled 282

Mt CO_2e. This reduction is accompanied by a 27% decrease in milk production and a 49% decrease in meat production (see Table 8).

In the EU LIFE scenario, CH_4 emissions decrease by **29%** due to changes in production of livestock product. This equals emission reductions of **67 Mt CO_2e** (given CH_4 emissions of 234 Mt CO_2e in the base year in 2020[4]). This is in line with a reduction in meat production by 21%, while milk production remains at 2020 levels.

Table 9: Emission reduction from production changes in livestock farming in the different scenarios

Study	Scope	Emissions in base year	Emissions in target year	Emission reduction from production changes	% of reduction in total emissions in base year
Agora Agriculture (2024)	CH_4 emissions from enteric fermentation, CH_4, N_2O emissions from manure management, N_2O emissions from manure application	282	93	-152	-54%
EC 2024b LIFE	CH_4 emissions*	234	167	-67	-29%

Note: % of emission reduction calculated as 'emission reduction from production changes/emissions in base year'
It also includes some CH_4 emissions from rice cultivation and field burning, but as this share was only 1% of the total CH_4 emissions from agriculture in 2020, it is negligible.
The colour code indicates the level of the GHG reduction ambition, green=/>40%, yellow= 20% up to 40%, grey = 0% up to 20%.
Source: Authors' own compilation (Oeko-Institut), based on different studies.

4.3.3.2 *Livestock mitigation technologies*

Mitigation of GHG emissions in the livestock sector is achievable through technical measures. These measures can be categorised into those emission reductions associated with agricultural infrastructure development measures, such as biogas plants for anaerobic digestion of manure, and those involving the use of additives. Additionally, there are management-related measures, such as increasing efficiency through breeding or improving cow longevity.

The three types of mitigation measures have different prerequisites for implementation. The addition of additives is the easiest to implement, requiring minimal changes to the operating process and offering flexibility in duration. In contrast, infrastructure development measures necessitate available capital for necessary investments and a long-term operational perspective. Changes in management, while inherently low-cost, require knowledge and skills for effective implementation.

Detailed information on individual mitigation technologies and their potential is provided in Pérez Dominguez et al. (Pérez Domínguez et al. 2020) and André et al. (2024). Pérez Dominguez et al. (Pérez Domínguez et al. 2020) analyse **seven** technical mitigation options, while Agora Agriculture in André et al. (2024) assess the mitigation potential of **ten** technical mitigation options. This, of course, influences the absolute mitigation potential.

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[4] 2020: Figure from EU Inventory Submission 2023. This also includes some CH_4 emissions from rice cultivation and field burning, but as this share was only 1% in the total CH_4 emissions from agriculture in 2020, it is negligible.

The studies begin with different emission levels. While Pérez Domínguez et al. (Pérez Domínguez et al. 2020) present a reference scenario, the Agora scenario presents a target scenario whereby emissions are already 45% lower than those in the reference scenario provided by the JRC (2020). The absolute mitigation potential of technical measures increases with higher total emissions from animals. Conversely, starting with lower emissions in the Agora scenario results in smaller absolute emission reductions from technical measures, although the relative reduction might be higher.

The following table provides an overview of technical mitigation options for reducing emissions from livestock and their GHG mitigation potential.

Table 10: Overview of GHG mitigation potential in different technical mitigation options within the livestock sector

	Agora Agriculture 2024		Pérez Dominguez et al. (JRC 2020)	
Total emissions	130 Mt CO_2e		235 Mt CO_2e.	
Total reduction from technical options	-37 Mt CO_2e	-28% in total emissions	-50.7 Mt CO_2e.	-22% in total emissions
Mitigation options	Absolute reduction	Share in absolute reduction	Absolute reduction	Share in absolute reduction
Anaerobic digestion - construction	-8.47	23.2%	-12.7	25%
Feed additive: Methane inhibitors (3-nitrooxypropanol feed additive)	-9.23	32.7%	n/a	n/a
Feed additive: Linseed oil feeding (reduction CH_4)	-2.39	6.5%	-10.6	21%
Feed additive: Nitrate (Reduction CH_4)	-2.73	7.5%	-7.8	15%
Anti-methanogen vaccination	-0.98	2.7%	-7.7	15%
Breeding for ruminant feed efficiency - management	-0.95	2.6%	-8.8	17%
Breeding for milk yield - management	n/a	n/a	-1.9	4%
Low nitrogen feed – additive/management	-0.07	0.2%	-1.2	2%
Slurry removal/cooling - construction	-3.4	9.3%	n/a	n/a

	Agora Agriculture 2024		**Pérez Dominguez et al. (JRC 2020)**	
Manure additives (acidification)	-7.1	19.4%	n/a	n/a
Nitrification inhibitors for manure spreading - additive	-1.18	3.2%	n/a	n/a

Source: Authors' own compilation (Oeko-Institut) based on Agora Agrar Annex (2024) and Pérez Dominguez et al. (Pérez Domínguez et al. 2020)

It is evident that **additives** offer the highest mitigation potential, accounting for **54%** of the total mitigation potential in the Reference Scenario in Pérez Dominguez et al. (Pérez Domínguez et al. 2020) and make up **65%** in the Target Scenario in Agora Agriculture in André et al. (2024). There might be an overlap in the mitigation potential of the feed additives (3-nitrooxypropanol, linseed oil and nitrate). While each additive independently reduces methane emissions, their combined effects may vary. It is possible that their mechanisms overlap, but the exact extent of this overlap and the potential of their effects depends on the specific conditions. Further research is needed to fully understand these interactions and optimise the combined use of these additives.

Strategies to reduce enteric CH_4 emissions from livestock production include the use of feed additives to reduce rumen methanogenesis. Ongoing research is exploring technical mitigation options to reduce agricultural emissions. Emerging technologies, such as the 3-nitrooxypropanol feed additive (Bovaer), have the potential to significantly enhance mitigation efforts. In the Target Scenario by Agora Agriculture in André et al. (2024), these new technologies account for 33% of the total emission reductions from livestock. In the study by Pérez Dominguez et al. (Pérez Domínguez et al. 2020), this mitigation option was not included because of missing research studies and it was not ready for the market. Based on currently available studies, Bovaer is associated with low safety risks for consumers or the environment as minimal or no residues were found in meat or milk and its metabolic byproducts are not known to be toxic (Bampidis et al. 2021). Negative impacts on animal welfare could not be proven but research gaps remain (Kjeldsen et al. 2022). Oil addition does not imply safety risks but has negative effects on fibre digestibility in high-fibre diets and reduce feed intake, meaning that it may not be appropriate for grazing animals. Additionally, oil addition has been found to decrease milk production (Almeida et al. 2021). Adding nitrate to animal feed is limited by risks of nitrite toxicity. These risks may be limited through appropriate management of the level of nitrate in the diet and nutritional strategies though (Almeida et al. 2021; Hegarty et al. 2021). Moreover, milk from dairy cows that receive nitrate fed may not be usable for specific products such as milk powder for human babies due to risks of carry-over of nitrate to milk. Concerns regarding negative animal welfare effects due to changes in eating patterns and reduced dry matter intake remain and require further research (Kjeldsen et al. 2022).

Strategies to improve diet quality can reduce the emissions intensity of livestock production (Sutton et al. 2024), but may also entail negative health consequences from too high levels of fermentable carbohydrates and reduced particle size that reduces chewing activity and saliva secretion. Also, increasing the stocking rate or reducing access to pasture to reduce GHG emissions compromises animal welfare. Enhancing reproductive efficiency or breeding for increased productivity to decrease the emissions intensity of livestock production can have different consequences on animal welfare and health (Llonch et al. 2017).

In addition, uncertainties remain in measuring the effects of additives at the farm level. Beyond verifying the purchase of the additive, monitoring resulting emission reductions requires complex measurements, such as using respiration chambers to measure CH_4 emissions from enteric fermentation. In comparison, emission reductions from agricultural infrastructure development measures, such as the amount of animal manure processed in biogas plants, are more straightforward to quantify.

Besides the study by Agora Agriculture (2024) and the study by Pérez Domínguez et al. (2020) also the scenario in the EC's impact assessment (European Commission (EC) 2024b) shows the reduction potential from technical measures. The technical mitigation potential is influenced by both the effectiveness of individual measures and their adoption rates. Additionally, variability in biological processes during production affects the mitigation potential, which can vary depending on the literature sources used for model settings. An overview is provided in Table 11.

Table 11: Emission reductions from technical mitigation options in the different scenarios

Study/Scenario	Scope	Emissions in target year	Emission reduction from mitigation options	% of reduction in total emissions in target year*
		Mt CO2e		
Agora Agriculture 2024	CH_4 and N_2O emissions from livestock including N_2O emissions from manure spreading	93	**-37**	-28%
EC 2024b S2, S3	CH_4 emissions from livestock**	176	**-38**	-18%
EC 2024b LIFE	CH_4 emissions livestock**	137	**-29**	-17%
Pérez Dominguez et al. (JRC 2020)	CH_4 and N_2O emissions from livestock	184	**-51**	-22%

*Notes: *Calculation: Emission savings from technical mitigation options/(emissions in target year + emission savings from technical mitigation options), ** includes also some CH_4 emissions from rice cultivation and field burning, but as this share was only 1% in 2020 total CH_4 emissions from agriculture, this is negligible*

The colour code indicates the level of the GHG reduction ambition, green=/>40%, yellow= 20% up to 40%, grey = 0% up to 20%.

Source: Authors' own compilation (Oeko-Institut) based on different studies.

Regardless of the study and scope, the scenario results indicate that the mitigation potential of technical measures in the livestock sector is limited. The technical mitigation potential varies based on factors such as GHG prices, adoption rates, and the inclusion of mitigation technologies. Specifically, the potential ranges from a reduction of 14% at GHG prices of $50 per tonne of CO_2e up to an emission reduction of -39% at GHG price of $125 (Frank et al. 2019). The Agora Agriculture study (André et al. 2024) shows a reduction of 28% of total emissions under ambitious adoption rates and the comprehensive application of currently known and available mitigation technologies. These figures reflect only the technical mitigation potential known today. The case of the 3-nitrooxypropanol feed additive (e.g. Bovaer) demonstrates that new mitigation technologies can significantly alter the landscape.

Table 12 compares emission reductions from livestock under different scenarios and carbon prices according to Frank et al. (2019). At a carbon price of about $20 in 2050 ($50 in 2070), emission reductions range from -1% to -19% across different models (CAPRI, GLOBIOM, IMAGE, MAGNET).

When the carbon price is $50 in 2050 ($125 in 2070), reductions increase to -21% up to -36%. However, at a carbon price of $900 in 2050 ($2500 in 2070), reductions remain between -22% and -34%. At a carbon price of about $50 in 2070, emission reductions range from -14% to -32% across different models (CAPRI, GLOBIOM, IMAGE, MAGNET). When the carbon price is $125 in 2070, reductions increase to -26% up to -39%. However, at a carbon price of $2500 in 2070, reductions from technical mitigation options remain between -23% and -36%. This indicates that the mitigation potential does not significantly increase with higher carbon prices, suggesting a limit to the effectiveness of higher carbon prices.

The IMAGE model consistently shows the highest reductions across all scenarios, suggesting that it may be more sensitive to carbon pricing or take different assumptions on adoption rates and mitigation potential. Overall, the data implies that while higher carbon prices can drive significant emission reductions, the effectiveness of these reductions also depends on the specific model and assumptions used.

Table 12: Technical mitigation potential from livestock management at different carbon prices in 2050

Study/ Scenario	Scope	Livestock Emissions 2050 in Baseline	Emission reduction from mitigation options	% of reduction in livestock emissions in 2050*	Livestock Emissions 2070 in Baseline	Emission reduction from mitigation options	% of reduction in livestock emissions in 2070*
Frank et al. (2019)	All livestock emissions	Mt CO_2e		%	Mt CO_2e		%
$50 in 2050	CAPRI	382	**-22**	-6%	387	**-53**	-14%
	GLOBIOM	347	**-3**	-1%	358	**-57**	-16%
	IMAGE	402	**-75**	-19%	407	**-128**	-32%
	MAGNET	424	**-58**	-14%	440	**-104**	-24%
$125 in 2050	CAPRI	382	**-78**	-21%	387	**-99**	-26%
	GLOBIOM	347	**-82**	-24%	358	**-90**	-25%
	IMAGE	402	**-145**	-36%	407	**-159**	-39%
	MAGNET	424	**-118**	-28%	440	**-134**	-30%
$2500 in 2050	CAPRI	382	**-84**	-22%	387	**-102**	-26%
	GLOBIOM	347	**-83**	-24%	358	**-82**	-23%
	IMAGE	402	**-135**	-34%	407	**-147**	-36%

Study/ Scenario	Scope	Livestock Emissions 2050 in Baseline	Emission reduction from mitigation options	% of reduction in livestock emissions in 2050*	Livestock Emissions 2070 in Baseline	Emission reduction from mitigation options	% of reduction in livestock emissions in 2070*
	MAGNET	424	**-110**	-26%	440	**-124**	-28%

Source: Frank et al. 2018, supplementary material

4.3.4 Animal welfare, regional livestock densities and grassland-based production

Consumers are increasingly concerned about animal welfare which is becoming accepted as an integral component of sustainability (Llonch et al. 2017). Current practices of livestock farming that aim to achieve high performance of livestock often imply negative consequences for animal welfare. These include, for example, confined housing environments and non-curative interventions such as castrations or beak or tail trimming and health damage (Commission on the Future of Agriculture (ZKL) 2021). It is therefore crucial to take animal welfare into account in pursuing efforts to reducing the GHG emissions from livestock farming.

Improving animal health and welfare through better herd management and health monitoring can enhance animal productivity and thus decrease GHG emissions per livestock unit (Herrero et al. 2016; Sutton et al. 2024, S. 103). The potential for improving productivity through enhancing animal health is generally greater in lower and lower-middle income economies (Sutton et al. 2024, S. 103).

The Commission on the Future of Agriculture recommends adapting cattle herd sizes to meet climate targets and emphasising grassland-based cattle farming (Commission on the Future of Agriculture (ZKL) 2021). This should be paired with adjustments in consumption and an increase in the added value per animal to ensure farm incomes remain stable. The EU strategic dialogue (European Commission (EC) 2024a) highlights the need for concrete pathways to a sustainable transition, including support for biodiversity-focused management of semi-natural grasslands through grazing.

The regional concentration of animal farms significantly impacts many European countries. At the national level, livestock density varies from 0.2 livestock units (LSU) per hectare in Bulgaria, Latvia, and Lithuania to 3.4 LSU per hectare in the Netherlands. At regional (NUTS 2) level, even higher concentrations can be found in Nord-Brabant (7.4 LSU/ha), Limburg (6.7 LSU/ha) or Gelderland (5.0 LSU/ha) in the Netherlands or West-Vlaanderen (6.2 LSU/ha) or Antwerpen (6.1 LSU/ha) in Belgium (Eurostat 2023).[5] Such high concentration levels necessitate the import of animal feed, as the available fodder area is insufficient for the high number of animals. In addition, it also leads to negative effects, such as nitrogen surpluses due to the large amounts of manure produced in these regions, overgrazing, water pollution, biodiversity loss and risks to human health.

Decentralising and diversifying livestock production and processing facilities can help to reduce negative environmental impacts of intensive livestock farming. Additionally, reducing the concentration of production can support regional development and overall resilience (Bock et al. 2022). The IPES-Food (2019) supports reducing the number of animals per hectare in their report on a common food policy for the EU. Focusing on the regional scale, livestock production should be delocalised in order to integrate it with landscapes and sources of feed and waste should be used locally or directly on the farm.

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[5] The number of animals per farm is less important than the total number of animals in a region as there may be exchanges of animal fodder and manure between farms.

Poux und Aubert (2018) emphasise the need for a balanced and integrated approach to livestock and crop production, moving away from highly specialised systems towards more diversified and sustainable practices. The scenario envisions a shift towards mixed crop-livestock systems across Europe. This involves reintroducing livestock into arable regions and diversifying grassland regions to include more arable farming to support biodiversity and nitrogen management. This means converting some arable land back to grassland and vice versa. In Mediterranean regions, where permanent grasslands are less common, the scenario suggests using and transhumance (seasonal movement of livestock) to manage fertility and grazing.

André et al. (2024) suggest reducing gross nitrogen balance surpluses should be reduced to a maximum of 81 kg nitrogen per hectare per year at the NUTS-2 regional level by 2045 (reducing the overall total gross nitrogen balance surplus in the EU by 54% in 2045 compared to 2020), which is hardly lined with a reduction of animal numbers. The reductions are more significant in regions with higher initial surpluses, ensuring that regions with higher surpluses in 2020 still have higher surpluses in 2045, but at a significantly lower level (p. 93). Stricter animal welfare standards that require more space per animal would also reduce overall livestock densities.

The agro-ecological scenario described in Billen et al. (2024) entails a reduction in livestock density from 0.6 LSU/ha in the reference scenario (2014-2019) to 0.4 LSU/ha by 2050. This is to be achieved by re-integrating crop and livestock farming to distribute livestock more evenly across region and feed it with locally produced feed. Under the Farm to Fork scenario described in the study, livestock densities amount to 0.69 LSU/ha in 2050, which is a reduction of 13% compared to a business-as-usual scenario for 2050 under which livestock densities would reach 0.79 LSU/ha. This is also to be achieved by introducing mixed crop-livestock systems into previously stockless regions while most regions of specialised livestock farming would remain as such in this scenario (p. 13).

The different scenarios described in Röös et al. (2022) entail different consequences regarding regional livestock concentration. In the BAU scenario, livestock production continues according to current patterns with no significant changes in livestock densities. In the Agroecology-for-Exports scenario, a redistribution of livestock across the whole EU is assumed with a focus on intermediate intensity production systems. In the Localisation-for-Protectionism scenario, increased grazing intensity is assumed, and livestock is redistributed within individual EU countries based on the availability of cropland and grassland. In the Localisation-for-Sustainability scenario, grazing intensity is assumed to be reduced while ruminant meant production decreases by 66%, mainly through a shift in human diets. Grass-based ruminant systems are increased while livestock production is redistributed within individual EU countries. In the Local-agroecological-food-systems scenario, reduced grazing intensity is assumed with grass-based ruminant systems and a reduction of 37% of ruminant meant. To achieve this, support for "industrial" livestock holdings is abolished and support is provided for improving the productivity of smaller agroecological farms.

Table 13 provides an overview of livestock densities in different scenarios.

Table 13: Livestock densities in different scenarios

Study	Scenario	Scope	Unit	Year	Value
EC 2024b	S2,S3	All cattle activities	LSU/ha UAA	2040	0.32*
	S2,S3	Other animals (non-cattle activities)	LSU/ha UAA	2040	0.35*

Study	Scenario	Scope	Unit	Year	Value
	LIFE	All cattle activities	LSU/ha UAA	2040	0.23
	LIFE	Other animals (non-cattle activities)	LSU/ha UAA	2040	0.26
Agora Agriculture 2024	Agora Agriculture	All cattle	LSU/ha grassland	2045	1.12
Billen et al. 2024	Reference year	All animals	LSU/ha UAA	2050	0.60
	All BAU scenarios	All animals	LSU/ha UAA	2050	0.79*
	All agro-ecology scenarios	All animals	LSU/ha UAA	2050	0.40
	Farm to Fork	All animals	LSU/ha UAA	2050	0.69

*Note: *Authors' own calculation based on information available on the difference to other scenarios, The colour code indicates the level of the GHG reduction ambition, green=/>40%, yellow= 20% up to 40%, grey = 0% up to 20%.*
Source: Authors' own compilation (Oeko-Institut), based on different studies

4.3.5 Framework conditions and policy instruments

The transformation of animal husbandry is described as a cornerstone in the ZKL and the EU Strategic Dialogue. Essential prerequisites for the success of this transformation include the expansion of animal welfare and ensuring adequate income for livestock farmers (Commission on the Future of Agriculture (ZKL) 2021).

To achieve the transformation in animal husbandry, several measures are necessary. **Market-based instruments** are highlighted as key components of policies to support the agricultural transition. The introduction of emissions trading is currently being discussed as an instrument for reducing greenhouse gas emissions from livestock farming in the EU. The idea is to create financial incentives for livestock farmers to reduce their greenhouse gas emissions by allowing them to trade carbon credits. This could utilise both government-regulated compliance markets and voluntary markets determined by companies' sustainability goals. The Strategic Dialogue has monitored the European Commission's efforts to explore various models of Emission Trading Systems for agriculture (AgETS). While the Dialogue acknowledges the necessity of a robust policy, it believes that drawing definitive conclusions at this stage is premature (European Commission (EC) 2024b, p. 60). Therefore, it urges the European Commission to continue collaborating with stakeholders and experts to evaluate the feasibility and relevance of such a system. The World Bank Group's Climate Change Action Plan (2021-2025) emphasises the importance of carbon pricing to drive emission reductions and generate revenue with minimal economic disruption (World Bank Group 2021). However, the implementation of such a scheme in the livestock sector faces several challenges, including measuring and verifying emissions and ensuring fair participation of all stakeholders (Scheffler und Wiegmann 2024; Mal 2024).

The German Commission on the Future of Agriculture (ZKL) (2021) emphasises improving animal welfare as a goal in itself. Funding should be realigned to support farms that ensure high animal welfare. Sustainable technologies should be promoted and training and advice be provided to farmers (Commission on the Future of Agriculture (ZKL) 2021). More generally, measures include implementing appropriate licensing and certification schemes for livestock facilities and equipment, ensuring consistent application of building and fertiliser laws, and introducing animal welfare in all parts of the animal live, including breeding practices, more animal-friendly production, animal transports and slaughtering methods. Additionally, animal grazing can stimulate carbon sequestration in soils. As good livestock management practices that store carbon, adaptive multi-paddock systems (Howard 2022) and grassland-based cattle farming (Commission on the Future of Agriculture (ZKL) 2021, S. 70) are proposed.

The JRC (2022) also suggests to revise EU legislation on animal welfare, including on animal transport and the slaughter of animals. The Strategic Dialogue recommends to base the revised legislation on a holistic socio-economic impact assessment and recognise the interconnectedness of human, animal and environmental health (and thus addressing challenges like antimicrobial resistance) (European Commission (EC) 2024a, S. 66).

In a global context, animal health is prioritised over animal welfare, focusing on disease prevention to reduce economic losses of animal diseases, improve food safety and reducing risks of antimicrobial resistance (FAO 2023a, p. 12). Comparing national pathways that emerged from the United Nations Food Summit in 2021, the FAO found that animal welfare and reducing consumption of animal products was not mentioned by countries from other regions than Europe (FAO 2023b, S. 16).

On the other hand, consumer-side measures are needed that include labelling (Publications Office of the European Union 2020; FAO 2023b; Bock et al. 2022). The ZKL recommends transparent and mandatory EU labels regarding animal welfare, minimum standards for regional origin as well as more general sustainability criteria to be developed to guide consumers in making more sustainable choices (2021, p. 86). However, the ZKL states that ‘the necessary and highly demanding transformation of farm animal husbandry cannot be achieved in the foreseeable future purely with market-based measures such as labelling, and information directed at consumers’ (2021 p. 79). As part of suggested measures that go beyond labelling, the ZKL considers the introduction of an excise duty on animal-derived foodstuffs to internalise external costs of current agricultural production (2021, p. 84). Even the FAO supports changing food taxes and subsidies for food producers to reduce overconsumption of products like sugar, rice, trans fat or some animal products (depending on the national context) (FAO 2023a).

The problem of regional high livestock densities is addressed by the ZKL and also by the EU strategic dialogue. It has been pointed out that it is necessary to develop more self-sufficient farming practices. This should be supported by regional nutrient management between farms and aim to spread livestock production more evenly across regions, considering each area’s natural suitability. A more geographically dispersed livestock production could support a more regionally based feed production, less concentrated nutrient emissions, lower emissions from transporting products and waste as well as improving animal welfare and health (Commission on the Future of Agriculture (ZKL) 2021, p. 80). To improve the prospects of smaller farms, higher welfare processing structures should be implemented at regional level. Also, direct regional marketing could support regional, sustainably produced animal products (Commission on the Future of Agriculture (ZKL) 2021, p. 49).

The Strategic Dialogue recommends establishing territorial action plans with local stakeholders to develop specific emission reduction plans while taking into account other environmental concerns in the respective region (European Commission (EC) 2024a, S. 59). According to Agora Agriculture (2024), economic incentives should be provided to farmers who reduce livestock numbers and adapt more extensive farming practices through subsidies and payments for ecosystem services. Alternative income sources such as agroforestry, renewable energy production or developing new value chains in the bioeconomy should also be incentivised.

The IPES-Food (2019) argues for making CAP funding conditional on reducing antibiotic use and enhancing animal health, as well as introducing livestock density limits in line with the EU Organic Regulation in the longer run. Rural development under the CAP should offer support for sustainable territorial livestock management schemes. It also suggests using CAP funds under pillar 2 (rural development) to support the relocation of processing facilities and slaughterhouses to neglected areas to support mobile slaughter units. Additional support should be made available for alternative business models such as cooperatives, Community Supported Agriculture schemes or local purchasing platforms (Howard 2022).

The FAO, taking a global perspective suggests a different focus: For addressing emissions from the livestock sector, the efficiency of production should be increased, particularly among low-productivity producers, through i.a. better genetics, an intensification of livestock production in relevant locations and improved feeding practices, promoting new sources of protein feed, restoring degraded pasture and improving grazing management practices, shifting to integrated silvopastoral production or crop-livestock integration, adopt certification and labelling schemes. To reduce the GHG impact of animal-based food products, the FAO suggests shifting from large ruminants to small ruminant animals for meat products and from ruminant to monogastric animals FAO 2023a, p. 12). Generally, the FAO highlights the need to fit any measures to make agriculture more sustainable to the local context.

4.4 Land use and crop production

4.4.1 Introduction

To make crop production more climate-friendly, a variety of measures exist. Optimising crop rotation, using cover crops, reducing tillage or cultivation of legumes contribute to enhancing carbon stored in soils. At the same time, increased humus content enhances the fertility of soils as well as their water retention capacity and general resilience to climate change.

A more technology-focused approach to reducing emissions from agriculture focuses on strategies to "sustainably" intensify agricultural production and thus enhance productivity, e.g. by increasing the use of fertilisers, pesticides or machinery. Technological innovation such as the precision application of fertiliser or fungicides or digitalisation in livestock farming can also support the sustainable transformation of agriculture. It is argued in the literature that sustainable intensification will free land from agricultural use so that pressure on land use decreases (land sparing) (Benton und Harwatt 2022). The JRC (2022) assigns a key role to technologies like digital tools for precision farming, artificial intelligence in decision support systems, new plant breeding technologies, deficit irrigation, novel feed and food additives and others in the transition to sustainable food systems. Yet it emphasises that new plant breeding technologies need to be managed well to promote resilience and sustainability (p. 49f.).

However, it is questionable to what extent productivity gains can be achieved without an absolute increase in environmental impact (in terms of i.a. GHG emissions, nitrogen pollution or biodiversity loss) (Benton und Harwatt 2022, p. 20). In the literature on 'sustainable intensification,' efficiency gains are commonly prioritised over reducing overall environmental impacts (Benton und Harwatt 2022; Buckwell et al. 2014; Pretty et al. 2018; Garnett et al. 2013). According to Schutter et al. (2019), capital-intensive "techno-fixes" support intensive, large-scale monoculture-based production with negative environmental impacts (p. 58f.). Additionally, evidence of examples where agricultural intensification has spared land is scarce (Thaler 2017; García et al. 2020; Benton und Harwatt 2022). This is because it is challenging to protect land from agricultural expansion. Additionally, spared land can be negatively affected through pollution or microclimatic change from intensively farmed land. A sole focus on enhancing the efficiency of production is therefore insufficient to reduce pressures on land use (Chatham House 2022). In this context, the ZKL (2021) explicitly recommends replacing crop protection methods with higher risks for human health and the natural environment by low-risk and biological pesticides and natural mineral substances (p. 98).

At the same time, prioritising agro-ecological approaches in crop production and thus sharing land from agricultural use is conditional upon a considerable change in dietary habits. However, this would require a fundamental shift in the current economic thinking towards designing markets to primarily deliver public goods. This contradicts prevailing paradigms of economic thinking (Benton und Harwatt 2022).

4.4.2 Use of agricultural land and production (quantitative studies)

To meet climate targets, adapt to climate change, and preserve biodiversity, the use of agricultural land will need to change in the future. This is reflected in various scenarios. Three key points must be considered:

- the use of agricultural land for fodder production,
- the rewetting of organic soils,
- the use of agricultural soils to increase carbon sinks, either through planting trees or using the land for afforestation or natural revegetation.

Additionally, increasing the share of agricultural land with a high biodiversity value is crucial. The rewetting of organic soils and the increase of trees on agricultural land can also enhance biodiversity.

Reducing the fodder area creates opportunities for alternative uses. In the Agora scenario, the EU's fodder area is reduced by 32 million hectares (André et al. 2024), while the EC impact assessment projects a reduction of 12 million hectares compared to 2020 levels (European Commission (EC) 2024b). Alternative uses of this area will help achieve the goal of a climate-neutral EU by reducing emissions from agricultural organic soils through peatland rewetting and increasing carbon sinks on agricultural land through agroforestry systems or afforestation.

In the Agora scenario, 80% of peatland (2.8 million hectares) is rewetted, 13 million hectares are planted with lignocellulosic crops, and an additional 5 million hectares are designated for afforestation (André et al. 2024). The LIFE scenario included in the EC's impact assessment also aligns with these goals. Reducing the fodder area by 12 million hectares increases the land available for peatland rewetting, afforestation, and biodiversity enhancement. Compared to the S2/S3 scenarios, peatland rewetting is increased by 0.3 million hectares (1.3 million hectares in the S2/S3), land for afforestation increases by 4 million hectares (4.9 million hectares in S2/S3), and another 6.8 million hectares are available for natural revegetation. Furthermore, grassland can be managed more extensively, with 84% of grassland used as extensive grassland in the LIFE scenario (European Commission (EC) 2024b).

This effect is also demonstrated in the scenarios included in Röös et al. (2022). Compared to the 2012 base year, the area for vegetation regrowth, which creates an additional carbon sink, increases in these scenarios. In the BAU scenario, this increase is based on assumptions of yield improvements that free up cropland and grassland, even if the demand for animal products remains high. The sustainability scenario, which fully implements the nutrition recommendations from the planetary health diet, shows the highest share of land for vegetation regrowth. In this scenario, 48% of the land becomes available for vegetation regrowth, accompanied by a 72% reduction in grassland area and a 28% reduction in cropland area. The impact of this increase in vegetation regrowth is evident in the rise in carbon storage (see Table 20). In the local system scenario, higher production of ruminant meat and dairy compared to the sustainability scenario is assumed. This increases the use of grassland, leaving less area available for vegetation regrowth.

Table 14: Use of agricultural area in different scenarios

Study	Data/ Scenario	Year	Cropland	Grassland	Vegetation regrowth
Röös et al. 2022	BAU	2050	-3%	-35%	+17%
	Sustainability	2050	-28%	-72%	+48%
	Local system	2050	-32%	-13%	+23%

Note: The colour code indicates the level of the GHG reduction ambition, green=/>40%, yellow= 20% up to 40%, grey = 0% up to 20%.
Source: Röös et al. 2022

In the scenario by IDDRI (2018), there is no emphasis on peatland rewetting or increasing carbon sinks. However, by changing diets and shifting production, a total of 16 million hectares of land is freed up, even with 100% organic farming assumed, without synthetic fertilizers or pesticides, which significantly impacts yields. This freed-up land is used to maintain permanent grassland and export cereals to Mediterranean countries. By changing diets, the agricultural area in the EU is sufficient to feed a population of 530 million people in 2050 and export part of the milk produced.

Table 15 shows the trends in the production of cereals, pulses, fruits, and vegetables. In scenarios that include dietary changes and achieve emission reductions of over 40%, cereal production decreases mainly due to reduced demand from lower livestock numbers. To compensate for the reduced consumption of animal products, the production of pulses, fruits, and vegetables increases. However, in the BAU scenario in Röös et al. (2022) and the S2 and S3 scenarios (European Commission (EC) 2024b), cereal production continues to rise.

Table 15: Production of plants-based products in different scenarios

Study	Data/ scenario	Year	Cereal	Pulses	Fruits, vegetables
			Mt or % against reference		
Agora Agriculture (2024)	Base year 2020	2020	266	5*	107
	Scenario compared to 2020	2045	172 -35%	15* +200%	150 +40%
Röös et al. 2022	BAU compared to 2012	2050	+45%	+44%	+7%
	Sustainability compared to 2012	2050	-46%	+492%	+83%
	Local system compared to 2021	2050	-56%	+492%	+83%

Study	Data/ scenario	Year	Cereal	Pulses	Fruits, vegetables
Rieger et al. 2023	Lancet_Low compared to baseline	2050	n/a	n/a	+27%
	Lancet_High compared to baseline	2050	n/a	n/a	+70%
	Lancet_Full Compared to baseline	2050	n/a	n/a	+100%
EC 2024b impact assessment	S2, S3 compared to 2020	2040	268 +1%	n/a	126 +18%
	LIFE compared to 2020	2040	215 -19%	n/a	123 +15%

*Note: * Includes pulses and soya*
The colour code indicates the level of the GHG reduction ambition, green=/>40%, yellow= 20% up to 40%, grey = 0% up to 20%.
Source: Authors' own compilation (Oeko-Institut)

Billen et al. (2024) show the development of cropland, grassland and livestock edible production in Tg nitrogen for different scenarios. The BAU scenario maintains current production levels for cropland and grassland, with stable livestock populations relying on imported feed. The BAU-20%fert. scenario reduces synthetic fertiliser use by 20%, leading to a 6% decrease in crop production, a slight 2% decrease in grassland production, and a 17% reduction in livestock production due to lower feed availability. The Farm to Fork scenario incorporates agro-ecological practices and reduced fertiliser use, resulting in a 20% drop in crop yields, slightly reduced grassland production, and a 13% reduction in livestock density with a shift towards organic farming (see Table 16). The Agro-Ecology (AE) scenario significantly reduces crop production by 36% through agro-ecological practices, maintains grassland production with a focus on organic methods, and reduces livestock density by 35-45% with no feed imports, adjusting production to local feed resources. These scenarios highlight the trade-offs between maintaining current production levels and adopting more sustainable agricultural practices, with the AE scenario showing significant environmental benefits but requiring substantial changes in farming practices and dietary patterns. In scenarios achieving more than a 40% reduction in N_2O emissions, the production of all products declines. The minimum decrease is found for grassland in the Agro-Ecology (AE) scenario. Here grassland production experiences only a slight decrease due to the emphasis on sustaining productivity through organic practices and the use of local feed resources.

Table 16: Agricultural production in different scenarios in Billen et al. 2024

Data/ Scenario	Year	Cropland production	Grassland production	Livestock edible production
			Tg N/yr	
S0	2014:2019	11.4	5.6	2.4
BAU	2050	+1%	0%	+4%

Data/ Scenario	Year	Cropland production	Grassland production	Livestock edible production
BAU-lowdiet	2050	+4%	0%	+4%
BAU-20fert.	2050	-6%	-2%	0%
Farm to Fork	2050	-20%	-16%	-21%
Agro-ecology	2050	-36%	-9%	-54%
Agro-ecology current diet	2050	-34%	-9%	-50%

Note: The colour code indicates the level of the GHG reduction ambition, green=/>40%, yellow= 20% up to 40%, grey = 0% up to 20%.
Source: Billen et al. 2024

4.4.3 Nitrogen input and nutrient balance

In sustainable agricultural systems, the ZKL envisages that available slurry and manure are used as fertiliser while - if possible - mineral fertiliser is no longer added so that nitrogen surpluses are reduced (Commission on the Future of Agriculture (ZKL) 2021, S. 70–71). Integrating livestock and crops is promoted as a key factor in strengthening resilient farming livelihoods as they can be a source of nitrogen where synthetic fertilisers are not available or too expensive (Howard 2022). Additionally, integrated nutrient management including crop rotations, nitrogen biological fixation, reduced tillage, use of cover crops among others should contribute to optimising fertiliser use and reducing N_2O emissions (Nabuurs et al. 2022).

The Farm to Fork strategy aims to reduce nutrient losses by at least 50% by 2030. Consequently, some scenarios focusing on the implementation of this strategy include assumptions about the development of nitrogen surpluses, which are considered external drivers of the scenario (Agora Agriculture 2024, EC 2024b, LIFE scenario). Therefore, in the scenarios, agricultural practices were adapted (e.g. reduced nitrogen input, changes in livestock density) to achieve the target.

Table 17 shows the development of nitrogen surpluses across different scenarios. The scenarios in Röös et al. (2022) find an increase in nitrogen surpluses in almost all scenarios. In the BAU scenario, intensification led to higher nitrogen inputs per unit output, a trend seen in scenarios with low agroecological practices. The Local-agroecological-food-systems scenario achieved an 85% reduction in nitrogen surpluses compared to 2012.

Most of the other scenarios (except the BAU scenario in Billen et al. (2024)) show reductions in nitrogen surpluses range from about -5/-10% to up to -50% in the more ambitious scenarios. Scenarios that align with the Farm to Fork strategy's target of halving nutrient losses are those that include a reduction in animal numbers (European Commission (EC) 2024b EC LIFE, Agora Agriculture 2024, Billen et al. 2024 Agro-ecology). By introducing technical measures alone (e.g. EC S2, S3 scenarios), nitrogen surpluses will not decrease sufficiently to meet the targets of the Farm to Fork strategy. In the ambitious target scenarios, nitrogen surpluses of about 5 Mt N will remain.

Table 17: Development of nitrogen surpluses in different scenarios

Study	Scenario	Base year	Scenario year	Development of nitrogen surplus in % of base year	Nitrogen surplus in base year Mt N	Nitrogen surplus in target year
Agora Agriculture 2024*	Agora Agriculture	2020	2045	-54%	n/a	n/a
EC 2024b	S2, S3	2020	2040	-2%	10.8’	10.6’
EC 2024b	LIFE	2020	2040	-49%	10.8’	5.5
Rieger et al. 2023**	Lancet_Low	Ref_2030	2030	-3.2%	n/a	n/a
	Lancet_high	Ref_2030	2030	-5.3%	n/a	n/a
Röös et al. 2022	BAU	2012	2050	+217%	n/a	n/a
	Sustainability	2012	2050	+200%	n/a	n/a
	Local System	2012	2050	-85%	n/a	n/a
Billen et al. 2024	BAU		2050	+5%	11.8	12.4
	BAU-20%fert.		2050	-12%	11.8	10.4
	BAU_lowdiet		2050	-1%	11.8	11.7
	Agro-ecology		2050	-59%	11.8	4.8
	Agro-ecology_current diet		2050	-58%	11.8	5
	Farm to Fork		2050	-28%	11.8	8.5
IDDRI 2018	TYFA	2010	2050	-90%	8.8	0,9

*Note: * Scenario assumption: halving nitrogen surpluses by 2045; ’ own calculation based on information from Table 21 EC 2024b; ** no information available for 2050 from the Magnet model; ~ read from a graph.*
The colour code indicates the level of the GHG reduction ambition; green=/>40%, yellow= 20% up to 40%, grey = 0% up to 20%. The table also contains information on scenarios not included in the overview in chapter 3. However, they are included here for information purposes.
Source: Authors’ own compilation (Oeko-Institut)

4.4.4 GHG mitigation potential (quantitative studies)

4.4.4.1 GHG mitigation for N_2O emissions from agricultural soils

N_2O emissions from agricultural soils are primarily influenced by nitrogen inputs from synthetic fertilisers, manure, other organic fertilisers, crop residues, and grazing animals. Additionally, N_2O emissions from agriculturally used peatlands are included under agricultural soils, contributing 12% to the total direct N_2O emissions from soils at the European level, with significant regional variations. Reducing nitrogen input to soils decreases N_2O emissionsy. Changes in agricultural practices – such as increasing organic farming, cultivating more legumes, or growing crops that require less nitrogen – along with management and technical measures aim at reducing nitrogen inputs and N_2O emissions.

Detailed information on individual mitigation technologies and their potential is provided in Pérez Dominguez et al. (Pérez Domínguez et al. 2020) and André et al. (2024). The Pérez Dominguez et al. study (Pérez Domínguez et al. 2020) analyses **eight crop sector-related** mitigation options. This also includes a measure for reducing CH_4 emissions from rice cultivation, which is not included here due to its minor importance for Europe. The following table outlines the mitigation measures for reducing N_2O emissions from agricultural soils and the share of the single measures in the total mitigation potential for the Pérez Dominguez et al. (Pérez Domínguez et al. 2020) and André et al. (2024).

The studies begin with different emission levels. While Pérez Domínguez et al. (Pérez Domínguez et al. 2020) present a reference scenario, the Agora scenario presents a target scenario in which emissions are already 45% lower than those in the reference scenario provided by the JRC (2020). The absolute mitigation potential of technical measures increases with higher total N_2O emissions from agricultural soils. Conversely, starting with lower emissions in the Agora scenario results in smaller absolute emission reductions from technical measures, although the relative reduction might be higher.

Table 18: Overview of GHG mitigation potentials from different technical mitigation options for crop production

	Perez Dominguez 2020 (EC 2022b)		**Agora Agriculture 2024**	
	Absolute emission reductions in Mt CO_2e	**Share of total mitigation potential**	**Absolute emission reductions in Mt CO_2e**	**Share of total mitigation potential**
Better timing of fertilisation	0.1	0.3%	0.81	11%
Precision farming	12.0	44%	1.51	20%
Variable rate technology*	3.6	13%	0.06	1%
Nitrification inhibitors	11.0	40%	5.32	69%
Increase legume share in grassland	0.7	2.5%	n/a	n/a
Total mitigation	**27.5**	**100%**	**7,7**	**100%**

*Note: *Variable rate technology allows for adjustments in the application rate to precisely match the specific needs for fertilizer, lime, seeds, and other inputs at each location within the field.*
Source: Authors' own compilation (Oeko-Institut) based on Pérez Dominguez et al. (Pérez Domínguez et al. 2020) (Table 10 and information in text)

The implementation of precision farming and the use of nitrification inhibitors offer the greatest mitigation potential in both studies. However, research on nitrification inhibitors indicates ecotoxic effects especially on aquatic species and on the root development of several terrestrial plant species (Kösler et al. 2019). Moreover, there are indications that nitrification inhibitors not only reduce the activity and abundance of nitrifying bacteria but also impact microbial groups that are not involved in the nitrification process (Corrochano-Monsalve et al. 2021). As part of the approval process of nitrification inhibitors to the market (per EU REACH regulation), such impacts are not assessed in sufficient detail (Frelih-Larsen et al. 2022). Some synthetic nitrification inhibitors might also lead to increased ammonia emissions under certain pedo-climatic conditions (Wang et al. 2020; Chunlian Qiao et al. 2015). Additionally, concerns about risks to human health remain as residues of specific inhibitors were found in milk (Ray et al. 2021).

In addition to the measures outlined in the table, further actions are available, such as rewetting agricultural soils on peatlands to reduce N_2O emissions and implementing measures to reduce ammonia emissions, which in turn decreases indirect N_2O emissions from agricultural soils.

Without including peatland rewetting measures, Pérez Domínguez et al. (2020) estimate a mitigation potential of 27.5 Mt CO_2e. The EC's impact assessment (European Commission (EC) 2024b) shows a mitigation potential of 44 Mt CO_2e from technical measures to reduce N_2O emissions from agricultural soils in the S2/S3 scenarios. In the LIFE scenario, the mitigation potential from technical measures is lower, at 34 Mt CO_2e, due to reduced nitrogen demand. The proportion of N_2O emissions that can be reduced by implementing technical mitigation measures remains consistent across all scenarios included in the impact assessment at about **35%**.

With a reduction of only 7.7 Mt CO_2e, the technical reduction potential in the Agora Agriculture scenario (2024) is significantly lower than in other studies. This could be due to the generally lower use of fertilisers. However, the total reduction in N_2O emissions from agricultural land is estimated at 31 Mt CO_2e, which corresponds to a 40% reduction compared to 2020. It is unclear whether the overall reduction in fertiliser use is solely due to the lower nitrogen requirement due to larger areas of biodiversity and other crops or whether other measures also play a role. Table 19 shows the development of N_2O emissions from agricultural soils across different scenarios, including the emission reductions achieved compared to the base year. The scenarios results do not differentiate between mitigation achieved through technical measures and mitigation resulting from changes in demand due to organic farming, increased legume cultivation, or the use of crops that require less nitrogen.

Table 19: Development of N_2O emissions from agricultural soils in different scenarios

Study	Scenario	Base year	Emissions in base year	Emissions in target year	Emission in % of base year
Agora Agriculture 2024*	Agora Agriculture	2020	78	47	-40%
EC 2024b	S2, S3	2020	119	85	-28%
EC 2024b	LIFE	2020	119	63	-47%

Billen et al. 2024	BAU	2014-2019	162**	158	-3%
	BAU-20%fert.	2014-2019	162**	150	-8%
	Agro-ecology Agro-ecology current diet	2014-2019	162**	71	-56%
	Farm to Fork	2014-2019	162**	117	-28%
IDDRI 2018	TYFA	2012	174.7	59.98	-66%

*Note: * N_2O emissions from agricultural soils without manure application and without N_2O emissions from peatland, ** Base year refers to the S0 scenario calculated by the model to calibrate with current reference situation. This is the basis for comparing the scenarios with the current situation.*
The colour code indicates the level of the GHG reduction ambition, green=/>40%, yellow= 20% up to 40%, grey = 0% up to 20%.
Source: Authors' own compilation (Oeko-Institut)

Billen et al. (2024) do not assume any technical improvements. Therefore, across all scenarios, the common assumption is that the yield response to fertilisation remains at the currently observed status in each region. Compared to the base year, N_2O emissions decrease by 3% in the BAU scenario due to a reduction in NH_3 emissions and a reduction in N-losses. A significant reduction of 56% in N_2O emissions is observed only in the agro-ecology scenarios, which involve a substantial decrease in livestock numbers. The Farm to Fork scenarios, which implement organic farming and reduce fertiliser use as part of the Farm to Fork strategy, show a 28% reduction in N_2O emissions compared to the base year.

Scenario results reveal that almost halving N_2O emissions compared to the base year is possible. This is reflected in the results of Billen et al. (2024) Agro-ecology, of the LIFE scenario (European Commission (EC) 2024b) and of Agora Agrar (2024) (see Table 19). However, this requires structural changes, such as reducing livestock numbers and altering demand through organic farming, increased legume cultivation, or the use of crops that require less nitrogen. These changes would lead to reduced production of both animal and plant-based products. However, by improving the management on the farm level and implementing technical mitigation options, N_2O emissions can be reduced by up to 28% compared to the base year (see Table 19, European Commission (EC) 2024b, S2,S3).

4.4.5 Carbon removals and reduction of CO_2 emissions from peatlands

Agriculture contributes to GHG neutrality by enhancing carbon sinks on agricultural land. Increasing carbon sinks can be achieved through measures such as growing winter crops, increasing the share of legumes, converting cropland into grasslands, and growing trees on agricultural land. Pérez Dominguez et al. (Pérez Domínguez et al. 2020) highlight the mitigation potential of growing winter crops and increasing the share of legumes. By these two measures nearly **30 Mt CO_2** can be sequestered in the soil across Europe (see Table 10, p. 42). The Agora Agriculture scenario also assumes the implementation of these measures. However, it does not anticipate any additional effects on CO_2 sequestration. Instead, it assumes that many of these measures are crucial under changing climate conditions to ensure that soil organic carbon stocks in cultivated arable soils remain constant (Agora Agriculture 2024, p. 95).

Additional carbon sinks from planting trees on agricultural land, whether in the form of wooden strips (agroforestry, fast-growing trees) or as new areas for afforestation or vegetation regrowth, are reflected in the Agora Agriculture study (2024), the EC's impact assessment (European Commission (EC) 2024b), and Röös et al. (2022).

The Agora Agriculture (2024) scenario assumes an annual average **CO_2 sequestration of 32 Mt** from fast-growing trees. This estimate is based on establishing fast-growing trees on 8% of agricultural land (12.7 million hectares). This is based on the assumption that during the establishment phase, each hectare of fast-growing trees sequesters between 47 and 52 tonnes of CO_2 equivalent in aboveground biomass and between 14 and 19 tonnes in belowground biomass (André et al. 2024, p. 53 and Annex, Table A5, p. 24). In addition to an increased carbon sequestration rate, 80% of peatlands (2.9 million hectares) will be rewetted. This will reduce CO_2 emissions in the LULUCF sector and N_2O emissions in the agricultural sector by an additional **72 Mt CO_2e** (108 Mt CO_2e in 2020 to 36 Mt CO_2e in 2045/2050).

The scenarios included in Röös et al. (2022) present higher carbon sequestration rates. According to the scenario narratives, land freed up due to decreased demand or productivity increases is assumed to undergo vegetation regrowth. This process allows for the offsetting of a portion of agricultural emissions through the establishment of new carbon sinks. Vegetation regrowth on freed land enables carbon sequestration, offsetting 52% of emissions in the Business-as-usual scenario. In the Localisation-for-sustainability and Local-agroecological-food-systems scenarios, vegetation regrowth results in net-negative GHG emissions from agriculture. The highest vegetation regrowth is found in the sustainability scenario, assuming dietary changes in accordance with the planetary health diet. In this scenario, large areas are freed up due to changes in demand, resulting in 48% of agricultural land becoming available for vegetation regrowth (see Table 14). As a result, significant emission reductions in the agricultural sector due to dietary changes, combined with carbon storage from vegetation regrowth, lead to substantial negative emissions of -807 Mt CO_2e in the sustainability scenario (see Table 20). In the local system scenario, it is assumed that the production of ruminant meat and dairy is higher than in the sustainability scenario. This leads to increased use of grassland, reducing the area available for vegetation regrowth.

Table 20: Emissions from agriculture and carbon sequestration in Mt CO_2e in Röös et al. 2022

	BAU	Sustainability	Local System
Emissions from agriculture	588	290	279
Net emissions from agriculture and LULUCF	280	-807	-335
Additional carbon sequestration*	308	1097	614

Note: No information was found on the carbon sequestration rates per hectare. Short calculation for sustainability: UAA 2012 = 174 million ha, 48% = 84 million ha, Carbon sequestration of 1097 Mt CO_2/ 84 million ha = 13.1 t CO_2 sequestration per hectare
Source: Röös et al. 2022, Figure 4, p. 11

The EC's impact assessment (European Commission (EC) 2024b) also highlights the increased carbon sequestration potential resulting from changes in demand. In the LIFE scenario, compared to scenarios S2/S3, there is an increase of 6.8 million hectares in natural vegetation, 4.0 million hectares in forest land, and 0.3 million hectares in rewetted soils. In the LIFE scenario, the GHG balance in the land use sectors (agriculture and LULUCF) improves by **111 Mt CO_2e** compared to other scenarios, due to emission reductions from the agricultural sector and additional carbon sequestration on agricultural land. Consequently, the GHG balance shifts from -84 Mt CO_2e to -195 Mt CO_2e.

The studies do not include information on LULUCF emissions. The EC2024 study only provides data on net removals in the LULUCF sector, without distinguishing between emissions and removals.

4.4.6 Biodiversity, peatlands, organic farming

4.4.6.1 ***Landscape** features including agroforestry, biodiversity, grassland*

The way in which land is cultivated has a major impact on biodiversity. Larger agricultural management units that are cultivated by the intense use of machinery has entailed a loss of landscape features and habitats such as hedges or field margins. This, along with the use of pesticides, nutrient surpluses through excessive fertiliser use, soil compaction and deep tillage harm soil biodiversity. Applying slurry and sewage sludge to soils can additionally pollute soils through medicines and microplastics contained therein (Commission on the Future of Agriculture (ZKL) 2021).

The ZKL formulates in its vision that ‘biodiversity is seen and valued as a fundamental resource, forming the basis of ecosystem functions. Activities that promote biodiversity and especially insects are the order of the day. […] Agroforestry structures have been expanded and there is no further land-take with surface sealing’ (ZKL 2021, p. 41).

Promoting agricultural practices that enhance carbon sequestration, integrate crops and livestock, diversify farms and reduce chemical inputs can enhance biodiversity (European Environment Agency (EEA) 2022; Fischer et al. 2021; Schutter et al. 2019; Nabuurs et al. 2022).

Quantitative studies indicate that biodiversity increases in the more ambitious scenarios. In André et al. (2024), 20% of semi-natural landscape features can be implemented at the regional level (NUTS 2). The LIFE scenarios show a 14% greater increase in areas with high biodiversity value compared to the S2/S3 scenario (European Commission (EC) 2024b).

4.4.6.2 *Area of rewetting peatlands*

Only 3.9 million hectares of the total agricultural area are drained peatlands, representing just 2% of the total agricultural area. Significant peatland areas are found in Germany (33%), Poland (24%), the Netherlands and Ireland (both 9%), and Finland (7%), with smaller areas in Denmark, Latvia, Lithuania, and Sweden. However, when considering agricultural emissions, including CO_2 and N_2O emissions from peatland use, peatlands account for 22% of these emissions (European Environment Agency (EEA) 2023).

The rewetting of peatlands bears significant potential for avoiding GHG emissions from the agricultural sector. This can be supported by using peat substitutes and banning peat extraction at EU level. Additionally, converting arable land into grassland, conserving grassland, and promoting paludiculture can support the conservation and restoration of peatlands in the EU. This could be funded by GHG pricing systems (Commission on the Future of Agriculture (ZKL) 2021).

The strategic dialogue only briefly highlights the importance of peatlands: ‘Specific actions will be needed for peatland areas: While recognising that all peatlands are different, they emit CO_2, which can be curbed through effective water management practices in specific regions. Increasing water levels in peatlands should be incentivised’ (European Commission (EC) 2024a, S. 58).

In a global context, the FAO (2023a) discusses wetlands together with forests and emphasises the protection of existing (forests and) peatlands and their role in ensuring water availability for agriculture, thus focusing on food security while mentioning their role as a carbon sink as an additional function. The FAO proposes integrating restoration efforts into productive schemes through paludiculture to enhance carbon stocks while securing income through the production of crops. Additionally, subsidies and commodity price support should be phased out for production on drained land and redirected to promoting paludiculture (p. 24-25). The FAO does not mention the complete rewetting of peatlands.

Few quantitative studies consider peatland rewetting. Only Agora Agriculture (2024) and the EC’s impact assessment (European Commission (EC) 2024b) include assumptions on this topic. Pérez Dominguez et al. (Pérez Domínguez et al. 2020) also highlight the significant mitigation potential of peatlands. The Agora scenario assumes that 80% of peatland is rewetted and using the remaining 20% primarily as shallow-drained grassland. By this, emissions from peatland can be reduced by 67% compared to 2020. 80% of rewetted peatlands is used as paludiculture to create additional farm incomes.

4.4.6.3 *Organic farming*

Organic farming implies great potentials for the protection of ground water and surface water, enhanced soil fertility, biodiversity, higher carbon sequestration rates and lower N_2O emissions, adaptation benefits including erosion prevention and flood protection, nitrogen, and energy efficiency and to a lesser extent for animal welfare compared to conventional agriculture. It is thus a key option in the sustainable transformation of agricultural systems (Sanders und Heß 2023).

As part of the Green Deal’s Farm to Fork strategy, the EU has a target of at least 25% of the agricultural land to be under organic farming by 2030.[6] In 2021, 9.9% of EU agricultural land was under organic farming.[7]

Table 18 provides an overview of the share of organic farming in different studies. Many of the ambitious scenarios increase the share of organic farming to at least the level proposed by the Farm to Fork Strategy (European Commission (EC) 2020). Notably, the TYFA and the agro-ecology scenario in Billen et al. (2024) assume organic farming practices across all agricultural land.

Table 21: Overview of assumptions regarding the share of organic farming in different scenarios

Study	Scenario	Share of organic farming in total agricultural area
Agora Agriculture 2024*	Agora Agriculture	No differentiation between organic farming and conventional farming
EC 2024b	LIFE	25%
Billen et al. 2024	BAU-20fert.	No increase compared to current levels
	Agro-ecology Agro-ecology current diet	100% organic farming
	Farm to Fork	25% organic farming

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[6] See https://agriculture.ec.europa.eu/farming/organic-farming/organic-action-plan_en.

[7] https://www.eea.europa.eu/en/analysis/indicators/agricultural-area-used-for-organic.

Study	Scenario	Share of organic farming in total agricultural area
IDDRI 2018	TYFA	100%
Röös et al. 2022	Sustainability	Remains at 2012 levels (5.7% of total area)
	Local Systems	50% of area

Note: The colour code indicates the level of the GHG reduction ambition, green=/>40%, yellow= 20% up to 40%, grey = 0% up to 20%.
Source: Authors' own compilation (Oeko-Institut)

However, enhancing organic farming in the EU entails reduced production quantities compared to conventional agricultural practices (Kremmydas et al. 2024; Benton und Harwatt 2022) and may thus lead to increased demand for land (Nabuurs et al. 2022, S. 798). Enhancing crop productivity as well as substantially reducing the consumption of animal products and food waste will be necessary to compensate for the reduced supply of agricultural products and prevent the use of additional land as cropland (Rasche und Steinhauser 2022; Einarsson et al. 2022; Barbieri et al. 2019). For the EU, increased organic management of animal farms would result in a reduction of total livestock numbers by 2030. According to projections by IFOAM, reduced livestock numbers and reduced cereals demand as well as reduced cereals use for feeding organic livestock would more than balance lower cereals production under organic farming (Lampkin und Padel 2023).

The extent to which human diets can be changed to lower the global demand for land is an open question (Benton und Harwatt 2022). Many studies assume an increasing global food demand resulting from a growing world population (Tilman et al. 2011; Fukase und Martin 2020; Alexander et al. 2019; Willett et al. 2019). However, the quantitative data indicate that successful dietary changes could create opportunities for expanding organic farming.

4.4.7 Framework conditions and policy instruments

A variety of political and economic instruments must sustain the transformation towards environmentally sustainable agriculture.

Clear standards, robust monitoring and evaluation frameworks, transparency on the production process of agricultural products and education as well as capacity building are mentioned as key elements in the transition to a sustainable food system at EU level (Bock et al. 2022). The Strategic Dialogue recommends developing a consistent methodology at EU level to evaluate the climate impact of agricultural products and systems as well as setting sectorial goals for specific agricultural activities including livestock that are aligned with the broader EU climate goals (European Commission (EC) 2024a, S. 58).

The FAO emphasises that crop production needs to become more efficient as well as more resilient to climate impacts in the broader context of achieving food security and healthy nutrition. To achieve this, it promotes a list of activities that include "technological" approaches such as improving crop breeding and genetics or enhancing precision agriculture as well as regenerative agricultural practices such as reduced tillage, planting of cover crops, the use of compost or biochar to preserve soil health and enhance soil carbon stocks (FAO 2023a).

Sources of funding include market revenues from the sale of agricultural products, funds from consumer levies (e.g. for local production), market instruments such as carbon trading, private law instruments, public direct funding from public of private authorities as well as redistributing avoided externality costs (Commission on the Future of Agriculture (ZKL) 2021, S. 83). The "true cost" of food and feed production must be better reflected in market prices (European Commission (EC)

2024a) and should inform investments, subsidies as well as tax rates (Bock et al. 2022). **Negative environmental externalities should be priced** by establishing emission rights (either as quotas or as an emissions trading scheme) for the agriculture sector (Bock et al. 2022). Specifically, **excise duties** on sugar, salt and fat could promote change on the consumption side. Fruits, vegetables and pulses could be promoted via a reduced VAT rate, for example (Commission on the Future of Agriculture (ZKL) 2021, S. 59), or higher VAT rates for unsustainable production systems could fund long-term conservation contracts to go beyond legal obligations (Bock et al. 2022). Tax reductions are also recommended by the Strategic Dialogue (2024a) to foster coherent price signals (p. 12). **Public payments** should be made available for providing public goods including rewetting of peatlands (Commission on the Future of Agriculture (ZKL) 2021) and enhancing technology developments towards low emissions and environmentally friendly agricultural practices (Mitter et al. 2020, p. 5; Benton und Harwatt 2022). Next to assistance schemes for more limited projects aimed to sustainably transform agricultural systems, **government guarantees** are proposed to support investments in high-risk projects with potentially high positive impacts (Bock et al. 2022, S. 56). An agricultural emissions trading scheme is mentioned as one potential carbon pricing mechanism by the Strategic Dialogue (European Commission (EC) 2024a, S. 60).

Several studies emphasise the **key role of the CAP** in supporting the transformation of agriculture within the EU by providing funding for the provision of public goods. To this end, direct payments should be gradually and completely transformed into payments that reward sustainable agricultural practices, eco-scheme payments should be increased (Commission on the Future of Agriculture (ZKL) 2021, p. 93). Various studies argue that commodity-linked coupled payments as well as CAP income support payments should be phased out in the long run though to refocus CAP payments on public goods provision only (Schutter et al. 2019; Mitter et al. 2020; Fischer et al. 2021). The EU's strategic dialogue on the other hand recommends to restructure income support and deliver it in a more targeted way through basing it on famers' economic viability (European Commission (EC) 2024a, S. 43).

Outcome-based approaches (Lóránt und Allan 2019) and **coupling CAP payments to the provision of public and environmental services** are highlighted in various studies as means to promote environmentally friendly and regenerative farming practices (Bock et al. 2022; Schutter et al. 2019; European Commission (EC) 2024a; André et al. 2024). Under the rural development pillar of the CAP, a premium is proposed for applying a set of agro-ecological practices (e.g. ambitious crop rotations or on-farm feed production. Further coupled payments are suggested for permanent grasslands/pastures, fruit and vegetable production as well as trees (agroforestry) (Schutter et al. 2019).

For financing the transition, the EU's Strategic Dialogue additionally recommends establishing an '**Agri-food Just Transition Fund**' outside the CAP to support investments by farmers, including capacity building. Additionally, public-private collaboration should be strengthened and a dedicated pan-EU financing platform that facilitates credit protection, risk-sharing loans and guarantees mechanisms should be established. Loan facilities should be expanded to make funding available, particularly for the financing of large-scale transition projects (European Commission (EC) 2024a, S. 45–46).

Market-based instruments are highlighted as key components of policies to support the agricultural transition. To reduce negative externalities from agricultural production, the ZKL emphasises the use of market instruments to reduce nitrogen surpluses where other measures have not been successful in the past (Commission on the Future of Agriculture (ZKL) 2021, p. 84). For avoided emissions of organic soils, trading of mitigation results could be an option; yet establishing a dedicated emissions trading scheme would be complicated and could not be implemented in the shorter term (Commission on the Future of Agriculture (ZKL) 2021, p. 71).

Further approaches suggested include **supporting the establishment of alternative market outlets** (e.g. short supply chains, direct sales to consumers) (Bock et al. 2022). Regional production, processing and consumption structures should be supported by labels of origin and direct marketing of products (Commission on the Future of Agriculture (ZKL) 2021). Also, adapting competition policies to strengthen farmer organisations and cooperatives in price negotiations as well as investing in **training and skills development** of farmers is recommended (Bock et al. 2022). Course contents in the education of agricultural stakeholders must include information on the required agricultural transformation (Commission on the Future of Agriculture (ZKL) 2021) To facilitate learning and exchange of expertise among farmers and stakeholders, **regional initiatives** can support research and technological innovation (European Commission (EC) 2023).

The WBGU (2021) suggests introducing a **'sustainable food supply' certificate** for retail trade which could be linked to compliance with basic principles of the Planetary Health Diet or to ensuring that for at least 50% of the food comprehensive information on environmental externalities is provided. According to the JRC (2022), **EU schemes and labels** could be developed that are based on harmonised minimum standards for sustainability. At the same time, more clarity about the scope and assessment process of labels is needed to enable a comparison and benchmarking of labels as well as operators and value chains. Also, more information is needed about the origin of products and their ingredients to make informed public procurement decisions.

The WBGU (2021) additionally proposes to set **quantified targets for reducing the consumption of resources** including a ceiling for the use of biomass. Analogous to sustainability standards for biofuels such standards should be set for other uses of biomass as well (p. 8).

The report on the EU's strategic dialogue suggests introducing a **benchmarking system** for agriculture across different sustainability objectives and ambitions such as biodiversity, GHG emissions, pollution reduction, animal welfare, water quality, working conditions. Such a system should contribute to developing appropriate labelling and certification standards (European Commission (EC) 2024a, S. 41). Additionally, a **European board on agri-food** should be established where developments and strategies related to the sustainable transition of the agri-food sector are discussed on a regular basis by various stakeholders (pp. 50ff.). An **Integrated Nutrient Management Plan** at EU level should help to use nutrients more efficiently and reduce negative environmental impacts from fertiliser application (European Commission (EC) 2024a, S. 61–62). To strengthen organic farming the EU Strategic Dialogue recommends sustainable public procurement, promoting the European organic logo, ensuring adequate funding for organic farms as well as organic research and promoting knowledge dissemination (European Commission (EC) 2024a, S. 63).

Other stakeholders take diverging views on appropriate strategies and instruments to change agricultural practices: FoodDrinkEurope also suggests establishing harmonised sustainability standards to assess on-farm sustainability impacts across diverse production systems and regions. Additionally, it supports voluntary carbon and biodiversity credit markets to creative incentives for farmers to implement sustainable practices (Whittow et al. 2023). The biggest organisation representing European farmers Copa Cogeca calls for reducing administrative burdens and avoiding more bureaucracy for farmers though. It supports the demand for a more transparent food trade chain while emphasising the goal to reach a higher percentage of retail prices to go to the producers' side (Copa Cogeca 2024a, 2024b).

4.5 Trade

4.5.1 Introduction

Currently, the EU is largely self-sufficient in terms of major agricultural products including staple crops, sugar and animal products. It is dependent on imports of high protein animal feed such as soy, fruit and nuts as well as coffee, tea, cocoa and spices. The main food exports are cereal preparations, dairy products, wine, cereals and mixed food preparations and ingredients (European Commission (EC) 2023).

Climate impacts of the agricultural sector go far beyond direct emissions from agricultural activities on a specific area of land. The EU’s agriculture has severe land use impacts outside of the EU’s borders, in particular because it imports up to 70% of protein feed for livestock from third countries (IEEP 2019). Particularly these imports of animal feed entail negative environmental and social effects regarding deforestation, biodiversity, and food sovereignty in other parts of the world (ZKL 2021).

4.5.2 Results from quantitative studies

The development of future trade flows depends on several factors, including market prices, demand, environmental legislation, and climate targets. Therefore, extensive information and assumptions about developments in other regions of the world and within Europe are necessary. Trade balances are reported in only three of the studies.[8] All studies use different product categories and units. Agora reports in million tonnes, Billen et al. (2024) in million tonnes of nitrogen, and Rieger et al. (2023) in million Euros. Therefore, absolute figures are not comparable, but trend changes relative to a base year indicate some directions.

Billen et al. (2024) examine the effects of changes in trade balances across six scenarios, each with different assumptions regarding dietary changes and production volumes in agro-ecological environments. In the BAU-20% fertilizer scenario, without dietary changes, net exports of vegetal and animal products decrease due to reduced production resulting from lower fertilizer application. However, in the BAU low diet scenario, while production remains at the BAU level, changing diets decrease net exports for vegetal products compared to the BAU scenario but significantly increase net exports for animal products (2/3 of total production). In the agro-ecology scenario, Europe achieves self-sufficiency. There are no longer any feed imports (as per external scenario assumptions), while net exports of both vegetal and animal-based products continue at a low level. This is made possible by the assumed dietary changes, even with reduced production of animal and plant products (see Table 22). Without changing diets but maintaining agro-ecological production practices (agro-ecology current diet), Europe would become a net importer of animal products (1/3 of consumption). However, there would still be net exports of vegetal products due to lower demand. Billen et al. (2024) conclude that **if human diets included more than 45% animal protein (excluding fish), an agro-ecological Europe would become a net importer of animal products.** The current consumption of animal proteins is about 57% (Agora Agriculture 2020). The Farm to Fork scenario is a mixture of the BAU and agro-ecological scenarios, whereby higher production and consumption of dairy products and meat is assumed compared to the agro-ecological scenario. The import of animal feed is still permitted, but to a lesser extent than in the BAU scenario. A net export of plant and animal products remains.

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[8] Also IDDRI 2019 provides some figures in the study, mentioning that 20% of milk and 12 Mt of cereals are exported.

Table 22: Development of Trade balances in Billen et al. 2024

Study	Scenario	Unit	Vegetable food	Livestock feed	Animal products
Billen et al. 2024	S0= Reference year	Mt. N	+2.2	-2.9	+0.75
	BAU	Mt. N	+2.4 9%	-2.9 +0%	+0.84 +12%
	BAU-20%fert.	Mt. N	+1.9 -14%	-2.9 +0%	+0.7 -7%
	BAU_low diet	Mt. N	+2.1 -5%	-2.9 +0%	+1.8 +140%
	Farm to Fork	Mt. N	+1.4 -36%	-2.1 -28%	+0.23 -69%
	Agro-ecology	Mt. N	+0.6 -72%	0 -100%	+0.45 -40%
	Agro-ecology_current diet	Mt. N	+1 -55%	0 -100%	-0.49 -35%

Note: + net export, - net imports, original data in Billen et al. (2024) states – for exports and + for imports. In this table this has been changed to make it comparable throughout the studies.
The colour code indicates the level of the GHG reduction ambition, green=/>40%, yellow= 20% up to 40%, grey = 0% up to 20%.
The table contains also information on scenarios not included in the overview in chapter 3. However, they are included here for information purpose.
Source: Authors' own compilation (Oeko-Institut)

The Agora scenario indicates significant changes in trade balances for dairy products, vegetables, and fruits between 2020 and 2045, while the trade balances for other products remain constant. Net exports of dairy products double in the scenario until 2045 compared to 2020. This is caused by reduced consumption of dairy by -43% (see Table 6) and an increase in milk yields by 7% compared to 2020. The Agora scenario shows that despite a significant increase in the production of fruits (+53%) and vegetables (+31%, see Table 15), imports continue to rise. This is due to a roughly 150% increase in demand. Domestic production of fruits and vegetables is challenging due to international competition, high labour costs, and other environmental constraints.

Table 23: Development of trade balances in the Agora Agriculture scenario

Study	Scenario	Unit	Dairy	Meat	Cereals	Fruits and Vegetables
Agora Agriculture	Base year 2020	Mt	+18	+6	+17	Fruits:-10 Veg.:+2
Agora Agriculture*	Target 2045	Mt	+36 +100%	+6 0%	+18 +6%	Fruits:-16 +60% Veg.:-4

Note: + net export, - net imports
Source: Agora Agriculture 2024

In addition to trade balances for agricultural goods, the Agora Agriculture scenario also illustrates the development of virtual land. According to the scenario, the EU will shift from being a net importer of land (+1 million hectares) to a net exporter of land (-21 million hectares) by 2045. This change is primarily driven by increased exports of dairy products and reduced imports of feed. The arable land used for growing EU feed outside the EU is projected to decrease from 12 million hectares in 2020 to 5 million hectares in 2045. This reduction is due to a decrease in livestock numbers and a shift towards more residue and grass-based feeding.

The Boysen-Urban et al. (2022) also presents results from virtual land trade in the baseline and four different scenarios. However, the study concludes that Europe remains a net importer of agricultural land, with only minor changes across the different scenarios compared to the baseline. The study distinguishes between virtual land imports for primary agricultural commodities and food commodities. Virtual land imports for primary agricultural commodities are much smaller than those for food commodities. The most significant changes are observed in scenarios with dietary changes, which show an increase in net imports of virtual land for primary agricultural commodities compared to the baseline. This is due to an increased demand for cereals and horticultural products in the plant-based diet. However, the situation is reversed for virtual land imports of food commodities. In the diet scenario (see Table 24), virtual land imports significantly decrease, while in all other scenarios, land imports for food commodities increase.

Table 24: Virtual land trade in Boysen-Urban et al. (Boysen-Urban et al. 2022) in million ha

	Baseline	FWL	&cost5	&oil	&diet
Agriculture	-2.4	-2.2 (-8%)	-2.3 (-4%)	-2.3 (-4%)	-3.8 (+58%)
Food	-17.4	-18.8 (+8%)	-19.8 (+14%)	-18.7 (+7%)	-8.0 (-54%)

Source: Boysen-Urban et al. (Boysen-Urban et al. 2022), Figure 56

Rieger et al. (2023) show the trade effects for three scenarios with different dietary change levels compared to a reference level[9]. In general, production changes are smaller than demand changes due to international trade effects. Producers of these products in non-EU countries are also impacted by dietary shifts in Europe.

Table 25 highlights high trade volumes for dairy, as well as vegetables and fruits, in the 2030 baseline. While both imports and exports are substantial for vegetables and fruits, dairy stands out as a significant export good, with high export margins and minimal imports. Changes for vegetables and fruits occur in both 2030 and 2050 across all scenarios. Import volumes increase between 46% (Lancet_low 2030) and 1,078% (Lancet_full 2050), while exports of these products decline in all scenarios. In absolute terms, this would result in an increase in import volumes of € 348.7 billion for vegetables and fruits and exports of € 5.6 billion compared to the 2050 reference scenario. All other goods show changes in import or export margins below € 3 billion in 2050. In all EAT-Lancet scenarios, the export flows of animal-based products increase, with varying short- and long-term effects. By 2030, the EU-27 sees a smaller production decline, resulting in higher exports compared to the long-term scenarios. Beef exports show the largest increases, followed by pork and dairy products.

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[9] Figures for the reference level in 2050 are not available.

Table 25: Trade volumes in Rieger et al. (2023) in million Euro in comparison to baseline

	Total Base 2030		**Lancet low 2030**		**Lancet high 2030**		**Lancet low 2050**		**Lancet high 2050**		**Lancet full 2050**	
	Imp. bn.€	Exp bn. €	Imp.	Exp.	Imp.	Exp.	Imp.	Exp.	Imp.	Exp.	Imp.	Exp.
Beef	3.4	4.8	-23%	+13%	-54%	+55%	-16%	+1%	-50%	+4%	-71%	+9%
Pork	2.9	10.9	-12%	+6%	-33%	+17%	-16%	0%	-50%	3%	-70%	+6%
Dairy	2.4	24.0	-18%	+2%	-39%	+7%	-11%	+1%	-35%	+4%	+54%	+8%
Fruits&Veg	26.9	18.7	+46%	-8%	+167%	-18%	+127%	-15%	+530%	-30%	+1078	-37%
Sugar	0.9	1.3	-14%	+7%	-33%	+21%	-11%	+1%	-33%	+5%	-46%	+8%

Note: Baseline values are only available for 2030 and have been provided by the author, baseline values for 2050 are not available
Source: Rieger et al. 2023, Table 3

4.5.3 Framework conditions and policy instruments

The available studies feature discussions on agricultural trade, primarily focusing on the effects of trade agreements and carbon border adjustment mechanisms. These key points are briefly summarized below.

To counteract negative effects, the ZKL (2021) recommends establishing a level playing field in international competition through multilateral agreements in order to safeguard the competitiveness of agricultural products from the EU. The Strategic Dialogue calls for impact assessments prior to trade negotiations including impacts on agricultural producers, the environment, health, labour animal welfare as well as measures to counter potential negative effects (European Commission (EC) 2024a, S. 49). At the same time, international labelling on sustainability standards would need to be developed to ensure that the same standards apply worldwide and enhance transparency on environmental impacts. Border protection measures such as border tax adjustments or specific taxes or restrictions for low-sustainability products should be applied to prevent leakage of production to regions with lower social and environmental standards (ZKL 2021, p. 91). However, the Strategic Dialogue also calls for ending unethical double standards, for example by stopping to export pesticides that are banned within the EU to countries with less stringent regulations (European Commission (EC) 2024a, S. 49).

According to the World Bank, hastily removing trade barriers could lead to increasing GHG emissions though as lower food prices would entail an increased demand for food. Furthermore, removing trade barriers can foster deforestation in countries where grain and feed production are comparatively cheap (Sutton et al. 2024, S. 177).

Analysing the economic impact of ten upcoming EU free trade agreements, the JRC (2024) finds that these agreements have the potential to increase exports and imports with the respective countries. Among others, exports of dairy products and pig meat as well as beef, poultry and sheep meat imports are likely to increase because of the agreements. To address negative environmental consequences of these free trade agreements, international labelling on sustainability standards would need to be developed at the same time to ensure that the same standards apply worldwide and enhance transparency on environmental impacts. Currently, inconsistencies in standards, regulations and certification in food-safety systems are widespread though (FAO 2023b). The Bock et al. (2022) suggests to include sustainability chapters in new bilateral trade agreements with like-minded countries to enforce sustainability standards (p. 44).

Border protection measures such as border tax adjustments or specific taxes or restrictions for low-sustainability products should be applied to prevent leakage of production to regions with lower social and environmental standards (ZKL 2021, p. 91). The IPES-Food (2019) suggests to reinvest revenues that are raised this way in supporting the sustainability transition in developing countries. The World Bank (2024) warns of unintended consequences of introducing the Carbon Border Adjustment Mechanism (CBAM) for agricultural products as well as regulations to ensure deforestation free supply chains (EUDR). It recommends that technical assistance and capacity building should be provided to lower income countries to strengthen their MRV systems as well as enable smallholders to comply with new EU regulations (Sutton et al. 2024, S. 177).

In ambitious scenarios for the transformation of agriculture, international trade decreases though because short and transparency agricultural supply chains are preferred and external costs including for transportation are reflected by the prices of agricultural products (Mitter et al. 2020, p. 6). The summary of the EU’s strategic dialogue states clear messages on market transformation needs. Markets should drive sustainability and value creation across the chain and better internalize externalities (European Commission (EC) 2024a).

4.6 Other economic effects

4.6.1 Producer and consumer prices

According to the vision formulated in the EU’s report on its strategic dialogue, food remains affordable for all consumers while sustainable food becomes the default choice. This is facilitated by comprehensive food labelling, education programmes, adequate price signals, responsible marketing as well as sustainable public food procurement (European Commission (EC) 2024a, S. 24).

In the quantitative scenarios, information on changes in producer and consumer prices under varying dietary conditions can be found in Rieger et al. (2023) and Boysen-Urban et al. (Boysen-Urban et al. 2022). In the Rieger et al. (2023) study, dietary changes are modelled as preference shocks in the CAPRI and MAGNET models. Consequently, it is assumed that changing dietary preferences lead to increased demand and higher prices for vegetables and fruits, while prices for animal products decline due to lower demand. Table 26 shows the changes in producer and consumer prices compared to the reference scenario. In the EU-27, red meat, milk, and sugar prices experience the most significant declines due to substantial simulated demand reductions by European consumers. Especially in the short run (2030), there is a significant decline in producer prices for animal products (Lancet high: -18.4% for beef and -21.7% for dairy). In the long run, producer prices for beef and dairy are only 3.8% and 1.6% lower than the reference scenario, respectively. Conversely, producer prices for fruits and vegetables are projected to rise by between 11.5% and 35.1% by 2030. Over the long term, significant demand shifts for these products, ranging from 105% to 522%, are expected to increase producer prices by 25% to 129% by 2050. Eggs and poultry prices are less impacted as their consumption levels align more closely with the EAT-Lancet recommendations. In 2030, consumer prices will not change as significantly as production prices.

However, by 2050, the changes in consumer and production prices for animal products will be at the same level. These changes in consumer prices and demand result in higher total food expenditures, increasing by 2.8% to 9.4% in 2030 and 2.6% to 12.5% in the long run. By 2050, full implementation of the EAT-Lancet dietary recommendations could **raise food expenditures by 29%**, primarily driven by higher prices for vegetables and fruits.

Table 26: Changes in producer and consumer prices compared to reference scenario in Rieger et al. 2023

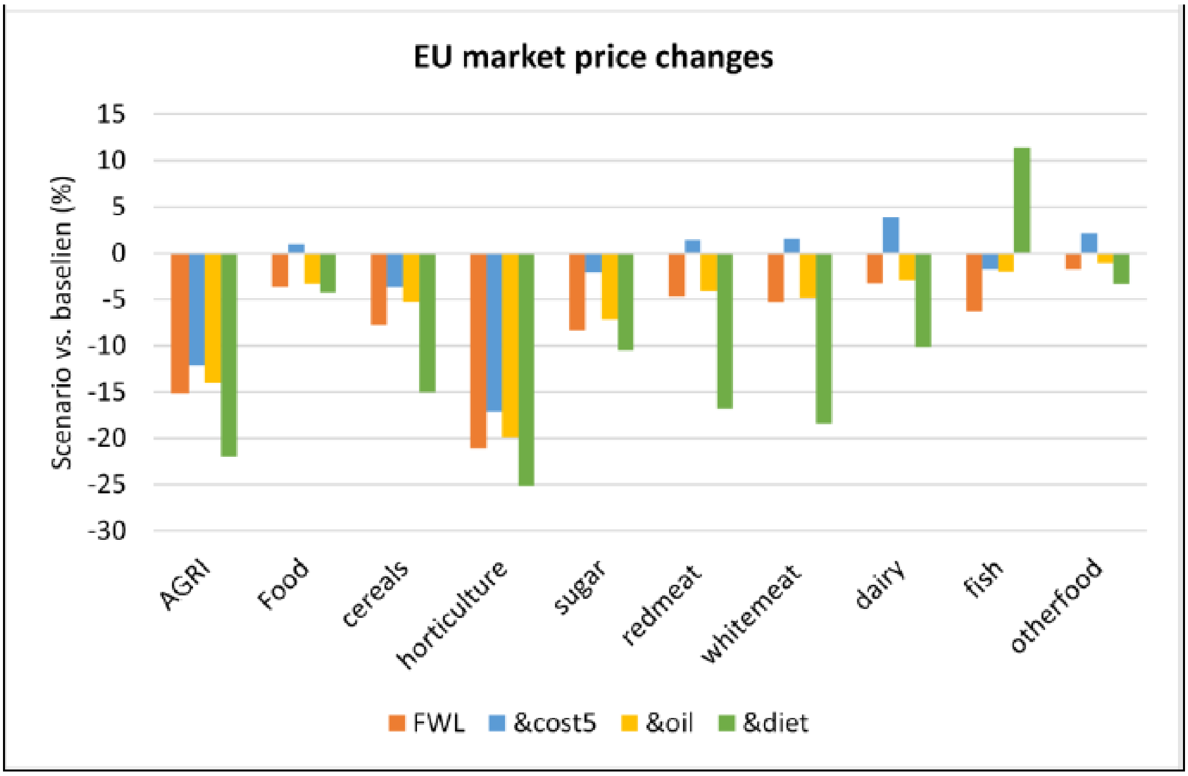
	Lancet low 2030		**Lancet high 2030**		**Lancet low 2050**		**Lancet high 2050**		**Lancet full 2050**	
	Prod.	Cons.	Prod.	Cons.	Prod.	Cons.	Prod.	Cons.	Prod.	Cons.
Beef	-6.6%	-3.7%	-18.4%	-10.4%	-0.4%	-0.3%	n/a	-1.7%	-3.8%	-3.7%
Pork	-5.1%	-1.5%	-15.4%	-4.4%	-0.05%	0.0%	n/a	-0.5%	-1.2%	-1.3%
Dairy	-7.1%	-4.7%	-21.7%	-14.1%	-0.1%	-0.1%	n/a	-0.8%	-1.6%	-1.6%
Fruits&Veg	+11.5%	+7.3%	+35.1%	+19%	+25%%	+16.3%	n/a	+45.8	+129%%	+73.3%

Note: The price changes between CAPRI in 2030 and MAGNET in 2050 are mainly due to differences in supply-side flexibility and modelling assumptions. MAGNET's flexible factor markets result in lower prices and higher output effects compared to CAPRI, aligning with a longer-term perspective.
Source: Rieger et al. 2023, Figure 3 p. 771, 772, Annex 1 Table 5.

Boysen-Urban et al. (Boysen-Urban et al. 2022) examine the development of EU market price changes across four different scenarios compared to a baseline scenario. All scenarios account for the impact of reducing food losses during production and food waste during consumption. The scenario results reveal that reducing food losses during production increases the quantities of agricultural and food commodities. This leads to a decrease in market prices and an increased demand for agricultural products due to lower costs. Reducing food waste at the consumer level decreases the demand for agricultural products, counteracting the increased demand from lower costs due to reduced food losses. However, balancing supply and demand can lead to increased food consumption as food becomes cheaper.

Unlike Rieger et al. (2023), Boysen-Urban et al. (Boysen-Urban et al. 2022) assume that market prices for horticultural products decline by about 20% compared to the baseline scenario in all scenarios, with the most significant drop occurring in the &diet scenario. This is primarily because of reducing food loss and food waste. Meanwhile, consumption and production of horticultural products increase by more than 20%. Market prices for animal products decline in three out of four scenarios, with decreases of less than 5% in the FWL and &oil scenarios and declines of more than 15% for red and white meat in the &diet scenario compared to the baseline. Market prices for dairy decrease by 10% compared to the baseline.

Figure 6: Changes in EU market prices in scenarios in Boysen-Urban et al. (Boysen-Urban et al. 2022)



Source: Boysen-Urban et al. 2022.

Boysen-Urban et al. (Boysen-Urban et al. 2022) also analyse the impact of the food basket under different scenarios. Generally, the budget share allocated to food decreases due to global reductions in market prices. However, in the &diets scenario, the budget share for food increases in both high-income and emerging regions when more sustainable and healthier diets are adopted. In the EU, this share **rises by 20%** compared to the baseline scenario. This is similar to the findings of Rieger et al. (2023), which show a 29% increase compared to the baseline, despite differing assumptions about market price developments.

4.6.2 Agricultural income

The report on the Strategic Dialogue on the future of EU agriculture sets out the vision that by 2035/2040, farmers receive a decent income from their production and all actors of the agri-food chain benefit from fair prices (European Commission (EC) 2024a, S. 21).

Information on the development of agricultural income is provided only by Rieger et al. (2023). This study concludes that shifts to healthier diets in the EU-27 generally increase sectoral farm income due to higher prices and production of vegetables and fruits, despite declines in animal products, feed, and sugar. Germany, which is specialised in animal-based products, faces short-term income losses that dissipate by 2050 as production factors adjust. Globally, agricultural income rises due to increased fruit and vegetable production in non-EU countries to meet EU demand (see Table 27).

Regions with high animal production see income decreases due to reduced EU demand and lower producer prices, while regions focused on vegetables and fruits experience income gains. For example, Ireland and Denmark face significant income losses in beef, dairy, and pork sectors, while Italy and Spain benefit from higher vegetable and fruit prices. However, Spain's Andalusia region suffers due to reduced olive oil demand according to dietary changes.

Income effects vary by region and farm type, with specialised animal product regions facing severe losses, especially in the short run until 2030. In Germany, farm incomes decrease on average, with permanent crop farms benefiting and pig, poultry, and dairy farms experiencing large negative changes. Significant declines in agricultural income in 2030 are due to falling producer prices for animal products, while production volumes are not declining as quickly. Reduced profitability leads to lower rental prices (especially for grassland), transferring some income losses to landowners, but significant structural changes are needed to adapt. In Italy, income losses from animal production can be offset in regions that focus on vegetable and fruit production. However, this is not the case in Germany, which leads the EU-27 in pork and dairy production. Here, income losses range from -4.9% to -12.4%.

In the long run, countries can adapt to changing dietary preferences as production factors adjust. By 2050, farm income in Germany is projected to increase by 2.8% (Lancet_low) to 22.7% (Lancet_full). Likewise, farm income across Europe and globally is expected to rise compared to baseline levels in scenarios with dietary changes. This growth is mainly driven by the rising demand for vegetables and fruits, along with a significant increase in their producer prices.

Table 27: Effects on changes in farm income in different countries in Lancet Low and Lancet high scenario compared to the baseline

Country	Lancet_low	Lancet_high	Lancet_low	Lancet_high	Lancet_full
Germany	-4.9%	-12.4%	+2.8%	+10.6%	+22.7%
EU-27	+0.3%	+5.4%	+9.7%	+36.2%	+71%
World	+0.2%	+1%	+1.8%	+7.1%	+14.3%
Denmark	-17.2%	-43%	n/a	n/a	n/a
Ireland	-24.8%	-66.8%	n/a	n/a	n/a
Italy	+3.2%	+12.3%	n/a	n/a	n/a
Spain	+3.4%	+15.7%	n/a	n/a	n/a

Source: Rieger et al. 2023.

4.6.3 Labour

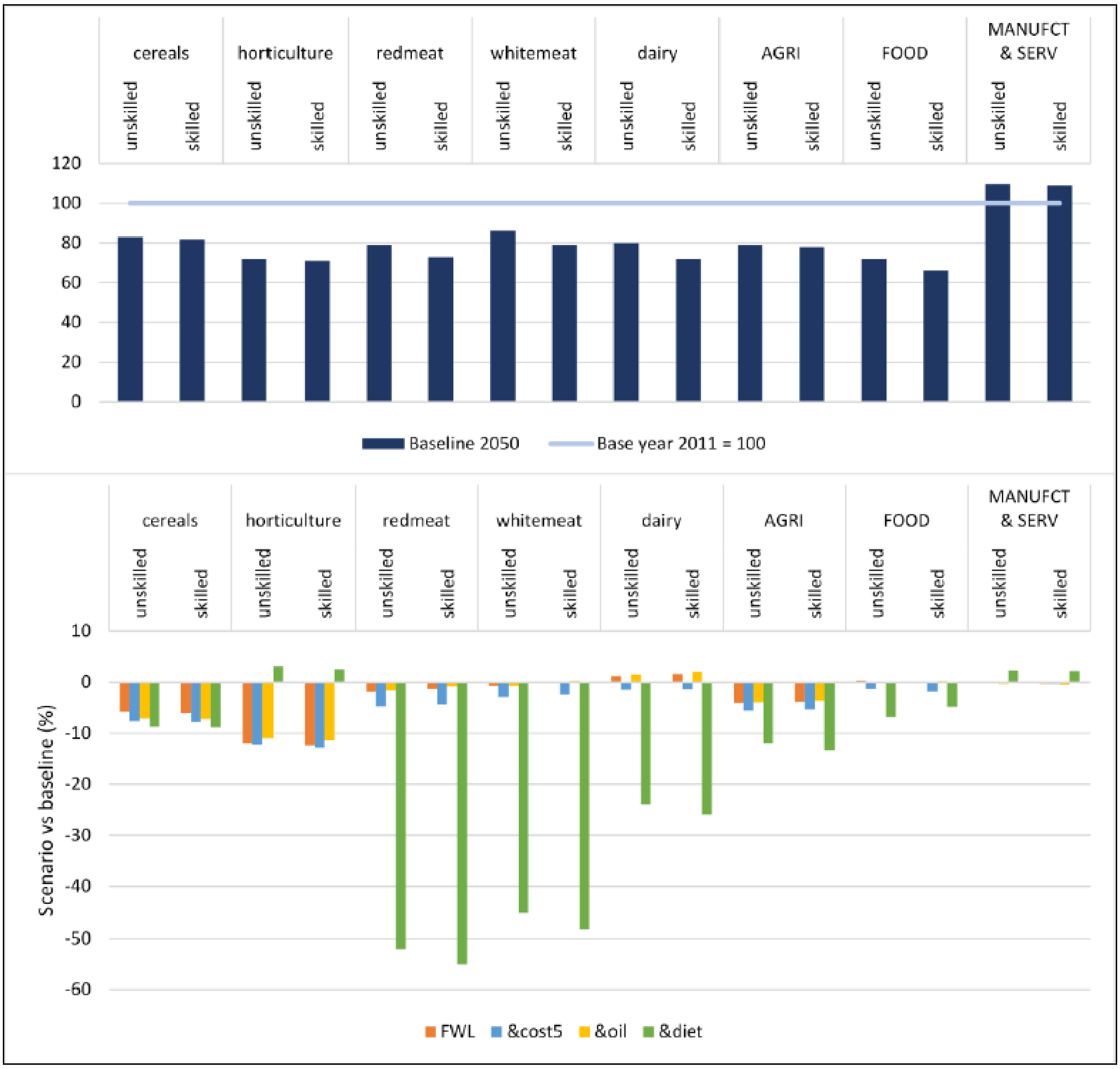
Significantly reducing livestock production would entail layoffs and unemployment in the livestock farming and meat processing sectors. At the same time, it is not clear how many new jobs could be created in industries producing lab-grown meat (Howard 2022).

The EC’s impact assessment provides information on development of labour demand for the LIFE scenario (European Commission (EC) 2024b). The CAPRI model shows that the LIFE framework has minimal labour impacts on agriculture, with a 0.6% decrease in total labour for crops. This is mainly due to reduced labour for cereals (-7%) and a slight decrease for vegetables and permanent crops (-0.4%). Labour hours for cattle and other animals also decline significantly (cattle activities -25% and other animals -24%), contributing to an overall 10.4% reduction in agricultural labour (European Commission (EC) 2024b, p. 213).

Information on the development of labour is also provided by Boysen-Urban et al. (Boysen-Urban et al. 2022). The baseline scenario already indicates a reduction in employment compared to the

2011 base year, and this trend continues in the scenarios. Across all scenarios, a decline in both skilled and unskilled workers is evident in the agricultural sector. The most significant decrease is observed in the &diets scenario, where employment of both unskilled and skilled workers drops by more than 10% overall. In contrast, the food sector experiences a smaller reduction, with unskilled worker employment decreasing by 6.9% and skilled worker employment by 4.9%. Labour demand in dairy and meat production shows drastic decreases. In meat production, declines range from 40% to 55%, while in dairy production, labour demand decreases by around 25% compared to the baseline. In horticulture production, the &diet scenario shows a slight increase in labour demand. However, all other scenarios indicate a decrease in labour demand, with a slightly higher reduction occurring in the &cost5 scenario.

Figure 7: Development of EU employment from 2011 to 2050 based on Boysen-Urban et al. (Boysen-Urban et al. 2022)



Source: Boysen-Urban et al. 2022

4.7 Other relevant drivers

4.7.1 Bioeconomy and circular economy

The bioeconomy is crucial for the agricultural sector as it promotes sustainable practices and enhances resource efficiency. By integrating bioeconomy principles, agriculture can reduce its environmental footprint by renewable biological resources and the recycling of waste products. For example, converting agricultural residues into bioenergy or bioplastics not only reduces waste but also provides alternative income streams for farmers. Additionally, the production of bio-based chemicals and materials can open new markets and economic opportunities, fostering rural development. The bioeconomy also encourages innovation in crop and livestock management, leading to more resilient and productive agricultural systems. Overall, embracing the bioeconomy can help the agricultural sector transition to a more sustainable and economically viable future.

In the context of **moving towards a circular economy**, the European Commission stresses that non-preventable waste can be used as feedstock and to produce bio-based products in other sectors of the economy (Publications Office of the European Union 2020). The report on the EU's strategic dialogue emphasises circular economy principles which are to become the norm throughout EU food systems. The sustainably sourced bioeconomy needs to be strengthened and biomass residues are used as material inputs in other sectors in its vision for the future (European Commission (EC) 2024a, S. 23). Scenarios which achieve economy-wide net-zero emissions by mid-century also strongly rely on the increased provision of biomass from the agricultural sector to replace carbon-intensive materials and products from other sectors (as well as its potential to remove and sequester carbon from the atmosphere) (Lóránt und Allan 2019). A strong reliance on technological innovation will additionally increase global demands for European bio-based industrial raw materials and innovative products (Mitter et al. 2020). The FAO argues for using use crop residues for feeding animals, reintegrating it to soils or using it to produce bioenergy. At the same time, stringent sustainability criteria and standards for bioenergy production are needed to set the right incentives (FAO 2023a).

None of the quantitative studies puts a big emphasis on bioeconomy. Only the Agora Agriculture scenario emphasises the importance of integrating bioeconomy principles into agricultural practices to achieve sustainability goals. The Agora Agriculture scenario emphasises the need for more efficient use of natural resources, such as water and soil, to reduce environmental impacts and improve sustainability. It promotes the adoption of circular economy practices, whereby waste and by-products are reused and recycled within the agricultural system, enhancing resource efficiency. The scenario underscores the role of innovation and technological advancements in driving the bioeconomy, including the development of new bioproducts, bioenergy, and biotechnologies that can reduce greenhouse gas emissions and improve productivity. Effective policy frameworks and incentives are crucial for supporting the transition to a bioeconomy, including financial support for research and development and policies that encourage sustainable practices and the adoption of bio-based products. Additionally, developing markets for bio-based products can provide new economic opportunities for farmers and rural communities while contributing to environmental sustainability. Overall, the Agora Agriculture scenario suggests that a strong focus on bioeconomy can lead to more sustainable and resilient agricultural systems, benefiting both the environment and the economy (André et al. 2024).

4.7.2 Adaptation

Adaptation to climate change is key to ensuring sustainable food production while minimising negative environmental impacts as much as possible. For Europe, it is key to considering regional differences in impacts: while northern Europe may see an increase in food production in the future, southern Europe will likely face greater water stress and biodiversity vulnerability. Adaptation measures therefore need to be tailored to local circumstances and challenges (Kebede et al. 2021).

The Strategic Dialogue emphasises the need to scale up adaptation to make farming resilient, use resources efficiently, be less dependent on agricultural inputs, protect soils, restore nature and diversity crops and animal breeds (European Commission (EC) 2024a, pp. 72ff.). As key adaptation strategies, water-resilient agriculture, innovative plant breeding approaches, biodiversity conservation and robust risk and crisis management are mentioned (Kebede et al. 2021; European Commission (EC) 2024a). Agora Agriculture (2024) additionally highlight adapting grazing strategies and livestock diets to include more forage and less concentrate feed as adaptation strategies for livestock management. They mention that by 2045, livestock farming will be significantly affected by extreme weather conditions such as heatwaves, heavy rainfall, and other severe weather events. These conditions will impact outdoor animal husbandry, influencing livestock diseases due to variations in temperature and precipitation patterns. Increased temperatures will critically affect livestock production, impacting reproduction, health, feed efficiency, and water availability. Additionally, rising temperatures, elevated carbon dioxide levels, and irregular precipitation will affect both the quantity and quality of forage. At the same time, they emphasise the need to reduce competition of feed crops with human food crops by reducing livestock numbers, changing dietary habits, and changing the feed composition of livestock (p. 82).

Scenarios focusing on ecological practices offer greater resilience to climate change and extreme weather events compared to scenarios relying only on technological solutions (André et al. 2024).

In addition to the previously mentioned measures such as water-resilient agriculture and breeding approaches, various agricultural practices play a role in climate adaptation and are incorporated into quantitative scenario studies. While most studies do not explicitly identify these practices as adaptation measures, they are often included in the context of agro-ecology or climate mitigation strategies.

- Conserving and building up soil organic carbon in cropland
    - Crop rotation: Improving crop rotations can improve the water management by increasing the daily water discharge and groundwater seepage in case of heavy rain and reduce evapotranspiration of water under dry conditions (Sietz et al. 2021). Diversifying crop rotations also improves resilience to inter-annual weather variability as they lower the risk of crop failure (Macholdt et al. 2020). Particularly, integrating forage or grain legumes in crop rotations maintain soil moisture so that water availability under hot and dry conditions is improved (Gaudin et al. 2015). Additionally, more complex crop rotations support soil health and fertility, enhance biodiversity as well as weed and pest control (Tiemann et al. 2015; Rusch et al. 2013).
    - Cover crops can reduce vulnerability to erosion from extreme rain events if these events do not overlap with the cover crop growth period. Under such conditions, cover crops can also reduce nitrogen leaching. Cover crops that increase infiltration and rooting depth can also support protection against droughts (Kaye und Quemada 2017).
    - Organic farming: Organic farming can enhance soil organic carbon stocks, reduces the need for synthetic fertilisers and enhances biodiversity and resilience (Gattinger et al. 2012; Müller et al. 2016). This is because organic farming implies more complex crop rotations, higher crop diversity and closed nutrient cycles. This leads to improved ecological and economic stability by reducing pest outbreaks and plant and animal diseases, reducing the need for external inputs and improving the utilisation of nutrients and water (Smith et al. 2011). Additionally, enhancing soil

organic carbon stocks and improving soil health and biodiversity leads to improved water capture and retention capacity and reduced soil erosion, thus providing greater resilience in the face of extreme weather events and changing weather conditions (IFOAM Organics Europe 2022).

- Soil organic carbon in grassland: Key factors influencing grassland's contribution to climate protection include the intensity of its use and species richness, which are interrelated. The intensity of grassland use significantly impacts carbon storage and greenhouse gas emissions, while species and functional diversity stabilise plant communities and enhance belowground carbon input. Increased plant species diversity leads to greater root input, boosting soil carbon storage (Yang et al.). The diversity of root input is crucial for carbon storage in grassland soils (Temperton 2023), with the optimised humification coefficient for root carbon being up to 2.3 times higher than for aboveground plant residues. Overgrazing enhances the degradation of grasslands. The specific impacts of grazing intensity on soil processes depends on local environmental characteristics though (Staddon und Faghihinia 2021). Across all climatic zones and grazing intensities, research showed that grazing below the carrying capacity of the system generally results in a decrease in SOC storage. For different regional climates, the results vary, however: under moist warm climatic conditions, any grazing intensity increases SOC stocks, while grazing decreases SOC stocks under moist cool climatic conditions. Under dry warm and dry cool climates, low and medium grazing intensities lead to increased SOC stocks (Abdalla et al. 2018).
- Trees on agricultural land/Agroforestry: Agroforestry enhances protection against erosion and flooding, biodiversity, provides improved habitat for wildlife and insects and improves soil fertility on silvopastoral as well as silvoarable fields (Torralba et al. 2016; Kay et al. 2019; Drexler et al. 2021). Woody structures can increase the resilience to the impacts of climate change such as heat stress and drought. They provide shade to soil as well as animals, reduce wind speeds and protect soil from erosion (Brandle et al. 2004). Through its cooling effect on the micro climate, agroforestry can reduce negative impacts from droughts and maintain or enhance yields under drought conditions (Seddon et al. 2020). The adaptation potential depends on the specific way in which trees are integrated and on natural site conditions though. Too high tree density may lead to strong competition for water for example (Ivezić et al. 2021) and too much shade can reduce crop yields, particularly in central and norther Europe (van der Werf et al. 2007).
- Peatland restoration: Peatland rewetting has direct local cooling effects and plays an important role in water regulation (Joosten 2021). Rewetting helps restore their natural ability to retain and slowly release water, which reduces flood risks, maintains stable water levels, and improves water quality by filtering pollutants (Greifswald Mire Centre und Wetland International 2023; Pschenyckyj et al. 2021). While restoring peatlands reduces GHG emissions and allows for net carbon sequestration, biodiversity, research indicates that hydrological regime and peat soil structure are difficult to fully restore though, even after a decade of restoration efforts. This may weaken the resilience of peatlands to future disturbances (Loisel und Gallego-Sala 2022).
- Afforestation may contribute to enhancing biodiversity, avoiding soil degradation and protecting other natural resources such as water. Additionally, larger forest areas can reduce landscape fragmentation and thus facilitate species migration under climate change conditions. The sustainable management of afforested land can further provide ecosystem services and reduce vulnerability to climate impacts (Climate Adapt 2024).

Table 28 shows the adaptation measures considered in the different scenarios.

Table 28: Adaptation strategies considered in different studies

Study/ Scenario	Soil carbon cropland	Soil carbon grass-land	Agroforestry/ trees on agricultural land	Peatland restoration	Afforesta-tion	Biodiversity conserva-tion
Agora agriculture 2024	Diversifies crop rotation	Reduced intensity of grassland use	8% of agricultural area lignocellulosic crops	Rewetting of 80% of agricultural used peatlands	5 million ha afforestation	20% of semi-natural area
Billen et al, 2024 Farm to Fork	25% organic farming in total area	Reduced grassland production	n/a	n/a	n/a	10% of area for ecological infrastructure
Billen et al. 2024 Agro-ecology	100% organic farming in total area	Reduced grassland production	n/a	n/a	n/a	-
EC 2024b S2/S3	Not considered	n/a	10.6 million ha lignocellulosic crops	Rewetting of 1.4 million ha	4.9 million ha afforestation	-
EC 2024b LIFE	25% Organic farming in total area	n/a	10.2 million ha lignocellulosic c(Agora Agriculture 2024)	Rewetting of 1.7 million ha	8.9 million ha afforestation	6.9 million ha high diversity landscape features
IDDRI 2019	100% organic farming in total area increased divers-ification of crops	Increase in extensive grazing area	n/a	n/a	n/a	10% of arable land with agri-environmental indicators
Röös et al. 2022 Sustainability	2012 level	Reduced grazing intensity	Considered under vegetation regrowth	Not considered	Considered under vegetation regrowth	Vegetation regrowth on 48% of agricultural area
Röös et al. 2022 Local systems	50% organic farming in total area	Reduced grazing intensity	Considered under vegetation regrowth	Not considered	Considered under vegetation regrowth	Vegetation regrowth on 23% of agricultural area

Source: Authors' own compilation (Oeko-Institut) based on different studies

Water use and water scarcity are addressed in the studies by Röös et al. (2022) and Boysen-Urban (2022). Both studies indicate that water use increases in scenarios with dietary changes due to the rise in water-intensive and irrigation-based horticulture production, while the area of non-irrigated crop production (such as cereals) decreases. However, the Röös et al. (2022) study shows that water use is lower in the sustainability scenario (+29% compared to 2012) and the local system scenario (+17% compared to 2012) compared to the baseline scenario (+40% compared to 2012). Water scarcity, influenced by the location of production, is higher in the sustainability scenario (+51% compared to 2012) than in the baseline scenario (+45%). Conversely, it is lower in the local system scenario (+38% compared to 2012) due to production being concentrated in regions with more abundant water resources.

Overall, Table 28 indicates that adaptation measures are primarily incorporated within the agro-ecology and mixed scenarios, which emphasise more extensive production methods and often include assumptions about dietary changes. In most cases, these measures are not explicitly identified as adaptation measures within the scenarios.

5. REFERENCES

Abdalla, M.; Hastings, A.; Chadwick, D. R.; Jones, D. L.; Evans, C. D.; Jones, M. B. et al. (2018): Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. In: *Agriculture, Ecosystems & Environment* 253, S. 62–81. DOI: 10.1016/j.agee.2017.10.023.

Agora Agriculture (2024): Annex: Agriculture, ofrestry and food in a climate neutral EU. The land use sector as part of sustainable food systems and bioeconomy. Hg. v. Agora Agriculture. Online verfügbar unter https://www.agora-agriculture.org/fileadmin/Projects/2024/2024-09_EU_Agriculture_forestry_and_food_in_a_climate_neutral_EU/land-use-study-annex.pdf, zuletzt geprüft am 10.01.2025.

Alexander, Peter; Reddy, Anjali; Brown, Calum; Henry, Roslyn C.; Rounsevell, Mark D.A. (2019): Transforming agricultural land use through marginal gains in the food system. In: *Global Environmental Change* 57, S. 101932. DOI: 10.1016/j.gloenvcha.2019.101932.

Almeida, Amelia K.; Hegarty, Roger S.; Cowie, Annette (2021): Meta-analysis quantifying the potential of dietary additives and rumen modifiers for methane mitigation in ruminant production systems. In: *Animal Nutrition* 7 (4), S. 1219–1230. DOI: 10.1016/j.aninu.2021.09.005.

André, E.; Bandy, J.; Brizay, A.; Chemnitz, C.; Dräger, T.; Grethe, H. et al. (2024): Agriculture, forestry and food in a climate neutral EU. Agora Agriculture. Online verfügbar unter https://www.agora-agriculture.org/publications/agriculture-forestry-and-food-in-a-climate-neutral-eu, zuletzt geprüft am 17.12.2024.

Bampidis, V.; Azimonti, G.; Lourdes Bastos, M. de; Christensen, H.; Dusemund, B.; Durjava, M. F. et al. (2021): Safety and efficacy of a feed additive consisting of 3-nitrooxypropanol (Bovaer® 10) for ruminants for milk production and reproduction (DSM Nutritional Products Ltd). In: *EFSA Journal* 19 (11), e06905. DOI: 10.2903/j.efsa.2021.6905.

Barbieri, Pietro; Pellerin, Sylvain; Seufert, Verena; Nesme, Thomas (2019): Changes in crop rotations would impact food production in an organically farmed world. In: *Nat Sustain* 2 (5), S. 378–385. DOI: 10.1038/s41893-019-0259-5.

Benton, Tim; Harwatt, Helen (2022): Sustainable agriculture and food systems: Comparing contrasting and contested versions. Hg. v. Chatham House. Online verfügbar unter https://www.chathamhouse.org/sites/default/files/2022-05/2022-05-24-sustainable-agriculture-benton-harwatt_4.pdf, zuletzt geprüft am 26.09.2024.

Billen, Gilles; Aguilera, Eduardo; Einarsson, Rasmus; Garnier, Josette; Gingrich, Simone; Grizzetti, Bruna et al. (2024): Beyond the Farm to Fork Strategy: Methodology for designing a European agro-ecological future. In: *Science of The Total Environment* 908, S. 168160. DOI: 10.1016/j.scitotenv.2023.168160.

BMEL (2020): Politik für eine nachhaltigere Ernährung: Eine integrierte Ernährungspolitik entwickeln und faire Ernährungsumgebungen gestalten - WBAE-Gutachten. Hg. v. BMEL. Wissenschaftlicher Beirat für Agrarpolitik, Ernährung und gesundheitlichen Verbraucherschutz (WBAE). Online verfügbar unter https://www.bmel.de/SharedDocs/Downloads/DE/_Ministerium/Beiraete/agrarpolitik/wbae-gutachten-nachhaltige-ernaehrung.html, zuletzt geprüft am 19.12.2024.

Bock, A.; Bontoux, L.; Rudkin, J. (2022): Concepts for a sustainable EU food system. Hg. v. Publications Office of the European Union. JRC. Online verfügbar unter https://publications.jrc.ec.europa.eu/repository/handle/JRC126575, zuletzt geprüft am 25.11.2024.

Boysen-Urban, K.; M'Barek, R.; Philippidis, G.; Ferrer Pérez, H. (2022): Exploring changing food attitudes to respect planetary boundaries. A global, model-based analysis. Hg. v. Publications Office of the European Union. European Commission (EC) (JRC technical report). Online verfügbar unter https://op.europa.eu/en/publication-detail/-/publication/82c2eb92-c11c-11ec-b6f4-01aa75ed71a1/language-en, zuletzt geprüft am 19.12.2024.

Brandle, J. R.; Hodges, L.; Zhou, X. H. (2004): Windbreaks in North American agricultural systems. In: *Agroforestry Systems* 2004, 2004 (61), S. 65–78. Online verfügbar unter https://digitalcommons.unl.edu/cgi/viewcontent.cgi?params=/context/agronomyfacpub/article/1389/&path_info=Hodges_2004_AS_Windbreaks_in_Sustainable_Agriculture_DC_ver.pdf, zuletzt geprüft am 14.03.2025.

Buckwell, Allan; Uhre, Andreas Nordang; Williams, Annabelle, Poláková, Jana; Blum, Winfried E.H.; Schiefer, Jasmin; Lair, G. et al. (2014): Sustainable intensification of European agriculture. IEEP. Online verfügbar unter https://ieep.eu/publications/sustainable-intensification-of-european-agriculture/, zuletzt geprüft am 24.10.2024.

Chunlian Qiao; Lingli Liu; Shuijin Hu; Jana E. Compton; Tara L. Greaver; Quanlin Li (2015): How inhibiting nitrification affects nitrogen cycle and reduces environmental impacts of anthropogenic nitrogen input. In: *Global Change Biology* 21 (3), S. 1249–1257. DOI: 10.1111/gcb.12802.

Clark, M.; Springmann, M.; Rayner, M.; Scarborough, P.; Hill, J.; Tilman, D. et al. (2022): Estimating the environmental impacts of 57,000 food products. In: *Proceedings of the National Academy of Sciences of the United States of America* 119 (33). DOI: 10.1073/pnas.2120584119.

Climate Adapt (2024): Afforestation and reforestation as adaptation opportunity. Hg. v. Climate Adapat. Online, zuletzt aktualisiert am https://climate-adapt.eea.europa.eu/en/metadata/adaptation-options/afforestation-and-reforestation-as-adaptation-opportunity, zuletzt geprüft am 14.03.2025.

Commission on the Future of Agriculture (ZKL) (2021): The future of agriculture: A common agenda. Recommendations of the Commission on the Future of Agriculture (ZKL). Online verfügbar unter https://www.publikationen-bundesregierung.de/pp-de/publikationssuche/the-future-of-agriculture-a-common-agenda-1983064, zuletzt geprüft am 22.10.2024.

Copa Cogeca (2024a): Bioeconomy. Online verfügbar unter https://copa-cogeca.eu/bioeconomy, zuletzt geprüft am 19.12.2024.

Copa Cogeca (2024b): From field to future: Copa and Cogeca Vision for the Future of EU Agriculture. Online verfügbar unter https://copa-cogeca.eu/Flexpage/DownloadFile/?id=13546883, zuletzt geprüft am 18.12.2024.

Corrochano-Monsalve, Mario; González-Murua, Carmen; Estavillo, José-María; Estonba, Andone; Zarraonaindia, Iratxe (2021): Impact of dimethylpyrazole-based nitrification inhibitors on soil-borne bacteria. In: *The Science of the total environment* 792, S. 148374. DOI: 10.1016/j.scitotenv.2021.148374.

Crippa, M.; Solazzo, E.; Guizzardi, D.; Monforti-Ferrario, F.; Tubiello, F. N.; Leip, A. (2021): Food systems are responsible for a third of global anthropogenic GHG emissions. In: *Nat Food* 2 (3), S. 198–209. DOI: 10.1038/s43016-021-00225-9.

de Jong, B.; Boysen-Urban, K.; Laurentiis, V. de; Philippidis, G.; BARTELINGS, H.; Mancini, L. et al. (2023): Assessing the economic, social and environmental impacts of food waste reduction targets - A model-based analysis. In: *1831-9424*. DOI: 10.2760/77251.

Downs, Shauna M.; Ahmed, Selena; Fanzo, Jessica; Herforth, Anna (2020): Food Environment Typology: Advancing an Expanded Definition, Framework, and Methodological Approach for

Improved Characterization of Wild, Cultivated, and Built Food Environments toward Sustainable Diets. In: *Foods* 9 (4), S. 532. DOI: 10.3390/foods9040532.

Drexler, Sophie; Gensior, Andreas; Don, Axel (2021): Carbon sequestration in hedgerow biomass and soil in the temperate climate zone. In: *Reg Environ Change* 21 (3), S. 1–14. DOI: 10.1007/s10113-021-01798-8.

Einarsson, Rasmus; Billen, Gilles; Aguilera, Eduardo; Garnier, Josette; Gingrich, Simone; Grizzetti, Bruna et al. (2022): The relative productivity of organic agriculture must be considered in the full food-system context. A comment on Connor (2022). In: *Agricultural Systems* 199, S. 103413. DOI: 10.1016/j.agsy.2022.103413.

ESABCC (2024): Towards EU climate neutrality: progress, policy gaps and opportunities. Online verfügbar unter https://climate-advisory-board.europa.eu/reports-and-publications/towards-eu-climate-neutrality-progress-policy-gaps-and-opportunities, zuletzt geprüft am 19.12.2024.

European Commission (EC) (2020): Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Farm to Fork Strategy for a fair healthy and environmentally-friendly food system (COM(2020) 381 final). Online verfügbar unter https://ec.europa.eu/info/sites/info/files/communication-annex-farm-fork-green-deal_en.pdf, zuletzt geprüft am 12.06.2020.

European Commission (EC) (2022): EU agricultural outlook for markets, income and environment 2022-2032. Brussels. Online verfügbar unter https://agriculture.ec.europa.eu/document/download/1492c9fa-7336-4542-8d3b-04443d4ac0ab_en?filename=agricultural-outlook-2022-report_en_0.pdf, zuletzt geprüft am 09.08.2023.

European Commission (EC) (2023): The EU pathway towards sustainable food systems transformation. Online verfügbar unter https://knowledge4policy.ec.europa.eu/publication/eu-pathway-towards-sustainable-food-systems-transformation_en, zuletzt geprüft am 02.10.2024.

European Commission (EC) (2024a): A shared prospect for farming and food in Europe. The final report of the Strategic Dialogue on the future of EU agriculture. Online verfügbar unter https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/main-initiatives-strategic-dialogue-future-eu-agriculture_en#strategic-dialogue-report, zuletzt geprüft am 16.12.2024.

European Commission (EC) (2024b): Securing our future: Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society. Commission Staff Working Document, Impact Assessment Report Part 1 (SWD(2024) 63 final). Online verfügbar unter https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2024%3A63%3AFIN, zuletzt geprüft am 18.12.2024.

European Commission (EC) (2024c): Transition pathway for the agri-food industrial ecosytem. Online verfügbar unter https://single-market-economy.ec.europa.eu/publications/transition-pathway-agri-food-industrial-ecosystem_en, zuletzt geprüft am 19.12.2024.

European Environment Agency (EEA) (2022): Rethinking agriculture. Online verfügbar unter https://www.eea.europa.eu/publications/rethinking-agriculture, zuletzt geprüft am 25.11.2024.

European Environment Agency (EEA) (2023): EEA greenhouse gas projections - data viewer. Data viewer on projections of greenhouse gas (GHG) emissions reported to the EU/EEA by European countries. Online verfügbar unter https://www.eea.europa.eu/data-and-maps/data/data-viewers/eea-greenhouse-gas-projections-data-viewer, zuletzt geprüft am 08.01.2025.

Eurostat (2023): Agri-environmental indicator - livestock patterns. Online verfügbar unter https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_livestock_patterns, zuletzt aktualisiert am 20.11.2024, zuletzt geprüft am 18.12.2024.

FAO (2023a): Achieving SDG 2 without breaching the 1.5 °C threshold: A global roadmap. How agrifood systems transformation through accelerated climate actions will help achieving food security and nutrition, today and tomorrow. Online verfügbar unter https://www.fao.org/interactive/sdg2-roadmap/en/, zuletzt geprüft am 24.10.2024.

FAO (2023b): Contribution of terrestrial animal source food to healthy diets for improved nutrition and health outcomes – An evidence and policy overview on the state of knowledge and gaps. Online verfügbar unter https://www.fao.org/3/cc3912en/cc3912en.pdf, zuletzt geprüft am 24.10.2024.

Ferrari, E.; Elleby, C.; Jong, B. de; M'Barek, R.; Pérez Dominguez, I. (2024): Cumulative economic impact of upcoming trade agreements on EU agriculture. Update 2024. Hg. v. Publications Office of the European Union. JRC. Luxembourg. Online verfügbar unter https://publications.jrc.ec.europa.eu/repository/handle/JRC135540, zuletzt geprüft am 25.11.2024.

Fischer, M.; Fromhold-Eisebith, M.; Grote, U.; Matthies, E.; Messner, D.; Pittel, K. et al. (2021): Flagship report: Rethinking land in the anthropocene: from separation to integration. German Advisory Council on Global Change (WBGU). Berlin. Online verfügbar unter https://www.wbgu.de/en/publications/publication/landshift, zuletzt geprüft am 25.11.2024.

Frank, S.; Havlík, P.; Stehfest, E.; Meijl, Hans; Pérez Dominguez, I.; van Dijk, Michiel et al. (2018): AgMIP - Agricultural non-CO2 emission reduction potential in the context of the 1.5 °C target. In: *Nature Clim Change* 9, Artikel JRC112796, S. 66–72. Online verfügbar unter https://data.jrc.ec.europa.eu/dataset/5a06cad1-6c12-4d17-b008-4b58956ec3d8, zuletzt geprüft am 08.01.2025.

Frank, Stefan; Havlík, Petr; Stehfest, Elke; van Meijl, Hans; Witzke, Peter; Pérez-Domínguez, Ignacio et al. (2019): Agricultural non-CO2 emission reduction potential in the context of the 1.5 °C target. In: *Nature Clim Change* 9 (1), S. 66–72. DOI: 10.1038/s41558-018-0358-8.

Frelih-Larsen, A.; Riedel, A.; Akinyede, R. O.; Gattinger, A.; Niether, W. (2022): Nitrification inhibitors: biological and synthetic. Hg. v. Umweltbundesamt. Online verfügbar unter https://www.umweltbundesamt.de/sites/default/files/medien/11850/publikationen/factsheet_nitrification_inhibitors.pdf, zuletzt geprüft am 14.03.2025.

Fukase, Emiko; Martin, Will (2020): Economic growth, convergence, and world food demand and supply. In: *World Development* 132, S. 104954. DOI: 10.1016/j.worlddev.2020.104954.

Gallani, V.; Klapp, A.-L. (2024): Building bridges between habit and health: An investigation into the nutritional value of plant-based meat and milk alternatives. ProVeg International. Online verfügbar unter https://proveg.org/article/elevating-plant-based-alternatives-a-nutritional-review-for-the-food-sector/, zuletzt geprüft am 18.12.2024.

García, Virginia Rodríguez; Gaspart, Frédéric; Kastner, Thomas; Meyfroidt, Patrick (2020): Agricultural intensification and land use change: assessing country-level induced intensification, land sparing and rebound effect. In: *Environ. Res. Lett.* 15 (8), S. 85007. DOI: 10.1088/1748-9326/ab8b14.

Garnett, T.; Appleby, M. C.; Balmford, A.; Bateman, I. J.; Benton, T. G.; Bloomer, P. et al. (2013): Sustainable Intensification in Agriculture: Premises and Policies. In: *American Association for the Advancement of Science* 431 (6141), S. 33–34. Online verfügbar unter https://www.science.org/doi/10.1126/science.1234485, zuletzt geprüft am 24.10.2024.

Gattinger, Andreas; Muller, Adrian; Haeni, Matthias; Skinner, Colin; Fliessbach, Andreas; Buchmann, Nina et al. (2012): Enhanced top soil carbon stocks under organic farming. In: *Proceedings of the National Academy of Sciences of the United States of America* 109 (44), S. 18226–18231. DOI: 10.1073/pnas.1209429109.

Gaudin, A.C.M.; Tolhurst, T. N.; Ker, A. P.; Janovicek, K.; Tortora, C.; Martin, R. C.; Deen, W. (2015): Increasing Crop Diversity Mitigates Weather Variations and Improves Yield Stability. In: *PLOS ONE* 10 (2), e0113261. DOI: 10.1371/journal.pone.0113261.

Greifswald Mire Centre; Wetland International (2023): Questions & Answers: Bringing Clarity on Peatland Rewetting and Restoration. Hg. v. Greifswald Mire Centre und Wetland International. Online verfügbar unter https://globalpeatlands.org/sites/default/files/2023-07/QA-peatland-rewetting_fin.pdf, zuletzt geprüft am 14.03.2025.

Hegarty, Roger S.; Passetti, Rodrigo A. C.; Dittmer, Kyle M.; Wang, Yuxi; Shelton, Sadie W.; Emmet-Booth, Jeremy et al. (2021): An evaluation of emerging feed additives to reduce methane emissions from livestock: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) & New Zealand Agricultural Greenhouse Gas Research Centre (NZAGRC) initiative of the Global Research Alliance (GRA). Online verfügbar unter https://cgspace.cgiar.org/items/06c09a20-98ab-41ca-9cfe-488348254000.

Herrero, Mario; Henderson, Benjamin; Havlík, Petr; Thornton, Philip K.; Conant, Richard T.; Smith, Pete et al. (2016): Greenhouse gas mitigation potentials in the livestock sector. In: *Nature Clim Change* 6 (5), S. 452–461. DOI: 10.1038/nclimate2925.

Houzer, Ella; Scoones, Ian (2021): Are Livestock Always Bad for the Planet? Rethinking the Protein Transition and Climate Change Debate. Hg. v. Institute of Development Studies. Brighton (PASTRES programme). Online verfügbar unter https://opendocs.ids.ac.uk/articles/online_resource/Are_Livestock_Always_Bad_for_the_Planet_Rethinking_the_Protein_Transition_and_Climate_Change_Debate/26430637?file=48182641, zuletzt geprüft am 25.11.2024.

Howard, P. et al. (2022): The politics of protein: Examining claims about livestock, fish, 'alternative proteins' and sustainability. IPES FOOD. Online verfügbar unter https://ipes-food.org/report/the-politics-of-protein/, zuletzt geprüft am 25.11.2024.

IFOAM Organics Europe (2022): Organic agriculture and its benefits for climate and biodiversity. Brussels. Online verfügbar unter https://www.organicseurope.bio/content/uploads/2022/04/IFOAMEU_advocacy_organic-benefits-for-climate-and-biodiversity_2022.pdf, zuletzt geprüft am 13.03.2025.

Ivezić, V.; Yu, Y.; van Werf, W. der. (2021): Crop yields in European agroforestry systems: A meta-analysis. In: *Frontiers in Sustainable Food Systems* 2021, 2021 (5). Online verfügbar unter https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2021.606631/full, zuletzt geprüft am 14.03.2025.

Jafari, Y.; Britz, W.; Dudu, H.; Roson, R.; Sartori, M. (2020): Can Food Waste Reduction in Europe Help to Increase Food Availability and Reduce Pressure on Natural Resources Globally? In: *GER J AGR ECON* 69 (2). DOI: 10.30430/69.2020.2.143-168.

Joosten, H. (2021): Global guidelines for peatland rewetting and restoration. Hg. v. SECRETARIAT OF THE cONVENTION ON wETLANDS. Convention on Wetlands. Switzerland (Ramsar Technical Report 11). Online verfügbar unter https://www.ramsar.org/sites/default/files/documents/library/rtr11_peatland_rewetting_restoration_e.pdf, zuletzt geprüft am 14.03.2025.

Kay, Sonja; Rega, Carlo; Moreno, Gerardo; Herder, Michael den; Palma, João H.N.; Borek, Robert et al. (2019): Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe. In: *Land Use Policy* 83, S. 581–593. DOI: 10.1016/j.landusepol.2019.02.025.

Kaye, Jason P.; Quemada, Miguel (2017): Using cover crops to mitigate and adapt to climate change. A review. In: *Agron. Sustain. Dev.* 37 (1), S. 1–17. DOI: 10.1007/s13593-016-0410-x.

Kebede, Abiy S.; Nicholls, Robert J.; Clarke, Derek; Savin, Cristina; Harrison, Paula A. (2021): Integrated assessment of the food-water-land-ecosystems nexus in Europe: Implications for sustainability. In: *Science of The Total Environment* 768, S. 144461. DOI: 10.1016/j.scitotenv.2020.144461.

Kjeldsen, M. H.; Jensen, M. B.; Lund, P. (2022): Potent methane reducing feed additives in a Danish context, and their reduction potential, additive effects, risks related to animal welfare and carry-over to milk and potential trade-offs. Danish Centre for Food and Agriculture. Online verfügbar unter https://pure.au.dk/portal/files/306097925/Rapport_FINAL_300123.pdf, zuletzt geprüft am 13.03.2025.

Kösler, Julia Elli; Calvo, Olga C.; Franzaring, Jürgen; Fangmeier, Andreas (2019): Evaluating the ecotoxicity of nitrification inhibitors using terrestrial and aquatic test organisms. In: *Environ Sci Eur* 31 (1), S. 1–11. DOI: 10.1186/s12302-019-0272-3.

Kremmydas, Dimitrios; Beber, Caetano; Baldoni, Edoardo; Ciaian, Pavel; Fellmann, Thomas; Gocht, Alexander et al. (2024): The EU target for organic farming: Potential economic and environmental impacts of two alternative pathways. In: *Applied Eco Perspectives Pol*, Artikel aepp.13470. DOI: 10.1002/aepp.13470.

Lampkin, N.; Padel, K. (2023): Environmental impacts of achieving the EU's 25% organic land by 2030 target: a preliminary assessment. Hg. v. IFOAM Organics Europe. Online verfügbar unter https://www.organicseurope.bio/news/study-on-the-environmental-impacts-of-achieving-25-organic-land-by-2030-published/, zuletzt geprüft am 24.10.2024.

Llonch, P.; Haskell, M. J.; Dewhurst, R. J.; Turner, S. P. (2017): Current available strategies to mitigate greenhouse gas emissions in livestock systems: an animal welfare perspective. In: *Animal : an international journal of animal bioscience* 11 (2), S. 274–284. DOI: 10.1017/S1751731116001440.

Loisel, Julie; Gallego-Sala, Angela (2022): Ecological resilience of restored peatlands to climate change. In: *Commun Earth Environ* 3 (1), S. 1–8. DOI: 10.1038/s43247-022-00547-x.

Lóránt, A.; Allan, B. (2019): Net-zero agriculture in 2050: How to get there. Report by the Institute for European Environmental Policy. IEEP. Online verfügbar unter https://ieep.eu/publications/net-zero-agriculture-in-2050-how-to-get-there/, zuletzt geprüft am 25.09.2024.

Macholdt, Janna; Styczen, Merete Elisabeth; Macdonald, Andy; Piepho, Hans-Peter; Honermeier, Bernd (2020): Long-term analysis from a cropping system perspective: Yield stability, environmental adaptability, and production risk of winter barley. In: *European Journal of Agronomy* 117, S. 126056. DOI: 10.1016/j.eja.2020.126056.

Mal, Mathieu (2024): Reducing emissions from agriculture. Reflection on the potential design and scope of an EU Emission Trading System for agriculture. Hg. v. EEB - European Environmental Bureau. Brussels. Online verfügbar unter https://eeb.org/wp-content/uploads/2024/10/Agri-ETS-Position-Paper.pdf, zuletzt geprüft am 14.03.2025.

Mitter, Hermine; Techen, Anja-K.; Sinabell, Franz; Helming, Katharina; Schmid, Erwin; Bodirsky, Benjamin L. et al. (2020): Shared Socio-economic Pathways for European agriculture and food systems: The Eur-Agri-SSPs. In: *Global Environmental Change* 65 (102159). DOI: 10.1016/j.gloenvcha.2020.102159.

Müller, Adrian; Bautze, Lin; Meier, Matthias; Gattinger, Andreas; Gall, Eric; Chatzinikolaou, Effimia et al. (2016): Organic Farming, Climate Change Mitigation and Beyond. Reducing the environmental impacts of eu agriculture. Brussels and Frick: IFOAM EU and FiBL. Online verfügbar unter https://orgprints.org/id/eprint/31483/.

Nabuurs, G-J.; Mrabet, R.; Abu Hatab, A.; Bustamante, M.; Clark, H.; Havlík, P. et al. (2022): Agriculture, Forestry and Other Land Uses (AFOLU). In: Priyadarshi R. Shukla, J. Skea, A. Slade, R. Al Khourdajie, R. van Diemen, D. McCollum et al. (Hg.): Climate change 2022. Mitigation of climate change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, S. 747–860. Online verfügbar unter Mitigation of climate change : Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, zuletzt geprüft am 08.01.2025.

OECD; FAO (2024): OECD-FAO Agricultural Outlook 2024-2033. Online verfügbar unter https://www.oecd.org/en/publications/oecd-fao-agricultural-outlook-2024-2033_4c5d2cfb-en.html, zuletzt geprüft am 16.12.2024.

Onwezen, M. C.; Bouwman, E. P.; Reinders, M. J.; Dagevos, H. (2021): A systematic review on consumer acceptance of alternative proteins: Pulses, algae, insects, plant-based meat alternatives, and cultured meat. In: *Appetite* 159, S. 105058. DOI: 10.1016/j.appet.2020.105058.

Pérez Domínguez, Ignacio; Fellmann, Thomas; Witzke, Peter; Weiss, Franz; Hristov, Jordan; Himics, Mihaly et al. (2020): Economic assessment of GHG mitigation policy options for EU agriculture: a closer look at mitigation options and regional mitigation costs - EcAMPA 3. Hg. v. Publications Office of the European Union. JRC. Luxembourg (JRC technical report). Online verfügbar unter https://op.europa.eu/en/publication-detail/-/publication/cce2a349-8052-11ea-b94a-01aa75ed71a1/language-en, zuletzt geprüft am 25.11.2024.

Poore, J.; Nemecek, T. (2018): Reducing food’s environmental impacts through producers and consumers. In: *Science* 360 (6392), S. 987–992. DOI: 10.1126/science.aaq0216.

Poux, X.; Aubert, P.-M. (2018): An agroecological Europe in 2050: multifunctional agriculture for healthy eating. IDDRI. Paris (No. 9). Online verfügbar unter https://www.iddri.org/en/publications-and-events/study/agroecological-europe-2050-multifunctional-agriculture-healthy-eating, zuletzt geprüft am 18.12.2024.

Pretty, Jules; Benton, Tim G.; Bharucha, Zareen Pervez; Dicks, Lynn V.; Flora, Cornelia Butler; Godfray, H. Charles J. et al. (2018): Global assessment of agricultural system redesign for sustainable intensification. In: *Nat Sustain* 1 (8), S. 441–446. DOI: 10.1038/s41893-018-0114-0.

Pschenyckyj, C.; Riondato, E.; Wilson, D.; Flood, K.; O’Driscoll, C.; Renou-Wilson, F. (2021): Optimising Water Quality Returns from Peatland Management while Delivering Co-Benefits fro Climate and Biodiversity. Synthesis Report. Online verfügbar unter https://thewaterforum.ie/app/uploads/2021/04/Peatlands_Synthesis-Report_Final_April2021.pdf, zuletzt geprüft am 14.03.2025.

Publications Office of the European Union (Hg.) (2020): Towards a Sustainable Food System : moving from food as a commodity to food as more of a common good : independent expert report. European Commission (EC). Luxembourg (Scientific opinion, 8). Online verfügbar unter https://www.europeansources.info/record/towards-a-sustainable-food-system/, zuletzt geprüft am 25.11.2024.

Rasche, Livia; Steinhauser, Jan (2022): How will an increase in organic agricultural area affect land use in Germany? In: *Org. Agr.* 12 (4), S. 513–530. DOI: 10.1007/s13165-022-00405-2.

Ray, A.; Nkwonta, C.; Forrestal, P.; Danaher, M.; Richards, K.; O’Callaghan, T. et al. (2021): Current knowledge on urease and nitrification inhibitors technology and their safety. In: *Reviews on Environmental Health* 2021, 2021 (36 (4)), S. 477–491.

Rieger, Jörg; Freund, Florian; Offermann, Frank; Geibel, Inna; Gocht, Alexander (2023): From fork to farm: Impacts of more sustainable diets in the EU -27 on the agricultural sector. In: *J Agricultural Economics* 74 (3), S. 764–784. DOI: 10.1111/1477-9552.12530.

Röös, Elin; Mayer, Andreas; Muller, Adrian; Kalt, Gerald; Ferguson, Shon; Erb, Karl-Heinz et al. (2022): Agroecological practices in combination with healthy diets can help meet EU food system policy targets. In: *Science of The Total Environment* 847, S. 157612. DOI: 10.1016/j.scitotenv.2022.157612.

Rusch, Adrien; Bommarco, Riccardo; Jonsson, Mattias; Smith, Henrik G.; Ekbom, Barbara (2013): Flow and stability of natural pest control services depend on complexity and crop rotation at the landscape scale. In: *Journal of Applied Ecology* 50 (2), S. 345–354. DOI: 10.1111/1365-2664.12055.

Sanders, Jürn; Heß, Jürgen (2023): Leistungen des ökologischen Landbaus für Umwelt und Gesellschaft. 2. Aufl. Thünen Institut (Thünen Report, 65). Online verfügbar unter https://www.thuenen.de/media/publikationen/thuenen-report/Thuenen_Report_65.pdf, zuletzt geprüft am 23.10.2024.

Scheffler, M.; Wiegmann, K. (2024): EU 2040 Climate Target: Contributions of the agriculture sector. Öko-Institut. Online verfügbar unter https://www.oeko.de/publikation/eu-2040-climate-target-contributions-of-the-agriculture-sector/, zuletzt geprüft am 19.12.2024.

Schutter, Olivier de; Jacobs, N.; Clément, C.; Ajena, F. (2019): Towards a common food policy for the European Union. The policy reform and alignment that is required to build sustainable food systems in Europe. IPES FOOD. Online verfügbar unter https://ipes-food.org/report/towards-a-common-food-policy-for-the-eu/, zuletzt geprüft am 25.11.2024.

Searchinger, T.; Waite, R.; Hanson, C.; Ranganathan, J.; Matthews, E. (2019): Creating a Sustainable Food Future: A menu of solutions to feed nearly 10 billion people by 2050. World Resources Institute (WRI). Online verfügbar unter https://www.wri.org/research/creating-sustainable-food-future, zuletzt geprüft am 19.12.2024.

Seddon, Nathalie; Chausson, Alexandre; Berry, Pam; Girardin, Cécile A. J.; Smith, Alison; Turner, Beth (2020): Understanding the value and limits of nature-based solutions to climate change and other global challenges. In: *Philosophical transactions of the Royal Society of London. Series B, Biological sciences* 375 (1794), S. 20190120. DOI: 10.1098/rstb.2019.0120.

Siegrist, Armin; Green, Ashley; Michel, Fabienne; Mathys, Alexander (2024): Comparing the nutritional value and prices of meat and milk substitutes with their animal-based benchmarks across six European countries. In: *Food Research International* 197, S. 115213. DOI: 10.1016/j.foodres.2024.115213.

Sietz, Diana; Conradt, Tobias; Krysanova, Valentina; Hattermann, Fred F.; Wechsung, Frank (2021): The Crop Generator: Implementing crop rotations to effectively advance eco-hydrological modelling. In: *Agricultural Systems* 193, S. 103183. DOI: 10.1016/j.agsy.2021.103183.

Sipka, S.; Rayner, L.; Dekeyrel, S.; Lausberg, P.; Brady, D. (2024): The Green Deal in times of polycrisis: Aligning short-term responses with long-term commitments. European Policy Centre. Online verfügbar unter https://www.epc.eu/en/publications/The-Green-Deal-in-times-of-polycrisis-Aligning-short-term-responses-w~5893c8, zuletzt geprüft am 19.12.2024.

Smith, J. U.; Wolfe, M.; Lampkin, N. (2011): Organic Farming and Biodiversity : A review of the literature. Online verfügbar unter https://www.semanticscholar.org/paper/Organic-Farming-and-Biodiversity-%3A-A-review-of-the-Smith-Wolfe/9221d49d454ed34177ab47fedddbf9c11799c8df.

Springmann, Marco; Clark, Michael; Mason-D'Croz, Daniel; Wiebe, Keith; Bodirsky, Benjamin Leon; Lassaletta, Luis et al. (2018): Options for keeping the food system within environmental limits. In: *Nature* 562 (7728), S. 519–525. DOI: 10.1038/s41586-018-0594-0.

Staddon, Philip L.; Faghihinia, Maede (2021): Grazing intensity is key to global grassland carbon sequestration potential. In: *Sustainable Environment* 7 (1), Artikel 1895474. DOI: 10.1080/27658511.2021.1895474.

Sutton, W. R.; Lotsch, A.; Prasann, A. (2024): Recipe for a livable planet: Achieving net zero emissions in the agrifood system. World Bank. Washington, DC (Agriculture and Food Series). Online verfügbar unter https://www.worldbank.org/en/topic/agriculture/publication/recipe-for-livable-planet, zuletzt geprüft am 16.12.2024.

Temperton, V. M. (2023): Bedeutung des Grünlandes für das Klima: Hohe Albedo, Resilienz und Langzeitkohlenstoffspeicherung. Online verfügbar unter https://www.fdr.uni-hamburg.de/record/12826, zuletzt geprüft am 14.03.2025.

Thaler, Gregory M. (2017): The Land Sparing Complex: Environmental Governance, Agricultural Intensification, and State Building in the Brazilian Amazon. In: *Annals of the American Association of Geographers* 107 (6), S. 1424–1443. DOI: 10.1080/24694452.2017.1309966.

Tiemann, L. K.; Grandy, A. S.; Atkinson, E. E.; Marin-Spiotta, E.; McDaniel, M. D. (2015): Crop rotational diversity enhances belowground communities and functions in an agroecosystem. In: *Ecology letters* 18 (8), S. 761–771. DOI: 10.1111/ele.12453.

Tilman, David; Balzer, Christian; Hill, Jason; Befort, Belinda L. (2011): Global food demand and the sustainable intensification of agriculture. In: *Proceedings of the National Academy of Sciences* 108 (50), S. 20260–20264. DOI: 10.1073/pnas.1116437108.

Torralba, Mario; Fagerholm, Nora; Burgess, Paul J.; Moreno, Gerardo; Plieninger, Tobias (2016): Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. In: *Agriculture, Ecosystems & Environment* 230, S. 150–161. DOI: 10.1016/j.agee.2016.06.002.

van der Werf, W.; Keesman, K.; Burgess, P.; Graves, A.; Pilbeam, D., Incoll, L. D., Metselaar, K., Mayus, M.; Stappers, R., Van Keulen, H., Palma, J.; Dupraz, C. (2007): Yield-SAFE: A parameter-sparse, process-based dynamic model for predicting resourcecapture, growth, and production in agroforestry systems. In: *Ecological Engineering* 2007, 2007 (29 (4)), S. 419–433. Online verfügbar unter https://doi.org/10.1016/j.ecoleng.2006.09.017, zuletzt geprüft am 14.03.2025.

Velten, E. K.; Calipel, C.; Duwe, M.; Evans, N.; Felthöfer, C.; Gardiner, J. et al. (2024): 2024 Report: State of EU progress to climate neutrality | ECNO. An indicator-based assessment across 13 building blocks for a climate neutral future. Hg. v. European Climate Neutrality Observatory (ECNO). Online verfügbar unter https://climateobservatory.eu/report/2024-report-state-eu-progress-climate-neutrality, zuletzt geprüft am 19.12.2024.

Wang, Haitao; Köbke, Sarah; Dittert, Klaus (2020): Use of urease and nitrification inhibitors to reduce gaseous nitrogen emissions from fertilizers containing ammonium nitrate and urea. In: *Global Ecology and Conservation* 22, e00933. DOI: 10.1016/j.gecco.2020.e00933.

Whittow, M.; Ranalli, G.; Davis, S.; Noon, L. (2023): Funding the EU transition to more sustainable agriculture: discussion paper. Hg. v. FoodDrinkEurope. Anthesis. Online verfügbar unter https://www.fooddrinkeurope.eu/wp-content/uploads/2023/12/231205-Discussion-Paper-on-funding-the-EU-transition-to-more-sustainable-agriculture.pdf, zuletzt geprüft am 19.12.2024.

Willett, Walter; Rockström, Johan; Loken, Brent; Springmann, Marco; Lang, Tim; Vermeulen, Sonja et al. (2019): Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. In: *Lancet (London, England)* 393 (10170), S. 447–492. DOI: 10.1016/S0140-6736(18)31788-4.

World Bank (2020): Addressing Food Loss and Waste: A Global Problem with Local Solutions. Online verfügbar unter https://openknowledge.worldbank.org/entities/publication/1564bf5c-ed24-5224-b5d8-93cd62aa3611, zuletzt geprüft am 19.12.2024.

World Bank Group (2021): World Bank Group Climate Change Action Plan 2021–2025: Supporting Green, Resilient, and Inclusive Development. Hg. v. World Bank Group. Washington, DC. Online verfügbar unter http://hdl.handle.net/10986/35799, zuletzt geprüft am 09.01.2025.

Yang, Y.; Tilman, D.; Furey, G.; Lehman, C.: Soil carbon sequestration accelerated by restoration of grassland biodiversity. In: *Nat Commun* 2019 (10 (1)), S. 1–7. Online verfügbar unter DOI: 10.1038/s41467-019-08636-w., zuletzt geprüft am 14.03.2025.

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