Report

Residual emissions in EU agriculture

Analysis of emission reduction scenarios

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EXECUTIVE SUMMARY

As the EU policy debate turns toward defining the next milestones on the path to climate neutrality by 2050, there is growing practical urgency around clarifying the roles of different sectors in the mitigation effort and their respective contributions to residual emissions at the point of climate neutrality.

Despite their central role in net-zero strategies, residual emissions remain poorly defined. In integrated assessment modelling, they are defined as emissions for which abatement is technically infeasible or economically unjustifiable under given assumptions (Luderer et al., 2018). The broader literature also emphasises the normative and political dimensions of determining acceptable residual emission levels and fair sectoral contributions (Dooley et al., 2021; Arendt, 2024).

Against this background, this report examines the potential for emission reductions in EU agriculture – a sector commonly referred to as "hard-to-abate" and expected to become the largest contributor to residual emissions (Lund et al., 2023; Smith et al., 2024). Agriculture plays a unique role as the largest sectoral source of global methane (CH_4) and nitrous oxide (N_2O) emissions; greenhouse gases with significantly higher warming potential than CO_2, and with additional implications for human health and other environmental dimensions. From a planetary boundary perspective, agricultural production has been a major driver responsible for shifting the Earth system toward, or over, the boundaries of a safe operating space for humanity (Campbell et al., 2017). Consequently, the agricultural climate mitigation trajectory is critical both for achieving climate neutrality and for advancing broader sustainability objectives, while retaining its essential role as a key source of human sustenance.

In this context, this analysis reviews a selection of scenarios developed for the EU agricultural sector to assess variations in residual emissions across different pathways, their composition by sub-sector and emission source, and the scenario characteristics that drive these differences. It focuses on the three largest emission sources: livestock enteric fermentation, manure management, and nitrous oxide emissions from agricultural soils.

Overview of the analysed scenarios

The selected scenarios adopt different analytical approaches to envisioning the EU agricultural sector at mid-century, reflecting diverse assumptions and model designs. Key characteristics are summarised below:

Core approach	Source	Scenario	End date	Remaining emissions from agriculture (Mt CO2e)	GHG reduction compared to 2023 emissions
Assessment of agriculture's possible contribution to climate neutrality, alongside the delivery of other sustainability objectives set out in (largely non-binding) EU policy frameworks; incorporate a techno-economic assessment of mitigation potential under different carbon pricing and technology assumptions in the context of shifting societal preferences with respect to food	**Agora Agriculture (2024)**	**Agora Agriculture**	2045/2050	**150**	59%
	2040 target IA (EC, 2024a)	**LIFE**	2050	**194**	47%
Assessment of the feasibility of a large-scale transition to an "agro-ecological Europe", with phase-out of synthetic inputs and EU protein self-sufficiency as key pillars, focusing on biophysical constraints and meeting nutritional needs	**TYFA (Aubert, Schwoob & Poux, 2019)**	**TYFA-GHG**	2050	**203**	44%
	TYFA (Poux & Aubert, 2018)	**TYFA main**	2050	**243**	33%
Techno-economic assessment of mitigation potential under different carbon pricing and technology assumptions, in the context of relatively static consumer preferences	**2040 target IA (EC, 2024a)**	**S2**	2050	**249**	32%
	2040 target IA (EC, 2024a)	**S3**	2050	**249**	32%
	EcAMPA 4 (Pérez Domínguez et al., 2025)	**CP scenario**	2050	**275**	25%

The examined scenarios show a wide range of possible GHG outcomes, from a level of residual emissions of 150 Mt CO_2e in 2045/2050 (*Agora* scenario) to 275 Mt CO_2e in 2050 (*EcAMPA 4 CP* scenario), representing a 59% and 25% reduction, respectively, relative to emission levels reported in 2023.

Scenarios that assume a shift in demand away from animal protein, alongside the deployment of mitigation technologies in the sector, show the most ambitious levels of emission reduction. They also demonstrate that a shift toward lower-emission on-farm practices in EU agriculture, when combined with a demand shift, can support global mitigation by reducing the risk of carbon leakage. From a trade perspective, such pathways can help maintain or improve the EU's trade balance in key agri-food commodities, in particular as reduced demand for animal feed lowers the trade deficit in feed grains, oilseeds, and other protein feedstocks, while reduced domestic overconsumption of animal protein supports a stronger net export position in dairy. Scenarios which do not model a demand shift beyond existing trends show a modest degree of emissions leakage and a deterioration in the trade balance in the absence of specific policy measures, such as a carbon border adjustment mechanism.

Most of the analysed scenarios explicitly model the adoption of various mitigation technologies, showing that technology-based approaches can play an important role in the mitigation effort, even though uncertainties remain around trade-offs and the scalability of individual types of interventions. In nearly all scenarios, the uptake of technologies is determined by the assumed implementation costs, as drawn from the literature, and by the application of a carbon price to agricultural emissions, which ranges from EUR 100 to EUR 470 per tonne of CO_2e across the analysed studies. For crop production, the use of nitrification inhibitors in synthetic fertiliser application is consistently identified as the main driver of emission reductions across scenarios, while in the livestock sector, the greatest technological mitigation potential is associated with 3-NOP feed additives, followed by anaerobic digestion. However, the use of these technologies often requires a certain level of intensification and consolidation, which may be undesirable from the perspective of other sustainability objectives.

In terms of production volumes, nearly all scenarios foresee a decline in animal-source food output and reductions in livestock herds, although the magnitude of change varies. The scenarios demonstrate how differences in underlying environmental priorities influence the relative composition of ruminant and non-ruminant livestock, resulting in varying ratios between these groups. Nonetheless, regardless of the livestock types prioritised, the overall reduction in animal population contributes to mitigating pollution and alleviating pressure on land and ecosystems.

Dairy production generally declines less than meat production, and the analysed scenarios show that a significant reduction in livestock herds can still maintain a high level of dairy provision – sufficient to provide for domestic dairy consumption remaining above the benchmark recommended by the EAT-Lancet Commission (Willett et al., 2019; Rockström et al., 2025), while also allowing the EU to retain its position as a leading exporter. Outcomes for crop production vary more widely across the scenarios, with most suggesting that, under favourable market and policy conditions, output can be maintained or even increased, especially for permanent and nitrogen-fixing crops. It is important to note, however, that while the models account for some climate change effects on agricultural yields, they do not fully capture additional warming, the increasing frequency and severity of extreme weather events, or the complex interactions between climate mitigation and adaptation measures.

Recognising that pursuing mitigation pathways with the lowest residual emissions is the safest course of action for limiting climate change and minimising or reversing temperature overshoot (Lamb, 2024), there is a clear case for policymakers to consider how the key elements of scenarios achieving the largest emission reductions could be facilitated through policy action. The fact that these scenarios generally show a wide range of positive co-benefits for public health, self-sufficiency, and environmental outcomes beyond climate further strengthens this case.

Findings on the implications of different transition pathways for food availability in the EU suggest that a combination of demand- and supply-side measures under an ambitious mitigation scenario can enhance the overall availability of food, including protein-rich products, while improving self-sufficiency and system resilience by reducing reliance on imported feed and other inputs. This indicates that renewed policy attention to sustainable consumption patterns is warranted at all governance levels. Shifts in the product mix will also be necessary, with structural changes in the livestock sector offering potential not only for stronger responses to the climate crisis but also to other interconnected crises, including pollution, land pressures and biodiversity loss.

The analysed scenarios do not provide significant detail or insight on the socio-economic impacts of the modelled reductions and their distribution, and thus cannot be used to draw detailed conclusions on these aspects. Nevertheless, all scenarios assume the application of a carbon price, implying transition costs that will ultimately be borne either by agri-food actors or the public budget. Policymakers will thus need to strike a balance between measures that distribute these costs across the sector and those financed through public support.

Structural changes in the sector will also require careful socio-economic assessment and targeted interventions to ensure a fair and inclusive transition.

At a foundational level, aligning efforts across stakeholder groups and ensuring the flow of public and private finance in the right direction requires a comprehensive and coherent vision for the structure of the EU agricultural sector in 2040, 2050, and beyond. From a climate perspective, this vision should consider overall emission reduction needs at the sector level, the composition of residual emissions by source (e.g. livestock, fertiliser application), and production modes within a well-defined, science-based climate transition pathway that provides long-term policy certainty. Crucially, the climate pathway must sit within an integrated approach that accounts for human health, animal welfare, climate resilience, biodiversity and other environmental dimensions, so that emission reductions are achieved in ways that reinforce, rather than undermine, broader sustainability goals.

1. INTRODUCTION

The European Union is legally committed to achieving net-zero greenhouse gas (GHG) emissions by 2050, as stipulated in the European Climate Law. The law further specifies that the EU "shall aim to achieve negative emissions thereafter" (EU, 2021, Art 2(1)). These objectives require that remaining emissions are fully balanced by carbon dioxide removals within the EU by 2050, with total removals exceeding remaining emissions from 2050 onwards. Achieving this goal depends not only on scaling up removal capacities but, critically, on significantly reducing emissions across all sectors.

The EU's capacity to remove carbon is constrained by biophysical, technological, and economic limits (ESABCC, 2025). Land-based removals, while essential, face growing challenges due to forest sink decline, driven by increased tree mortality and increased harvesting rates (Korosuo, 2024; EEA, 2024). Similarly, the more mature technological removal options such as bioenergy with carbon capture and storage (BECCS) or direct air carbon capture and storage (DACCS) remain limited by high costs, infrastructure needs, and uncertain scalability (see e.g., IEA, 2024; ESABCC, 2025). Reliance on industrial removal technologies can also carry a range of environmental and social risks (see e.g. Smith, 2016; Heck et al., 2018), while biomass- and soil-based removals, though offering many potential co-benefits, are vulnerable to reversal, notably as a result of a changing climate. These constraints suggest that pursuing mitigation pathways with the lowest residual emissions is the safest course of action for limiting climate change and minimising and reversing temperature overshoot (Lamb, 2024).

Despite their central role in net-zero strategies, residual emissions are often poorly defined, both conceptually and quantitatively. The term has emerged alongside the rise of net-zero as a policy framework, typically referring to emissions that are considered difficult or impossible to eliminate and thus must be counterbalanced through carbon dioxide removal. In the integrated assessment modelling literature, residual emissions are generally characterised as those for which abatement is either technically infeasible or economically unjustifiable under specific scenario assumptions (Luderer et al., 2018). The broader literature also underscores the central role of civil society involvement in determining appropriate levels of residual emissions, in order to ensure 'fair contributions' across different sectors and stakeholder groups (see e.g., Dooley et al., 2021; Arendt 2024), highlighting that defining residual emissions is as much a normative and political question as it is a techno-economic one.

National long-term strategies submitted under the UNFCCC continue to be vague on these points, lacking precision about which sectors residual emissions would originate from, and rarely offering specific projections of how residual emissions could be balanced by carbon removal (see e.g., Buck et al., 2023). Ambiguity in the criteria for determining what may constitute residual or "hard-to-abate" emissions and the resulting lack of clarity in the sectoral allocation of the GHG budget weaken policy signals and undermine the credibility of net-zero targets. A persistent lack of consensus on sectoral contributions to the achievement of net zero may in practice lead countries to pursue emission reduction pathways that are insufficient and reliant on unrealistic levels of carbon removal, heightening the risk of crossing climate tipping points as the 1.5C threshold is overshot.

Why agricultural emissions?

In policy and techno-economic analysis, residual emissions are frequently described as originating from 'hard-to-abate' sectors, with agriculture, industrial processes, and aviation commonly cited as key examples (e.g., Lund et al., 2023; Lamb, 2024). An analysis of 71 long-term national strategies found that, while only 26 of these quantified residual emissions, among those, agriculture emerged as both the sector with the least anticipated progress and the largest contributor to residual emissions. It accounted, on average, for 36% of total residual emissions in Annex I (industrialised) countries and 35% in non-Annex I countries (Smith et al., 2024).

Agricultural emissions, as categorised in the IPCC GHG Inventory Guidelines, include those arising from enteric fermentation, manure management, rice cultivation, burning of agricultural residues, direct and indirect nitrous oxide (N_2O) emissions from agricultural soils, and carbon dioxide (CO_2) emissions from the application of lime, urea, and other carbon-containing fertilisers. With the exception of CO_2 emissions from fertiliser use, these sources primarily emit non-CO_2 greenhouse gases, namely methane (CH_4) and nitrous oxide (N_2O).

Agriculture is the largest sectoral contributor to global methane and nitrous oxide emissions, accounting for approximately 42% of total anthropogenic CH_4 emissions and 74% of N_2O emissions. Given this substantial contribution, the mitigation trajectory within the agricultural sector is critical both from the perspective of climate change mitigation and broader sustainability objectives.

N_2O has a global warming potential approximately 273 times greater than that of CO_2 over a 100-year time horizon (IPCC, 2021), making even small quantities of emissions highly consequential for the climate. In addition to its warming effect, N_2O contributes to stratospheric ozone depletion, increasing UV radiation and posing further risks to environmental and human health, including via increased incidence of skin cancers and eye conditions (Turner et al. 2016; Seltzer et al.

2018). Although nitrous oxide is not regulated under the 2007 Montreal Protocol on ozone-depleting substances, its current anthropogenic emissions pose a greater threat to the ozone layer than any of the substances included under the protocol (UNEP & FAO, 2024).

Methane, by contrast, is a greenhouse gas with a much shorter atmospheric lifetime than CO_2 or N_2O, yet it has a disproportionately strong warming effect in the near term. Over a 20-year period, methane is approximately 84 times more potent than CO_2 in terms of its radiative forcing (IPCC, 2021), which makes it a critical focus for mitigation strategies aimed at reducing global temperature rise in the coming decades. Beyond its warming impacts, it is also a key contributor to the formation of tropospheric (ground-level) ozone (Butler et al., 2020), which adversely impacts human health, causing asthma, reduced lung function and chronic obstructive pulmonary disease, with both short- and long-term exposure associated with pre-mature mortality (REVIHAAP, 2013; COMEAP, 2015). It also causes cellular damage to plants, reducing the rate of photosynthesis, and leading to crop losses (Avnery et al., 2011). Ozone-induced damage to plants has been identified as a possible factor limiting the capacity of terrestrial ecosystems to absorb carbon, which may counteract part of the increased carbon uptake expected from CO_2 fertilisation in the conditions of rising atmospheric CO_2 levels (Sitch et al., 2007; Ciais et al., 2013; Arneth et al., 2010; Ainsworth et al., 2012).

Box 1: GWP* metric and its implications for agricultural methane emissions mitigation strategy

The GWP* "warming equivalent" metric has emerged alongside the widely used GWP100 in assessing the climate impacts of short-lived climate pollutants, particularly methane (CH_4), and has caused much debate in the policy space around the merits of reducing methane emissions from agriculture.

Methane is a powerful, but short-lived gas which is broken down by natural processes on a timescale of app. 12 years. This means that if global methane emissions remain constant, the atmospheric concentration of methane will stabilise, as the rate of emission matches the rate of decomposition. Under such conditions, continued methane emissions would not contribute to additional warming, holding temperatures at an elevated but nearly stable level, rising only very slowly due to slow adjustment of the climate system to past methane emissions increases. Conversely, if global methane emissions decline at a rate faster than app. 3% per decade, this would, in isolation, decrease warming, as atmospheric concentrations of methane fall.

GWP* more accurately reflects the dynamic temperature response compared to the cumulative, CO_2-equivalent framing of GWP100 in these scenarios – and, correspondingly, it also better captures the substantial warming impact of increased methane emissions. A new emission source of one tonne of methane per year has the same warming impact as 128 tonnes of CO2 per year over the first 20 years after the introduction of the new source – which is 4½ times larger than implied by GWP100 (Allen et al., 2022). This is significant in the current context of a continued increase in global methane emissions (Climate Watch, 2024).

A key distinction between GWP100 and GWP* lies in their treatment of counterfactuals. The perspective provided by GWP* concludes that stabilising methane emissions means that those emissions do not make an additional contribution to global warming. This is true in relation to current level of warming – but not relative to a counterfactual in which those emissions did not occur.

This is a primary reason why the practical and policy implications of adopting GWP* require careful consideration. A clear risk is the use of

GWP* to justify continued emissions on the grounds that stabilising methane levels does not contribute to additional warming. In practice, stabilising current emissions is insufficient given the need for net negative emissions to address expected temperature overshoot scenarios. This perspective also fails to consider that climate change itself is likely to amplify atmospheric concentrations of CH_4 (O'Connor et al., 2010; Mar et al., 2022). Relying on GWP* to argue for the desirability of stabilising, rather than reducing, methane emissions risks undermining efforts to achieve the reduced atmospheric greenhouse gas concentration required to meet the Paris Agreement goals.

The use of GWP* in policy also raises concerns, as, by design, the metric is agnostic to questions of fairness and historical responsibility. The time-dependent warming effects that GWP* emphasises have led some to argue in favour of policy design that penalises only increases in methane emissions, while adopting a neutral approach to elevated but constant emission levels (e.g. Cain, 2018). However, on a global scale, such an approach would effectively penalise new methane-emitting activities, such as expanding cattle production, in low-emitting countries in least developed regions. Simultaneously, it could allow historical emitters in wealthier nations to maintain high methane emissions without facing proportional responsibility for their past contribution to global warming and ongoing role in maintaining elevated temperatures. This dynamic risks reinforcing structural inequities, particularly if GWP* is used to allocate emission reduction targets or determine eligibility for financial support under international climate finance mechanisms (see also e.g. Persson (2020) for a discussion of policy effectiveness).

The insights provided by GWP* can be valuable for characterising methane's role in global temperature outcomes, as it serves to highlight both the disproportionate impact of increasing methane emissions on global warming and the significant potential of methane reductions for near-term climate mitigation (Clark et al., 2020; Costa et al., 2022). However, despite its analytical usefulness in certain contexts, there remains potential for the misuse of GWP* in a policy context, with potentially far-reaching negative consequences for global climate mitigation efforts (Hörtenhuber et al., 2022; Lesschen, 2021).

Agricultural emissions in the EU

In the EU context, the topic of residual emissions from the agricultural sector remains sensitive and unresolved. In 2023, non-CO2 emissions from agriculture accounted for 12% of the EU's total net GHG emissions (EEA, 2025), including 56% of all methane and 74% of all nitrous oxide emissions in the bloc. Although agriculture is not currently the largest sectoral contributor to the EU's total GHG emissions, it is projected to become the dominant source by 2040, as other sectors decarbonise more rapidly (EC, 2024a).

As the EU conducts negotiations on a 2040 climate target and the post-2030 policy architecture, a comprehensive understanding of the composition of residual emissions and their implications is essential. The EU Commission's legislative proposal (COM/2025/524) published in July 2025 upholds the 90% net GHG reduction target by 2040 recommended in the 2024 Communication (COM/2024/63), while introducing additional flexibilities. These include the incorporation of international credits, effectively lowering the level of ambition domestically, as well as emphasis on enhanced flexibility across sectors to ensure cost-effective mitigation, as a key principle that should be reflected in legislative proposals for the enabling policy framework. In contrast to the legislative text for the agreed 2030 climate target, the proposal also does not indicate the maximum or expected contribution from the land use, land-use change, and forestry (LULUCF) sector, thereby introducing further uncertainty regarding the allocation of the carbon budget across the economy.

Although no formal proposals for agriculture's contribution have been made, the European Commission's impact assessment accompanying the 2040 climate target communication suggests that a 30% reduction in agricultural emissions relative to 2015 levels may be required to meet an overall target of between 90-95% net emission reductions (EC, 2024). Meanwhile, agricultural emissions have declined by only 5% between 2005 and 2022 and are projected to decrease by a further 2% by 2030 under the additional measures currently planned by EU Member States (EEA, 2024). This suggests that the sector is not currently on a trajectory aligned with the 2040 target and is unlikely to deliver emission reductions necessary for the achievement of an economy-wide 90% net reduction target without further policy measures.

2. EXPLORING POTENTIAL LEVELS AND PROFILE OF RESIDUAL AGRICULTURAL EMISSIONS IN THE EU – SCENARIO OVERVIEW

The positioning of agriculture as a hard-to-abate sector will have implications for the policy measures considered within the post-2030 EU climate policy framework. In this context, this analysis aims to bring together a selection of scenarios developed for the EU agricultural sector to understand the variation in residual emissions across different pathways, their composition with respect to sub-sectors and emission sources, and the scenario characteristics that drive those variations. Through this analysis, it aims to contribute to identifying the key entry points for the discussion on the policy pathways for the sector and the profile of EU agricultural production in a net-zero economy.

The analysis focuses on scenario outcomes with regards to selected sources of agricultural emissions with the largest GHG impacts, including enteric fermentation, manure management, and N_2O emissions from managed agricultural soils. These categories warrant particular attention given their significance and close interdependence, although any changes in these activities will also impact other related emission sources.

The analysis does not consider emission pathways or mitigation measures for sources reported under the land use, land use change, and forestry (LULUCF) category, such as croplands and grasslands, even though these emissions are directly linked to agricultural land management. In particular, the analysis does not comment on measures and trajectories for emissions from peatlands (organic soils) under agricultural production, which are indirectly reflected under these two LULUCF reporting categories and present an important mitigation opportunity given their high mitigation potential per hectare over a short timescale. While data on emissions from organic soils has not been consistently reported by EU Member States, emissions from organic soils under agricultural production were estimated to be around 108 $MtCO_2e$ in 2020 (Agora Agriculture, 2025).

The analysis also excludes energy emissions from agricultural production associated with heating, hot water generation, machinery, and other sources. These emissions are reported together with other "small-scale fuel combustion" sources in the forestry and fishing sectors, and were reported to amount to approximately 75 $MtCO_2e$ across these sectors in 2023. Finally, the analysis does not cover the broader GHG impacts of the EU food system or product “embedded” emissions, including upstream or downstream emissions linked to agricultural production, such as from e.g. land conversion and fertiliser use associated with imported feed crops, or fertiliser manufacturing.

Table 1. Key agricultural GHG emission sources

IPCC reporting category	GHG Source/ Activity	GHG			Emissions (2023, $MtCO_2e$)
		CH_4	N_2O	CO_2	
3. AGRICULTURE	3.A Enteric fermentation	x			179,5
	3.B Manure management	x	x		62,6
	3.C Rice cultivation	x		x	2,3
	3.D N_2O emissions from managed agricultural soils		x		108,9
	3.F Burning crop residues	x	x		0,8
	3.G Liming			x	5,2
	3.H Urea application			x	3,5
	3.I Other carbon-containing fertilisers			x	0,6
	3.J Other agricultural emissions[1]	x	x		1,6
4. LULUCF	4.B Croplands			x	34,4
	4.C Grasslands			x	13

The scenarios selected for the analysis are drawn from four sources, with the aim of providing a representative overview of different pathways for the transformation of the EU agricultural sector through 2040–2050 and possible levels of residual emissions in agriculture. The selected scenarios reflect varying preferences and assumptions regarding efficiency trajectories, the adoption of emission mitigation technologies, the role of agroecology, and shifts in consumption patterns. The selection prioritised both the breadth of potential

[1] For example, emissions associated with storage of digested residues.

pathways and outcomes, as well as the recency of publication and the level of detail available regarding scenario assumptions.

I. 2040 target IA: The Impact Assessment accompanying the European Commission's Communication on the 2040 climate target (EC, 2024a)

The scenarios in the Impact Assessment accompanying the Communication on the EU climate target for 2040 are developed in the context of the European Climate Law, which mandates the achievement of climate neutrality by 2050. The assessment evaluates possible sectoral GHG reduction contributions towards a selected range of possible EU-wide GHG levels in the year 2040, without making assumptions about the post-2030 EU policy framework.

The assessment sets out to evaluate different 2040 target options based on their ability to deliver on seven specific objectives: ensuring the delivery of climate neutrality; minimising the EU's cumulative GHG budget; supporting a just transition; safeguarding the long-term competitiveness of the EU economy; providing predictability for the deployment of best-available, cost-effective, and scalable technologies; ensuring the security of energy and resource supply; and achieving environmental effectiveness.

It presents three core scenarios, along with a sensitivity analysis:

– Scenario 1 (S1): a net GHG reduction target of up to 80% for 2040: The first policy scenario relies on the Fit-for-55 energy trends delivering a "linear" reduction path between 2030 and 2050. No specific mitigation of non-CO_2 emissions is foreseen under this scenario up until 2040.

– Scenario 2 (S2): a net GHG reduction target of 85-90% for 2040: The second policy scenario builds upon the Fit-for-55 energy trends presented in scenario S1 while foreseeing a higher level of ambition in the land sector, i.e., deeper non-CO_2 emission reductions in agriculture and higher land carbon removals. These policy measures are complemented with a more widespread deployment of industrial carbon capture and e-fuels.

– Scenario 3 (S3): a net GHG reduction target of 90-95% for 2040: The third policy scenario builds on the second scenario, while adding a "fully developed carbon management industry" by 2040, with carbon capture covering all industrial process emissions.

– Complementary variant: The LIFE scenario is designed to reach net GHG reductions of at least 90%, demonstrating how demand-side measures can complement supply-side technologies, while allowing a direct comparison with the overall level of emission reductions in scenario S3. In the context of the EU's food system, this scenario assumes a consumption shift towards more sustainable and healthy diets, with food production following the Farm to Fork and the Biodiversity Strategy objectives, alleviating pressure on land and resulting in additional land-based carbon sequestration.

The central premise of the Commission's modelling is a cost-benefit approach to technology adoption. In the LULUCF and agricultural sectors, post-2030 emission reductions are driven by the application of a carbon price, which is the main factor steering decisions of economic actors with regards to the implementation of mitigation technologies. The carbon price is applied in combination with information on marginal abatement costs (MACs) (representing the cost of reducing one tonne of GHG emissions through individual climate mitigation interventions), derived from literature and existing models. On this basis, the uptake of mitigation measures is estimated, and the resulting residual emissions are calculated.

The Impact Assessment relies on a suite of interlinked models commonly used by the European Commission, Member States, and other stakeholders. These models have previously supported the Commission's proposals for the Long-Term Strategy, the 2030 Climate Target Plan, and the Fit-for-55 package. For the agricultural sector, key models include CAPRI, a global agro-economic model used to assess policy impact on agricultural activity and the environment (e.g., emissions, nutrient balances, and biodiversity); GAINS, a tool for the evaluation of costs and benefits of non-CO_2 GHG mitigation; and GLOBIOM, a land-use model that integrates agriculture, forestry, and bioenergy sectors.

II. EcAMPA 4: Economic assessment of GHG mitigation policy options for EU agriculture (Pérez Domínguez et al., 2025)

Economic Assessment of GHG Mitigation Policy Options for EU Agriculture (EcAMPA) was developed to evaluate the key considerations and impacts of potential integration of agriculture into the EU climate policy framework, through the deployment of a range specific GHG mitigation options in the sector, both technological and management-based. These options are integrated into agricultural economic models and tested under a range of illustrative policy scenarios. As in the case of the Commission's Impact Assessment, EcAMPA uses a set of techno-economic marginal abatement cost curves for selected GHG mitigation technologies at both regional and Member State levels to estimate the mitigation potential of individual technologies and broader policy impacts.

EcAMPA 4, the latest iteration in the series of EcAMPA studies, explores the economic and environmental impacts of GHG mitigation strategies in the

Agriculture, Forestry, and Other Land Use (AFOLU) sectors associated with a set of policy scenarios. The mitigation pathways considered include increased afforestation, reduced wood harvests through adjusted forest management practices, the protection of peatlands and the introduction of carbon pricing incentives within the AFOLU sectors to promote CO_2 removals and reduce methane and nitrous oxide emissions. The considered scenarios aim to support the analysis of policies which "may encompass the adoption of mitigation technologies or farm practices potentially linked to shifts in CAP payments or agri-environmental programs, or the imposition of mitigation targets for the Agriculture and Forestry sectors" (Pérez Domínguez et al., 2025, p.8).

This analysis focuses specifically on the carbon pricing (CP) scenario, which has the strongest focus on agricultural emissions among the scenarios outlined in the study and uses distinct carbon prices for the agriculture and LULUCF sectors.

The policy scenarios are simulated using the CAPRI model, employing the 2030 EU Medium-Term Agricultural Outlook (EC, 2020) as the baseline. The analysis extends to 2040 and 2050 using long-term projections from the GLOBIOM model.

III. Agora Agriculture: Agriculture, forestry and food in a climate neutral EU (Agora Agriculture, 2024)

The scenario developed by Agora Agriculture (2024) outlines a possible trajectory for the future of EU agriculture and forestry within the framework of the EU's climate neutrality objective. It presents a comprehensive pathway for the EU land use sectors that accounts for interactions between the food system, and the bioeconomy, all within the context of global markets for agricultural and forestry products.

While the scenario models climate neutrality by 2045 in line with Germany's legally binding target, the results are considered equally applicable to the EU's 2050 climate neutrality goal, in practice allowing an additional five years for the implementation of the proposed measures.

The scenario relies on two main building blocks: 1) a more sustainable demand for food, feed, and other biomass; and 2) efficient land use to optimise outcomes under a given demand trajectory, by mitigating trade-offs and maximising benefits. A GHG emissions tax is introduced to encourage the adoption of mitigation practices and support cost-effective transitions in production. The scenario also incorporates exogenous (i.e. determined outside of the model) assumptions about land use changes and evolving consumption patterns.

Quantitative analysis is primarily conducted using the CAPRI model, supplemented by qualitative scenario narratives and additional calculations to address areas not fully covered by CAPRI, which include the production of biomass for energy and material use on agricultural land, as well as changes in forest management, such as afforestation.

The scenario is unique among those analysed in that for each theme (biomass, food demand, livestock farming, arable farming, agricultural peatlands, and forest management) it proposes concrete policy solutions aimed at creating an enabling environment to support the envisioned transition.

IV. TYFA: Ten Years For Agroecology modelling exercise (Poux & Aubert, 2018; Aubert, Schwoob & Poux, 2019)

The TYFA project (Ten Years for Agroecology) differs from the other three scenarios analysed in that it does not take EU carbon neutrality as its starting point or seek to maximise GHG emission reductions as a primary objective, focusing, rather, on biodiversity conservation in farmed landscapes. It is designed to test the plausibility of an agroecological transition and a transformation of the EU food system, considering both consumption and production dimensions.

Its central research questions are: what level of agricultural production is compatible with the multifunctional assumptions associated with agroecology and the conservation of semi-natural habitats, including the principle of closing nutrient cycles at the lowest possible territorial level, and whether such a level of production would be sufficient to feed the European population or even generate a surplus, under specific dietary conditions.

Accordingly, the scenario explores the feasibility of scaling up agroecological practices across Europe, including the phasing out of synthetic fertilisers and pesticides, the preservation of total permanent grasslands area, the expansion of agroecological infrastructure, and the suspension of plant protein imports. It aligns agricultural output with adjusted dietary patterns, notably a shift toward healthier diets featuring reduced animal product consumption and increased intake of fruits and vegetables.

The original TYFA scenario (Poux & Aubert, 2018) was later complemented by an alternative variant, TYFA-GHG (Aubert, Schwoob & Poux, 2019), developed to enhance the climate performance of TYFA without altering significantly its underlying agroecological philosophy. TYFA-GHG focuses on reducing GHG emissions by decreasing the size of the cattle herd, thereby lowering emissions from enteric fermentation, without reducing the area of permanent grasslands, which remain essential for biodiversity conservation, the protection of natural resources, and effective nutrient cycling.

The scenarios are underpinned by the dedicated quantitative model TYFAm, which comprises five interconnected modules covering crop production, livestock systems, food demand, non-food biomass uses, and nitrogen flows. Notably, as TYFA was published earlier than the other scenarios analysed, its projections are based on the EU-28 (including the UK) as the unit of analysis.

Table 2. Summary of analysed scenarios: modelling drivers and GHG outcomes

		Exogenous dietary shift assumptions	Cost-benefit integration of efficiency-focused climate mitigation measures	Exogenous land use assumptions	End date	Carbon value - non-CO_2 emissions from agriculture (EUR)	Carbon value - LULUCF emissions (EUR)	Remaining emissions from agriculture (Mt CO_2e)	GHG reduction compared to 2023 emissions
2040 target IA	**S2**	No	Yes	No	2040	50	50	302	
					2050	470	50	**249**	**32%**
	S3	No	Yes	No	2040	290	50	271	
					2050	470	50	**249**	**32%**
	LIFE	Yes	Yes	No	2040	250	50	209	
					2050	470	50	**194**	**47%**
EcAMPA 4	**CP scenario**	No	Yes	No	2050	100	2.5	**275**	**25%**
Agora Agriculture	**Agora Agriculture**	Yes	Yes	Yes	2045/ 2050	200	100	**150**	**59%**
TYFA	**TYFA main**	Yes	No	Yes	2050	N/A	N/A	**243**	**33%**
	TYFA-GHG	Yes	Yes	Yes	2050	N/A	N/A	**203**	**44%**

Note: As the Commission's IA was released in the context of the 2040 target recommendation, some of the relevant assessment data have been presented with greater granularity for 2040 than for 2050. Accordingly, the analysis and tables in this paper include data points for both 2040 and 2050, even though the remaining emissions in 2040 are not considered "residual".

3. FOOD DEMAND AND CONSUMPTION PATTERNS

The analysed scenarios broadly adopt two distinct approaches to modelling food consumption shifts. The first involves the implementation of an exogenous change in consumption based on nutritional and environmental considerations, whereby the composition of the average diet in the target year is predetermined and imposed on the model. The second assumes a business-as-usual development of diets in the EU, based on observed trends and projections, with the EU Agricultural Outlook serving as the primary reference. In the latter case, changes in dietary patterns occur endogenously within the model, driven by rising producer prices and, consequently, higher consumer prices.

The *Agora, TYFA* and the Commission's *LIFE* scenarios assume an exogenous shift in consumption based on health and environmental rationales, and therefore all assume a reduction in the consumption of animal products. Lower intake of meat and dairy is compensated for by increased consumption of cereals, oilseeds, and vegetables – although the extent of these shifts varies considerably between scenarios.

All three scenarios incorporate nutritional guidelines in constructing their average target diets, albeit through different methodological approaches:

- The *LIFE* scenario assumes "a gradual 25% shift" towards an "optimal, sustainable and healthy diet" by 2040, as defined by the EAT-Lancet Commission (Willett et al., 2019).
- The *Agora* scenario calculates the target food intake by applying a weighted average: 80% based on the EAT-Lancet Planetary Health Diet, including calculations from Springmann et al. (2018), and 20% based on 2020 consumption patterns in each EU Member State.
- The *TYFA* scenario integrates dietary recommendations from the European Food Safety Authority and the World Health Organization. To preserve the cultural consumption profile, it builds on a reconstructed 2010 average food matrix, with key changes in protein sources, sugar, and fruit and vegetables.

None of these scenarios specify precise drivers behind the projected shifts in consumption patterns. Rather, they refer to broader societal trends, such as the increasing relevance of alternative proteins, evolving social norms and preferences, voluntary actions, and, in the case of *Agora,* highlight the need for enabling policy frameworks that support consumers in making more sustainable food choices.

The EcAMPA 4 and the Commission's S2 and S3 scenarios adopt a different approach, building on the EU Agricultural Outlook to establish the baseline (EC, 2020, for EcAMPA 4; EC, 2022, for S2 and S3). In the case of EcAMPA 4, the Outlook projections form the basis of the reference scenario (REF), with changes in consumption in the target year under the CP scenario estimated relative to the REF based on the expected consumer behaviour shift in response to a change in food prices induced by the introduction of a carbon price. This is not the case in the Commission's S2 and S3 scenarios which, notably, do not account for the effects of a carbon price on production volumes or consumer prices; consequently, no consumer response to changing food prices is captured.

Table 3. Selected dietary and food waste-related assumptions and outcomes

		Exogenous dietary shift assumptions	Total caloric intake[2] (kcal)	Livestock products consumption (per capita per day)[3]		Exogenous shift in food waste	End date	Remaining emissions from agriculture (Mt CO_2e)
2040 target IA	**S2**	No	2109	Beef	45 kcal	Extrapolation of existing EU policy framework (prior to the revision of the Waste Framework Directive)	2040	302
				Other meat	258 kcal			
				Milk and dairy	382 kcal			
	S3	No	As above	As above		As above	2040	271
	LIFE	Yes	2108	Beef	35 kcal	11 Mt reduction relative to 2020 levels (10% reduction at processing level 30% at retail and consumption stages)	2040	209
				Other meat	210 kcal			
				Milk and dairy products	337 kcal			
Ec MP	**CP**	No	Unavailable	Beef	-3,2% (EU total consumption in	Not included	2050	275

[2] Excluding alcoholic beverages.
[3] The analysed studies do not consistently report caloric or weight data for all food categories; values are presented in kilocalories and grams as available.

					volume, compared to REF[4])			
				Pork	+0,2%			
				Poultry	+0,5%			
				Milk & dairy	Unavailable			
Agora Agriculture	**Agora Agriculture**	Yes	2140	Beef	22 kcal (10g)	50% reduction at the retail and consumption stage relative to 2020 levels	2045/ 2050	150
				Milk and dairy	233 kcal (367g in milk eq.)			
				Pork	71 kcal (25g)			
				Poultry	63 kcal (37g)			
TYFA	**TYFA main**	Yes	2265	Meat	166 kcal	10% reduction relative to 2010 levels	2050	243
				Beef	29 g			
				Pork	36 g			
				Poultry	20 g			
				Dairy products	137 kcal (300g in milk eq.)			
	TYFA-GHG	Yes	app. 2250	Meat	147 kcal	As above	2050	203
				Beef	24g			
				Pork	35g			
				Poultry	20g			
				Dairy products	114 kcal (250g in milk eq.)			

[4] Caloric (kcal) data for the REF and CP diet profiles are not available; only relative changes in total consumption of selected products by volume are reported in the EcAMPA 4 study.

Baseline 2020 consumption data used for comparison in the text of the chapter are sourced from EC (2024a).

The varying degrees to which the EAT-Lancet Commission's Planetary Health Diet (PHD) is integrated into the *LIFE* and *Agora* scenarios translate into different average daily meat consumption targets, which are set at 245 kcal in the *LIFE* scenario and 159 kcal in the *Agora* scenario, notably exceeding the PHD's recommendation of 105 kcal[5]. These figures correspond to a 20% reduction in meat consumption relative to 2020 levels in *LIFE*, and a 46% reduction in *Agora*. The consumption of beef – given its high emissions per unit – is reduced significantly in both scenarios: by 54% in *Agora* and 27% in *LIFE*. The proportion of beef within total meat consumption remains similar (13% in *Agora*, 14% in *LIFE*).

The *TYFA* scenario differs significantly in both the underlying rationale and outcomes. It is driven to a lesser degree by a climate mitigation rationale than the other scenarios, and it centres the role of ruminants in nitrogen cycling and permanent grassland maintenance. Although ruminants are high-emission livestock, their ability to subsist on non-human-edible feed and contribute to natural nitrogen cycles is a deciding factor in their inclusion in *TYFA*.

As a result, the target beef consumption in *TYFA* is projected at 68 kcal in 2050 – and while this represents a slight decrease from 2010 levels, it is above 2020 beef consumption levels, EU Agricultural Outlook projections, and thresholds set in the other scenarios. The *TYFA-GHG* variant, which targets more direct emissions reductions, lowers overall meat consumption by 7g compared to the main TYFA scenario, with beef responsible for 6g of this decrease – yet the resulting beef consumption levels remain above the 2020 rate of 48 kcal per capita per day.

Notably, the relationship between the change in beef vs dairy intake rates is different in each of the three scenarios that incorporate an exogenous shift in consumption. While beef consumption in *TYFA* remains at an elevated level, the dairy consumption declines by 62% (in kcal terms) by 2050 compared to 2020 levels. This dynamic reflects the scenario's emphasis on conserving permanent grasslands facilitated by the extensification of dairy, with a higher ratio of meat to milk output serving as an indicator of lower production intensity (see e.g. Röös et al., 2016). The numbers of cattle other than dairy are adjusted to maintain the same total grassland area under grazing as in 2010.

In contrast, the *Agora* scenario sees a 43% decline in dairy intake – somewhat less sharp than the 54% reduction in beef – while the LIFE scenario shows only a 7%

[5] Based on Rockström et al. (2025). The earlier iteration of the EAT-Lancet Commission's report recommended 92 kcal (Willet et al, 2019).

decline in dairy consumption, compared with a 27% drop in beef. These shifts result in projected dairy intakes of 337 kcal in *LIFE*, 205 kcal in *Agora*, and 137 kcal in *TYFA*, against the Planetary Health Diet benchmark of 145 kcal[6].

Consistent with *TYFA's* prioritisation of ruminants over monogastrics, pork and poultry consumption is reduced by a greater degree than beef consumption. This contrasts with typical assumptions in climate transition scenarios, where ruminant meat is usually reduced more sharply than white meat. It also diverges from the observed EU trends, where beef consumption is declining and poultry consumption rising, driven by environmental, health and price considerations (EC, 2023). The *Agora* scenario, while showing a decline across all meat types, offers a slightly more conventional outlook by modelling a much less pronounced decline in the poultry category compared to beef and pork, citing higher feed conversion efficiency and a favourable consumption trend.

To compensate for the reduction in animal-based proteins and calories, all scenarios project increased consumption of cereals, legumes, fruits, and vegetables. The increased intake of legumes serves both nutritional and environmental objectives, given the role of legumes in protein provision for food and feed. In *TYFA*, forage legumes in crop rotations and in grassland are essential for enabling symbiotic nitrogen fixation as a prerequisite for phasing out synthetic fertilisers, while in the *Agora* scenario their importance is also linked to the growing market for plant-based meat alternatives, alongside their broader contribution to sustainable agricultural systems. Legume consumption rises to 90g (173 kcal) in *Agora* – over an elevenfold increase from the 2020 average of 8g – and to 30g (100 kcal) in *TYFA*, a more than threefold increase.

Fruit and vegetable consumption in *TYFA* and *Agora* is comparable in quantity: 400g and 516g, respectively. However, energy content differs markedly – 331 kcal in TYFA versus 201 kcal in *Agora* – possibly due to differing ratio of fruit versus vegetables, although *TYFA* does not provide disaggregated data. In weight terms, this rise in fruit and vegetable consumption represents an app. 150% increase compared to 2020, equivalent to an annual growth rate of 4%. The *LIFE* scenario does not provide specific figures for these categories.

Changes in consumption in scenarios which do not build on nutritional recommendations as an input into modelling are much more modest. In the Commission's projected evolution of per capita calorie intake in the EU for scenarios S2 and S3, beef consumption decreases by just 3 kcal (–6%), and 'other

[6] Based on Rockström et al. (2025). The earlier iteration of the EAT-Lancet Commission's report recommended 153 kcal (Willet et al, 2019).

meat' by 1 kcal (–0.4%) between 2020 and 2040, while milk and dairy consumption increases by 20 kcal (+6%). While these projections generally reflect a continuation of current trends, based on the Commission's Agricultural Outlook 2022, the assumed 6% increase in dairy consumption against 2020 levels (in kcal terms) appears to diverge from the Outlook, which shows an overall slight decline of 0,3% per year through to 2032, based on kg of milk equivalent. This may mean that the EU consumption of dairy is exaggerated, although drawing definitive conclusions is difficult, as the discrepancy is not addressed in the IA.

Changes in food demand driven by price increases in *EcAMPA 4* remain limited. The *EcAMPA 4 CP* scenario projects a 3.1% decrease in beef consumption relative to the reference scenario (*REF*, which assumes continued agricultural development based on existing market trends and policy frameworks[7]), while pork and poultry consumption increase slightly, by 0.2% and 0.5% respectively. These shifts are explained by increased beef prices prompting consumers to substitute beef with more affordable options such as poultry and pork. There are also very small increases in consumption of pulses (0.8%) and fruits (0.1–0.2%).

[7] EcAMPA 4 REF scenario draws on the 2020 EU Agricultural Outlook, with the CAPRI model calibrated to the Medium Term Outlook produced by the Aglink-Cosimo model in house),

4. AGRICULTURAL PRODUCTION AND TRADE IMPLICATIONS

Overall livestock activity decreases across nearly all analysed scenarios. This reduction is driven variously by changes in producer prices, exogenous shifts in demand, or adjustments in production intensity. The only exceptions are scenarios S2 and S3 in the Commission's Impact Assessment, which show a slight increase in meat production – from 43 Mt in 2020 to 45 Mt in 2040 – based on projections from the EU Agricultural Outlook extrapolated into the future.

Table 4. EU supply of animal-based products

		Milk and meat production (Mt)		End date	Remaining emissions from agriculture (Mt CO_2e)
2040 target IA	S2	Meat	45	2040	302
		Raw milk	161		
	S3	As above		2040	271
	LIFE	Meat	34	2040	209
		Raw milk	145		
EcAMPA 4	CP	Beef	5.4	2050	275
		Dairy	155		
		Pig meat	22		
Agora Agriculture	Agora Agriculture	Meat	22	2045/2050	150
		Beef	3		
		Dairy	106		
		Pig meat	9		
		Poultry	10		
TYFA	TYFA main	Beef	6	2050	243

		Pig meat	7		
		Poultry	3		
	TYFA-GHG	Comparable data unavailable		2050	203

The *TYFA, Agora Agriculture,* and *LIFE* scenarios all exhibit declines in livestock herds and animal-source food output due to market adjustments stemming from reduced demand. The lowest projected meat production levels for the target year are featured in the *TYFA* and *Agora* scenarios, representing app. 50% drop from 2020 meat production levels (20 Mt and 22 Mt, respectively, down from 43 Mt (EC, 2024b)). The *LIFE* scenario projects final meat production approximately midway between current levels and the reductions seen in *TYFA* and *Agora*.

Although overall production levels in the *Agora* and *TYFA* scenarios are similar, the composition differs: pig production levels are comparable, but poultry production in *Agora* is roughly double that in *TYFA*, while beef production in *TYFA* is about twice that of Agora.

EcAMPA 4 CP also shows an overall decrease in meat production, though to a much smaller extent, owing to limited demand effects of carbon pricing, resulting in an app. 8% reduction in beef supply, 2,5% reduction in pig meat supply, and less than 1% reduction in poultry supply compared to the REF scenario.

In the case of milk production, the S2 and S3 scenarios show levels very close to those from 2020 (160 Mt of raw milk), while the EcAMPA 4 scenario shows a minimal decrease compared to 2020 levels (-0,03%). The *LIFE* and *Agora* scenarios demonstrate larger decreases in dairy production, of -9% in the case of *LIFE* and -34% in the case of *Agora.*[8]

While the supply of beef and dairy products declines as cattle populations fall, the relative extent of these reductions differs in each scenario. A marked 71% decline in beef cattle production in *Agora* is attributed to the fact that beef is a by-product of milk production. Because milk consumption declines less than beef consumption, the relative share of beef cattle falls, leading to a significant reduction in suckler cow husbandry. In contrast, *TYFA*'s herd management strategies increase, rather than decrease, the beef-to-dairy ratio, at the same time

[8] Comparable production values are not provided for TYFA, which only discloses Mt of dry matter number for milk production.

as an expansion of dairy herds is simulated relative to 2010, in order to preserve a similar area of grassland.

The differing relative rates of decline in beef and dairy production between the *TYFA* and *Agora* scenarios can also be directly attributed to diverging assumptions about milk yields. While *Agora* forecasts improved efficiency with yields per cow increasing to 7,700 litres in 2045*, TYFA* assumes reduced yields due to extensification, with a higher number of animals (heifers and calves) per unit of milk, and average yields reduced to approximately 5,335 litre per head, or about one-third less than the *Agora* average.

In the case of plant-based food production, both the *TYFA* and *Agora* scenarios anticipate an expansion in fruit and vegetable production, enabled by increased land availability and rising demand. In *TYFA*, fruit and vegetables are the only two categories in which output increases, as the total production of all plant-based food and feed biomass declines by approximately 30% relative to 2010, due to a reduced need for feed and a reduction in yields accompanying the transition to organic farming methods.

Qualitatively, the *TYFA* scenario envisions the development of fruit and vegetable crops across Europe, supporting more localised, rainfed, and seasonal production systems. This leads to a form of de-specialisation in Mediterranean regions, which are currently major consumers of irrigation water for fruit and vegetable cultivation. Overall, land under permanent crops is projected to increase by 30% due to rising fruit consumption, while the area under fresh vegetable production doubles (based on seasonal production methods, without an increase in heated greenhouse area). In relative terms, the share of cereals declines in favour of protein crops and green-harvested legumes such as alfalfa and clover, which together occupy approximately one-quarter of arable land. Silage maize production also decreases, reflecting a shift towards a grass-fed approach in dairy farming.

In the *Agora* scenario, to support overall economic outcomes, the production of fruit and vegetables increases significantly, as the intake of these food groups doubles. This is in line with the rationale that fruits and vegetables offer high added value per hectare and can generate new market opportunities. As the study notes, in 2017, 1.2% of the EU's utilised agricultural area was used for the production of fresh vegetables, and approximately 1.9% was used for fruit cultivation. However, the total value of the EU's output of fruit and fresh vegetables at basic prices represented 14% of the value of all agricultural goods and services produced in the EU that year (Eurostat 2019, in Agora Agriculture, 2024). Accordingly, under the *Agora* scenario, domestic production increases by 31% for vegetables, 53% for fruits, and 187% for pulses and soya compared to

2020, in order to maximise the associated economic potential. In contrast to TYFA, the share of land under permanent crops remains largely unchanged in the *Agora* scenario, although the proportion allocated to fruit trees increases.

EcAMPA 4 makes no observations regarding the possible development of fruit and vegetable production – or legumes – although introducing legumes into grasslands and rotations is among the mitigation technologies applied. Overall, the study indicates that the carbon price leads to considerable negative impacts on both crop and livestock production levels. In the crop sector, EU oilseed production (predominantly rapeseed) is relatively the most affected by the carbon price.

Notably, despite the assumed increase in the intake of plant-based foods, the *LIFE* scenario shows decreases in EU production of most crop categories, including cereals, vegetables, and permanent crops, while the production of oils and oilseeds shows a slight increase. The lack of additional supply in response to increased demand may be explained by the existing barriers to increasing the competitiveness of EU fruit and vegetable production internationally, although this is not made explicit in the Impact Assessment.

Food availability

The question of food production and the closely related question of food availability under different climate mitigation scenarios have increasingly been invoked as an issue of food security in the EU. Concerns in this area are often rooted in differing – and not always clearly articulated – perspectives on what constitutes food security.

Food availability constitutes one dimension of food security, alongside other dimensions which are equally important in determining whether populations experience food insecurity, including access to food, utilisation, as well as stability and sustainability of food systems (FAO, 1996; HLPE, 2020).

While all of these dimensions warrant attention, at present, food availability in the European Union is not at risk. The EU remains largely self-sufficient in key agricultural commodities and continues to generate production surpluses, maintaining its position as a net exporter of food products in terms of value (EC, 2024b). It is a major exporter of wheat and barley and is broadly capable of meeting domestic consumption needs for other staple crops such as maize and sugar. It is not only largely self-sufficient in animal products, but also ranks among the world’s top dairy exporters.

However, a key vulnerability in the EU's agri-food system lies in its reliance on imported high-protein animal feed. The EU exhibits low self-sufficiency in high-protein crop production, relying on imports to meet approximately two-thirds of its needs. The EU is also dependent on imports for other key agricultural inputs, notably fertilisers. Fertiliser prices are closely linked to energy markets, with nitrogen fertiliser production being especially energy intensive. In 2022, rising fertiliser prices and supply constraints driven by energy market volatility raised significant concerns about food production across Europe (EC, 2022).

In the context of the need to reduce emissions, continued global population growth and the influence of input prices on agricultural production have led some to argue that the key to ensuring food security lies in producing more food, but in a more efficient manner, with lower GHG impact per unit of production, particularly in the context of animal-source foods. This approach, commonly referred to as sustainable intensification or the production pathway (Alexandratos & Bruinsma, 2012; Cole & McCoskey, 2013; Garnett, 2014; Garnett et al., 2013), is reflected in the core scenarios S2 and S3 of the 2040 target IA, as well as the EcAMPA CP scenario. These scenarios largely maintain existing levels and the current profile of agricultural production, achieving emission reductions primarily through technological and efficiency-oriented mitigation strategies. Their emphasis on supply side measures results in limited or no use of shifts in consumption patterns and food waste reduction as levers to enhance food availability. These approaches reduce emissions per unit of output and, in the conditions of largely stable production levels, also result in reductions in absolute emissions – although the total emission reductions achieved in these scenarios are lower than those driven by exogenous dietary shift assumptions and they do not provide comparable co-benefits for other environmental dimensions.

As indicated in the EU Agricultural Outlook projections, dietary patterns and the resulting demand play a crucial role in food availability and self-sufficiency. Reducing both food waste and the share of animal-source food in diets can significantly enhance the resource-use efficiency of food production and contribute to improved food security (Bodirsky et al., 2020). A reduction in animal production, along with lower meat and dairy consumption would substantially increase the availability of cereals for direct human consumption, thereby improving food security potential (EEA, 2024). These dynamics are also demonstrated in the analysed demand-driven scenarios.

In the case of the *TYFA* scenario, the question of food-feed competition and its negative impacts on food security and the environment is central to how the scenario is constructed, with a key aim of minimising this competition to the furthest degree possible. As monogastric animals (e.g., pigs and poultry) consume cereals and protein crops that directly compete with human food production, *TYFA* sets out to minimise their role in the target diet and models a significant reduction in their numbers, with indirect climate mitigation and environmental benefits, not least related to reduced feed demand. In contrast, ruminants – due to their ability to convert grassland biomass, which is inedible for humans, into nutrient-dense food – are considered desirable and are retained in the model at levels consistent with 2010 beef production. Under these and other assumptions set out in the *TYFA* scenario, a key finding is that agricultural production (including both crops and livestock) remains sufficient to meet European food demand in 2050, despite an overall reduction in production volumes amounting to a total 30% decline in caloric terms.

It should be noted that *TYFA*'s assumptions regarding food-feed competition associated with pig and poultry production and their consequent undesirability are based on the most common existing practices and do not reflect the potential of extending the concept of low-opportunity-cost livestock feed to monogastrics. Such feed would include co-products from the industrial processing of plant and animal sources, as well as food system losses and waste. Monogastric animals, particularly pigs, have the ability to consume a wide range of feed sources, and converting these leftover streams into animal protein can effectively recycle nutrients that would otherwise be lost (Garnett et al., 2015). The *TYFA* authors acknowledge that there are alternative ways of feeding monogastrics, particularly within a circular economy framework, and that these animals – being omnivorous – are well-suited to diets based on waste and by-products. While the *TYFA* scenario assumes that 1/6 of monogastric' feed comes from waste, the authors note that the development of a model based on granivorous "recyclers" would represent an interesting avenue for further investigation.

Reducing food-feed competition is also a feature of the LIFE and *Agora* scenarios, although these models adopt a different approach to the contribution of different livestock products in the average target diet by reducing the share of cattle-derived products within overall animal-source food intake. Nonetheless, as the *Agora* study elaborates, despite a projected near-halving of meat production in the EU between 2020 and 2045, per capita protein availability is expected to increase – even after accounting for the lower bioavailability of plant-based proteins compared to animal-derived proteins. The reduced demand for animal feed leads to a 55% decrease in feed imports by 2045, freeing up arable land abroad with the potential for it to be used to meet the food needs of local populations or other importing countries.

Critically, all three demand-driven scenarios demonstrate that sufficient food availability can be maintained to meet nutritional needs of EU citizens while significantly reducing the use of mineral fertilisers. *TYFA*, in particular, illustrates the possibility of eliminating dependence on mineral or extra-EU nitrogen fertiliser imports altogether, contributing to the self-sufficiency and stability dimensions of the EU food system, as well as offering benefits for the EU's trade balance.

Food supply under conditions of a changing climate

Climate change is already affecting agriculture in Europe through rising temperatures and shifting precipitation patterns. These changes have led to the northward migration of agro-climatic zones, an earlier onset of the growing season, and notable variations in crop yields, forest productivity, and livestock performance. Although crop yields in Europe have historically followed an upward trend, recent studies suggest that climate change has contributed to a stagnation in yield growth, particularly in Western Europe (e.g. Moore & Lobell, 2015). The combined effects of heatwaves, droughts, and excessive rainfall have increased production costs, caused substantial disruptions to agricultural production (e.g. Webber et al., 2018), and led to significant economic losses in both annual and perennial crops.

The JRC PESETA IV study (Feyen et al., 2020) indicates that some of the negative impacts of climate change on crops such as wheat, barley, and sunflower could be partially offset by higher atmospheric CO_2 concentrations. However, while this effect may be observed in parts of Northern Europe (albeit with considerable model uncertainty), it is unlikely to benefit Southern European Member States, where declining water availability under projected climate scenarios significantly constrains crop yields (Hristov et al., 2020). According to the study, at 2°C of global warming, irrigated maize yields in Southern Europe could decline by more than 10%, while under rain-fed conditions, maize yield losses could reach 20% across the EU, and up to 80% in some Southern European countries. For wheat, the projections are more uncertain, primarily due to variability in precipitation forecasts, as wheat is largely dependent on rain-fed agriculture. Under the high-emissions RCP8.5 scenario, yields are projected to increase by 5–16% in Northern Europe but decrease by up to 49% in Southern Europe by 2050. While losses are projected to be somewhat lower under a 1.5°C warming scenario compared to 2°C, the study also notes that these estimates likely underestimate the impacts of extreme weather events, including heat stress and droughts.

In addition, while elevated CO_2 concentrations in the atmosphere may support plant growth, resulting in increased yields in some regions, they have also been associated with a decrease in protein content (Taub & Wang, 2008), as well as reduced presence of key minerals such as calcium, zinc, iron, and magnesium in staple crops such as wheat, rice, and barley (Myers et al. 2014).

Overall, climate change is expected to exacerbate the regional divergence in agricultural production across Europe, with significantly declining outputs in the South and potentially increasing yields in the North. This spatial shift could have important implications for intra-EU trade and mutual reliance among Member States (Hristov et al., 2020), while posing challenges to existing production and processing systems (Franke et al., 2022; EC, 2023).

In addition to affecting yields and crop nutritional quality, negative effects compounded by ozone formation resulting from elevated methane emissions, climate variability and extreme weather events can disrupt the broader food system. Increased temperatures and humidity during the post-harvest period shorten storage times, alter product quality during processing, and increase risks to food safety – all of which can contribute to rising food prices (EEA, 2024). These disruptions are likely to threaten the stability of the EU food supply, a core dimension of food security, with potentially wide-ranging socio-economic consequences and implications for EU-wide governance.

The European Commission's 2040 Target Impact Assessment (IA) includes a discussion of findings from the JRC PESETA IV study, citing estimates that illustrate the potential effects of climate change on crop yields in Europe. Despite these findings, however, neither the Commission's scenarios nor the other analysed pathways directly incorporate quantitative estimates of climate change impacts on production at the scale indicated by the PESETA study.

The 2040 target IA notes that the GLOBIOM model includes climate impacts for different EU regions, accounting for both negative effects and potential positive impacts of CO_2 fertilisation. On average, crop yields decrease under all levels/scenarios of global warming, with an average yield decrease of -2.2% in 2050 under an RCP2.6 scenario and -2.6% under an RCP7.0 scenario. The IA explicitly states, however, that these impacts on agricultural productivity in most EU regions appear relatively small when compared to other studies, such as PESETA IV, which estimate significantly larger losses. Furthermore, it remains unclear if and to what extent the GLOBIOM estimates are integrated into the main policy scenarios presented in the IA.

The Agora Agriculture study acknowledges that the impacts of climate change on agriculture and forestry are not analysed in depth. While the CAPRI model used in the study incorporates some effects of climate change into agricultural yield projections, the authors note that the frequency, scale, and impact of extreme weather events remain highly uncertain and are therefore not considered in the scenario. Given that *EcAMPA 4* relies on the same modelling framework and does not explicitly address climate impacts, it is reasonable to assume that similar limitations apply.

In the *Agora* scenario, overall increases in crop yields are projected. The authors recognise that, in light of progressing climate change and soil degradation, such assumptions may appear counterintuitive. However, they are based on expectations of continued advances in agricultural technology, including improvements in machinery, irrigation systems, and plant breeding (Lipper et al., 2018; Senapati & Semenov, 2020). The study also cites Schils et al. (2018), who estimate that grain yields in Europe currently reach only 30–90% of their biophysical potential, suggesting scope for further productivity gains.

The *TYFA* scenario is distinctive in that, unlike other scenarios, it models a decrease in crop yields. This reduction is based on the yield gaps associated with the adoption of organic production methods rather than the impacts of climate change.

The magnitude of the yield reduction for organic agriculture is based on data from Ponisio et al. (2015) and is assumed to remain constant throughout the analysis period up to 2050. This assumption of maintaining current organic yield levels through 2050 is adopted to balance potential yield losses due to climate change with possible productivity gains arising from organic farming innovations. The assumption is considered conservative, given the acknowledged potential for agroecological innovations and existing practices that can be used to minimise yield gaps, as well as caution in accounting for the uncertainties associated with climate impact models and the spatial variability of these impacts.

The *TYFA* study also includes a set of figures derived from a sensitivity analysis assessing the effects of further uniform yield decline of up to 60% relative to 2010 levels, representing a severe climate change scenario that exceeds the adaptive capacity of the agroecological practices envisioned in *TYFA*. Under these conditions, the demand for food and feed surpasses supply, resulting in a shortfall equivalent to approximately 10% of the utilised agricultural area. The authors note that this finding does not fundamentally challenge the overall approach but highlights the need for more careful consideration of land allocation, prioritisation of cereal and dairy exports, and adjustments to the 2050 food balance. This type of sensitivity analysis is not available for the other scenarios reviewed.

In a more qualitative sense, the *TYFA* scenario incorporates climate change considerations by embedding adaptive and mitigative strategies within its pathway. Agroecological practices – such as increased organic matter inputs, reduced use of dewormers, and lower fertilisation rates – are expected to improve soil structure and water retention, thereby enhancing resilience to increased water stress. Although irrigation requirements are not explicitly quantified in the model, water demand is mitigated through structural changes, including diversified crop rotations that reduce reliance on water-intensive crops like maize, greater emphasis on rainfed and seasonal fruit and vegetable production, and promotion of extensified grazing systems with hardy livestock adapted to drier conditions.

While such measures can be expected to enhance yield stability and strengthen the overall resilience of agricultural production, the analysed scenarios do not quantify how different design choices – such as the selection of mitigation measures or the balance between extensive and intensive approaches – affect the relationship between adaptation outcomes and mitigation results.

Trade implications and assumptions

With only minor adjustments in the levels of agricultural output (1-2% change relative to the baseline), trade effects of an increased ambition for S2 and S3 are also limited. In the case that the rest of the world does not implement more ambitious policies, the impact assessment suggests that the EU's role as an importer of agriculture and forestry products will increase in relative terms with an increase in ambition. In the case that other countries follow suit, the model indicates largely the same EU share in global imports in 2050 as was reported in 2020.

The *EcAMPA 4 CP* scenario also points to the potential negative impacts of emission reduction efforts on the competitiveness of EU agriculture, due to carbon pricing and the associated added costs. Domestic prices increase, which leads to a reduction in demand for EU-produced goods, subsequently replaced by cheaper imported alternatives. The associated decrease in agricultural production levels within the EU, and, conversely, increase in production in the rest of the world leads to emissions leakage. The study estimates that, without accompanying policy measures such as e.g., a carbon border adjustment mechanism, carbon pricing as envisaged in the *EcAMPA 4 CP* scenario would result in emissions leakage equivalent to approximately 7% of the EU's gross mitigation.

In contrast, the *Agora* scenario demonstrates that carbon pricing accompanied by shifts in consumption does not lead to a worsening trade balance. A shift in food consumption patterns towards less animal-based protein, results in a substantial decrease in animal feed demand. This reduction – estimated at 46% – leads to a corresponding 49% decline in the area of arable land used for feed crop production within the EU and a 55% reduction in feed imports (Agora Agriculture, 2024). As a consequence, the amount of arable land required in third countries to produce feed for EU markets decreases by approximately 7 million hectares, easing land use pressures and contributing to GHG reductions globally. Driven by the reduced demand for animal feed, the EU's trade deficit in feed grains, oilseeds, and other protein feedstocks declines, while its position as a net exporter of cereals is retained.

Additionally, the *Agora* study emphasises the EU's comparative advantage in dairy production, attributed to its extensive grasslands and favourable climatic conditions. As a result, the decline in EU dairy production is projected to be smaller than the reduction in domestic consumption, leading to a net increase in exports. Meanwhile, reductions in EU pig and poultry meat production closely mirror the decline in domestic consumption, which means the EU position as a net exporter is retained without major changes to the trade balance. As opposed to dairy, the highly standardised nature of pig and poultry production globally diminishes the EU's potential for maintaining a long-term comparative advantage in these sectors.

A sensitivity analysis conducted by *Agora* – applying the scenario's changes to agriculture and forestry without altering 2020 food consumption patterns or reducing food waste – highlights the critical role of demand in determining outcomes related to competitiveness, trade balance, and emissions leakage. Under this alternative scenario, instead of becoming a net exporter of approximately 9 million hectares of virtual land, the EU would become a net importer of around 15 million hectares by mid-century to meet its food needs. The increased imports and decreased exports of agricultural products would lead to higher agricultural production in non-EU countries, resulting in additional greenhouse gas emissions of approximately 59 Mt CO_2e compared to the main *Agora* scenario.

Notably, the impact assessment does not elaborate on the specific impacts of the *LIFE* scenario on the trade balances in agri-food products, even though positive competitiveness and self-sufficiency outcome, similar to those shown in the *Agora* scenario, could be expected as a result of, for example, decreased reliance on imported feed and fertilisers as a result of shifts in production and improved efficiencies.

In the *TYFA* scenario, shifts in food consumption patterns also contribute to reduced pressure on land resources, both within the EU and globally. Trade balances are integrated into the model's assumptions, with one key premise being the restoration of EU protein self-sufficiency, primarily through phasing out plant protein imports.

The *TYFA* scenario simulates an increase in dairy herds which, coupled with a decrease in domestic dairy consumption, results in a surplus of dairy products equivalent to approximately 20% of total dairy production. This surplus is assumed to be available for export, providing similar benefits as in the case of

Agora. *TYFA* also assumes a return to a zero trade balance for products derived from granivore farming (e.g., pigs and poultry), with the value of exports matching that of imports.

The scenario's reduction in granivore production, along with the extensification of ruminant farming, leads to a significant decline in domestic demand for cereals traditionally used as animal feed, allowing the EU to maintain its cereal export capacity. *TYFA* assumes that this surplus production is composed entirely of wheat, with a resulting wheat surplus of approximately 12 million tonnes. This figure is consistent with the average net wheat export levels observed in the EU-28 during the 2000s.

5. IMPACT OF MITIGATION TECHNOLOGIES ON GHG OUTCOMES

Within certain limits, GHG emissions from the agricultural sector can be mitigated through various technologies and management practices that reduce emissions while maintaining current production levels and profiles. Although classifications vary across sources, for the purposes of this overview, cropping practices such as the use of legumes in crop rotations or catch and cover crops are excluded from the "technology" category, as they are somewhat distinct from predominantly efficiency-oriented practices.

Mitigation technologies are explicitly incorporated, to varying degrees, in all of the scenarios analysed except for the main *TYFA* scenario. The following section provides an overview of these technologies as they apply to the livestock and arable sectors.

Table 5: Livestock sector mitigation technologies and management approaches

Mitigation technologies	Description	Scenarios incorporating the specified technologies
Anaerobic digestion	A process that reduces CH_4 emissions from stored manure and N_2O emissions from cattle slurries by using microorganisms to decompose animal waste in an oxygen-deprived environment, yielding biogas that can be used to substitute fossil-based energy sources	2040 target IA EcAMPA 4 CP Agora Agriculture TYFA-GHG
Feed additives	**3-NOP** (3-nitrooxypropanol): acts as a methane inhibitor in the rumen, disrupting enzymes involved in CH_4 production **Nitrate**: acts as an alternative hydrogen sink in the rumen, reducing CH_4 production	**3-NOP**: 2040 target IA, Agora, EcAMPA 4 CP **Nitrate**: Agora, EcAMPA 4 CP **Linseed oil**: Agora, EcAMPA 4 CP **Red seaweed:** 2040 target IA

	Linseed oil: lipids in linseed inhibit hydrogen production and therefore its availability for CH_4 formation **Red seaweed**: acts on enzymes responsible for CH_4 synthesis in the rumen, in a manner similar to 3-NOP	**Unspecified**: TYFA-GHG
Low protein/nitrogen feeding	Reduction in protein, a nitrogen containing compound, in feed reduces nitrogen excretion and consequently NH_3 and N_2O emissions	EcAMPA 4 CP Agora Agriculture
Vaccination	Vaccination triggers the animal's immune system to produce antibodies that supress the growth of CH_4-producing microbes (methanogens) in the rumen	EcAMPA 4 CP Agora Agriculture
Selective breeding	Genetic selection to improve e.g. feed conversion efficiency, reducing required feed intake rate and therefore CH_4 production	2040 target IA Agora Agriculture
Manure additives (acidification)	Acidification reduces the pH of slurry, inhibiting microbial activity and decreasing CH_4 and NH_3 emissions	Agora Agriculture
Slurry removal and cooling	Rapid extraction and cooling of cattle and pig slurry reduces microbial activity, minimizing CH_4 production	Agora Agriculture
Nitrification inhibitors	Nitrification inhibitors, when applied to e.g. pig or cattle slurry or dairy cow feed, block the activity of nitrifying bacteria, slowing down the conversion of ammonium to nitrate and reducing N_2O emissions	Agora Agriculture

Table 6: Crop sector mitigation technologies and management approaches

Mitigation technologies	Description	Scenarios incorporating the specified technologies
Nitrification inhibitors	Nitrification inhibitors, when applied with mineral fertiliser, slow down the transformation of ammonium to nitrate, reducing N_2O emissions	2040 target IA EcAMPA 4 CP Agora
Precision agriculture	Precision agricultural technologies, as applied to crop production, can be defined as "an information and technology-based crop management system to identify, analyse, and manage spatial and temporal variability within fields" (Heimlich, 2003), which allows for an optimisation of inputs and thus GHG emission reductions. Precision technologies include e.g. Variable Rate Technology (VRT), remote sensing technologies, Global Positioning Systems (GPS) and Geographical Information Systems (GIS)	2040 target IA EcAMPA 4 CP Agora
Variable rate technology (VRT)	VRT is a technology that is used to apply a site-specific and variable application of fertiliser (i.e. the rate of fertiliser application is based on the needs of the precise location), and, as such, constitutes a subset of precision farming. However, given broader application scope and lower implementation costs, VRT is separated from precision technologies in the 2040 target IA and Agora studies	2040 target IA EcAMPA 4 CP Agora
Better timing of fertilisation	Better timing of fertilisation aims to align the timing of application of fertiliser or manure with the timing of crop demand, thus minimising fertiliser losses and therefore N_2O emissions.	EcAMPA 4 CP Agora

Scenarios S2 and S3 are the only analysed cases in which GHG emission reductions are achieved solely through the implementation of agricultural mitigation technologies. At the set carbon price of EUR 290 in 2040, the Commission's modelling estimates a maximum total abatement potential of app. 36,3 Mt CO_2e by 2040 for CH_4 emissions from the livestock sector, with the largest mitigation potential associated with the use of feed additives (40%) and selective breeding to improve productivity, fertility, and longevity (36%), followed by farm-scale anaerobic digestion with biogas recovery (24%). A similar overall potential is estimated for N_2O emissions from the crop sector (app. 37,4 Mt CO_2e)[9]. This reduction is achieved solely through the use of nitrification inhibitors (66% of the mitigation potential) and variable rate technology (34%). Notably, precision farming technologies beyond VRT are estimated to only be utilised at carbon prices exceeding EUR 1000 (up to a total of 2,6 Mt CO_2e).

The mitigation technologies considered in the IA enable a reduction of total emissions to 271 Mt CO_2e in scenario S3 by 2040, with a further decrease to 249 Mt CO_2e projected by 2050 as the carbon price increases from EUR 290 to EUR 470 during the 2040s. These GHG outcomes can be compared with the results of the "without additional mitigation" sensitivity analysis conducted for both the core scenarios and the LIFE scenario. Here, "emissions without additional mitigation" refers to the emissions trajectory resulting from applying a carbon price of zero to non-CO_2 GHG emissions up to 2050. Consequently, emissions reductions arise solely from two primary drivers: (a) agricultural policies as reflected in the EU Agricultural Outlook 2022, and (b) existing and proposed legislation[10]. In the case of LIFE, this also includes changes in the food system, such as dietary shifts, food waste reduction, and the gradual implementation of the Farm to Fork Strategy objectives by 2040, which include a reduction in nutrient losses by 50% by 2030. These factors lead to sectoral activity changes – particularly in terms of livestock herd size and the use of manure and mineral fertilisers – relative to the core scenarios (S2 and S3).

A sector trajectory assuming no deployment of additional mitigation technologies with no changes in food consumption and production, as is the case for all core scenarios, shows remaining agricultural emissions of 351 Mt CO_2e by 2040 and 347 Mt CO_2e by 2050. However, a "no additional mitigation" pathway

[9] This excludes the estimated N_2O emission reductions from the fallowing of histosols (app. 4,7 Mt CO_2e of N_2O emission reductions at the price of EUR 290).

[10] This trajectory assumes the adoption of the European Commission's proposed revision of the Industrial Emissions Directive, as reflected in the co-decision process up to July 2023. The proposal includes the application of Best Available Techniques (BAT) to agro-industrial cattle farms with more than 500 livestock units, targeting methane emissions from these sources. However, the final adopted text excludes cattle from the Directive's scope.

incorporating assumptions of the LIFE scenario results in remaining emissions significantly lower than in the other scenarios reaching 269 Mt CO_2e in 2050.

Similarly to LIFE with "no additional mitigation", the *TYFA* scenario does not incorporate specific efficiency-focused mitigation technologies explicitly, with emission reductions arising predominantly from changes in production mix and the application of regenerative crop management practices. The simulation shows the remaining emissions to amount to approximately 243 Mt CO_2e.

In the case of N_2O emission reductions from agricultural soils, it should be noted however, that, both in the case of LIFE "without additional mitigation" and *TYFA*, these are driven by reductions in nutrient surpluses and overall fertiliser inputs (alongside demand-side changes), without a clear elaboration of how these reductions and efficiencies are achieved. The achievement of nutrient use efficiency rate as high as that required in the *TYFA* scenario (92% in the case of nitrogen from manure available on cropland, and just under 80% for all nitrogen) would require careful timing and application of organic fertiliser, likely involving practices elsewhere categorised as precision application methods – rather than being solely a consequence of the changes in the soil-plant system. The remaining scenarios, i.e. *Agora*, *EcAMPA*, and the main *LIFE* scenario, explicitly incorporate a suite of mitigation technologies, and clarify the share of total GHG reductions attributable to those technologies.

Box 3: Addressing nitrogen surpluses and closing the nitrogen cycle

With nitrogen pollution contributing to the transgression of nearly all planetary boundaries (Sutton et al., 2021), avoiding unproductive nitrogen surpluses is a key agri-environmental objective. As a result, nearly all of the analysed scenarios highlight the importance of enhancing nitrogen use efficiency (NUE) – defined as the ratio of crop nitrogen uptake to the nitrogen available in the soil.

The *TYFA* scenario in particular offers valuable insights into the theoretical composition of EU agricultural production that could sufficiently support domestic consumption in the absence of synthetic fertiliser inputs. The assumption of a complete phase-out of synthetic nitrogen, combined with a phase-out of pesticides[11] has significant implications for the organisation of cropping systems, including yields, rotation complexity, and crop diversity, as well as their interactions with livestock systems.

In *TYFA*, the substitution of synthetic mineral nitrogen inputs occurs through symbiotic fixation by legumes, which requires a significant increase in the proportion of legumes in cropland and grassland. The circularity is achieved through direct N residues in arable land (roots and green cover), and nitrogen transfers via ruminant livestock production, from temporary and permanent grasslands to cultivated areas.

For such transfers to be possible at a sufficient level across all European territories, grasslands would have to be reintroduced in highly specialised areas where cropland dominates. The authors of the *TYFA* exercise acknowledge that such redeployment of livestock production and grasslands in field crop areas would entail a deep systemic shift, considering the existing socio-economic context and spatial distribution of production.

With these assumptions in place, the authors of the TYFA scenario compare the total nitrogen outputs from cropland (defined as the nitrogen content of all crops harvested, whether for food, feed, or industrial uses) with nitrogen inputs – derived, in TYFA's case, from legumes in rotation and livestock manure. Constructing this input-output balance allows for testing whether an adequate nitrogen supply can be ensured for the production profile outlined in TYFA. As the authors emphasise, this is a necessary condition but not sufficient in itself to confirm the feasibility of phasing out synthetic nitrogen at the EU level. If nitrogen outputs exceed inputs – and no protein feed is imported in the scenario – this would suggest that the transition away from synthetic nitrogen inputs is unfeasible under the given assumptions. Conversely, if inputs meet or exceed outputs, this may indicate feasibility, though such a conclusion must be tested at regional and local levels, which is beyond the scope of the study and the capabilities of the TYFA model.

Based on the scenario's thresholds and data on nitrogen inputs and production, the nitrogen balance indicates a slight surplus, with an input/output ratio of 109%. This result is derived from an estimated total nitrogen output in crops of approximately 10.6 Mt N, and nitrogen inputs from symbiotic fixation by legumes in rotation – including soybean, forage legumes, temporary grasslands, fodder legumes, and intercropping legumes – of approximately 8.2 Mt N. The gap is filled by livestock manure: approximately 2.7 Mt N from the dairy and beef sectors, and an additional 0.6 Mt N from monogastric production (including hens, broilers, pigs, sheep, and goats). In TYFA, these nitrogen inputs depend on numerous variables, including the assumption of a livestock system comprising approximately 78 million heads of cattle, within an extensive grazing framework in which dairy cows spend 75% of their time on pasture and 25% in stables, among other parameters.

The resulting nitrogen balance of 109% suggests that, under the scenario's assumptions, there may be sufficient nitrogen available for crop production without synthetic inputs. However, as the authors conclude, the surplus is too marginal to be interpreted conclusively, especially given the considerable uncertainties in the assumptions, the absence of spatial analysis, and the implied need for significant improvements in nitrogen use practices and reduction of nitrogen losses.

In the context of *Agora's* target production profile, the mitigation potential of various technologies could amount to 37 Mt CO_2e per year, which would account for 19% of total livestock sector reductions by 2045, with the other 81% resulting from reductions in livestock population. The largest contributions among

[11] The use of pesticides is not further discussed in this paper, but it is an important consideration in the context of climate mitigation given the practical trade-offs involved in the deployment of certain types of regenerative agricultural practices such as reduced tillage.

mitigation technologies come from 3-NOP type additives (25%), anaerobic digestion (23%), and manure acidification (19%). Slurry removal and cooling is linked to a 9% reduction, and the use of nitrate and linseed additives is responsible for respectively 8% and 7%. The scenario also sees a small role for breeding for feed efficiency (3%), anti-methanogen vaccination (3%) and low-protein feeding (0,2%). The 37 Mt CO_2e mitigation potential estimate for the livestock sector is based on what the authors acknowledge to be an optimistic 50% adoption rate of the three technologies not considered in other scenarios (i.e. manure acidification, slurry cooling and the application of nitrogen inhibitors to manure), as well as 3-NOP feed additives. For the remaining technologies available in CAPRI at the time of analysis, the following adoption rates in 2045 are modelled: 94% uptake for breeding for feed efficiency, 33% for anti-methanogen vaccination, 24% for nitrate feed additives and 12% for linseed feed additives. The use of anaerobic digestion based on size effect on cost is 15% for cattle and 68% for pigs. Considering uncertainties around technology effectiveness and combined impacts, *Agora* estimates a potential emissions savings associated with the adoption of technological mitigation options of 26–47 Mt CO_2e, with the lower bound of this range based on a 25% adoption rate of the four technologies added by *Agora* to the suite available in CAPRI and the upper threshold based on a highly ambitious adoption rate of 75%.

The central estimate of the overall emission reduction potential associated with livestock mitigation technologies in *Agora*'s scenario is very close to that estimated in the Commission's S3 scenario (37 and 36,5 Mt CO_2e respectively), despite significant differences in the EU livestock herd sizes in the two scenarios that the mitigation technologies can be applied to – this is predominantly driven by the incorporation of additional technologies, not considered in the 2040 target IA, rather than different assumptions around the diffusion and uptake of technologies shared between the two scenarios.

The mitigation potential associated with crop related mitigation technologies in *Agora's* scenario is more limited than in the case of livestock, estimated to be around 7,7 MtCO_2e by 2045. The use of nitrification inhibitors is the biggest driver of this reduction (69%), with more limited contributions of the other mitigation options (19% from precision farming, 11% from optimised fertilisation timing and less than 1% from variable rate technology). The *Agora* study specifies the diffusion rate associated with each of these technologies that allow for the delivery of those levels of emission reductions; these are: 61% uptake of nitrification inhibitors across the relevant processes in 2045, 12% uptake for optimised fertiliser timing, 9% for precision farming and 0,7% for variable rate technology.

The overall potential of crop-related mitigation technologies in the *Agora* scenario is markedly lower than in the *LIFE* scenario – 5.3 Mt CO_2e from nitrification inhibitors and 0.06 Mt from variable rate technology, compared with 18.4 Mt and 8.9 Mt, respectively, in the *LIFE* scenario at the same carbon price (EUR 200). This difference may partly reflect variations in the land area eligible for fertiliser application, and thus for the use of mitigation technologies. The *Agora* scenario excludes fertilisation on extensive areas, including rewetted organic soils, agroforestry and afforested land, and new semi-natural landscape elements on formerly productive land. Both scenarios appear to draw on the approach developed by Barreiro-Hurle et al. (2021) for the reduction of gross nitrogen balance surplus using NUTS-2 level data, with *Agora* detailing some modifications applied to that approach. However, due to limited detail in the Commission's Impact Assessment, the exact reasons for the significant difference in overall technological mitigation potential cannot be fully determined.

Among the analysed scenarios, the *EcAMPA 4 CP* scenario demonstrates the highest mitigation potential from livestock-related measures in absolute terms – app. 48 Mt CO_2e – despite the relatively low carbon price of EUR 100. Of this total, about 40% results from the use of 3-NOP feed additives, 35% from anaerobic digestion, 13% and 11% from nitrate and linseed feed additives respectively, and 2% from low-protein feed. Similar to the *Agora* scenario, *EcAMPA 4 CP* exhibits a more limited mitigation potential in the crop sector compared to livestock, with estimated reductions of 9 Mt CO_2e from nitrification inhibitors and an additional 3 Mt CO_2e from precision farming technologies, including VRT.

6. LAND USE AND LAND USE CHANGE: GRASSLANDS

While a detailed examination of GHG outcomes within the LULUCF category falls outside of the scope of this analysis, the assumptions made with regards to land use and land use change are a decisive factor in the design of some of the analysed scenarios.

The question of permanent grassland[12] maintenance is among the key considerations in this respect. Permanent grasslands cover nearly one-third of the EU agricultural area (Eurostat, 2023) and, when managed effectively, play a key role in the provision of a wide range of ecosystem services, including water purification, protection against erosion and flooding (Macleod et al., 2013) and pollination of food crops (Klein et al., 2007; Scheper et al., 2013), among others. This potential, however, has been under threat from ploughing for the purpose of cropping operations, excessive nutrient inputs, agricultural intensification, consolidation of farming operations, climate change, and the abandonment of land (Habel et al., 2013, Boch et al., 2020).

In the case of the *TYFA* scenario, the role that ruminants can play in mobilising permanent grasslands is one of key motivating factors behind maintaining ruminant livestock numbers. The extent of permanent grassland in the baseline year serves as the basis for determining the overall size of the cattle herd, which is calibrated to maintain a stocking density of approximately 1 LSU/ha. This approach is adopted to keep the European area under permanent grassland constant by 2050 and ensure better management of those grasslands, while decreasing the demand for animal feed by prioritising livestock production based on non-human-edible crops.

While the structure of crop production (e.g., presence of perennial crops, rotations with a high share of N fixing crops) is altered significantly in *TYFA*, the broad land use categories, such as cropland, grassland, and forests remain stable, following logically from the hypotheses made. While the share of arable land area under agroecological structures increases slightly, the *TYFA* scenarios do not offer any additional sequestration potential through afforestation, as no land is freed up for other purposes than food production and no specific hypotheses are made on forest management improvement.

The *Agora* scenario takes a similar approach to permanent grassland, by keeping its area constant between 2020 and 2045 while reducing management intensity, in recognition of its role from a biodiversity perspective. It also assumes 5 Mha of

[12] Defined as land used for five or more years for herbaceous fodder or forage production.

afforestation at the expense of agricultural land. These assumptions, paired with the projected increase in settlements area, lead to a decrease in agricultural land by -7,66 Mha by 2045.

The extent of grasslands in both the *TYFA* and *Agora* scenarios is therefore determined a priori as an input to the modelling process. This sets them apart from the other analysed scenarios, in which land use change is an output of the modelling, driven by assumptions regarding the cost-effectiveness and feasibility of adopting mitigation measures in the land sector more broadly, as well as by food demand.

The Commission's Impact Assessment scenarios rely on changes in the forest carbon sink for the achievement of economy-wide GHG outcomes and therefore involve changes in the forest area. The land use changes in the scenarios are driven by actions to enhance the LULUCF net removals and changes in energy demand in S2 and S3, which result in more land for forests (+4.9 Mha in 20404 compared to 2020), restoration of wetlands (+1.4 Mha), and a small increase in cropland to accommodate lignocellulosic crops for energy (+1.2 Mha) (although the total cropland area remains well below levels recorded between 2000 and 2015). In parallel to these developments, land area categorised as "Grassland and other natural land" decreases by 9,3Mha (-12,7%).

The *LIFE* scenario presents a more modest reduction in "grassland and other natural areas" (-6.6 Mha compared to 2020), alongside a decrease in cropland (-5.8 Mha) and a substantial increase in forest area (+8.9 Mha). The key distinction from scenarios S2 and S3 lies in the reallocation of agricultural land previously dedicated to livestock and fodder production. In *LIFE*, land shifts from intensively grazed use to more extensive grassland systems, high-diversity landscape features with increased natural vegetation, forest land, and rewetted organic soils. Overall, lower demand for livestock products induces land use changes that result in less cropland (-7 Mha) and more grassland (+2.7 Mha) compared to S2 and S3.

Similarly, in the *EcAMPA 4 CP* scenario, the application of a carbon price on non-CO_2 emissions from agriculture leads to significant land use changes. The carbon price incentivises a reduction in cropland (–11 Mha by 2050 compared to 2020) and a much more modest reduction in grassland (including some shrubland, -1 Mha), which are largely converted into additional forest land (+14 Mha).

Overall, these results align with the outcomes that the *TYFA* scenario explicitly seeks to avoid – namely, the expansion of forest land at the expense of grasslands, albeit to varying degrees. It is important to note, however, that the definition of land classified as grassland is not consistent across scenarios, and not all grasslands converted in the Commission's and EcAMPA scenarios are necessarily of high ecological value. These land use changes are also the result of the application of a carbon price in a profit-maximising scenario where carbon pricing is the dominant policy instrument, applied in the absence of complementary safeguards. As such, these outcomes are not inevitable in a real-world policy context.

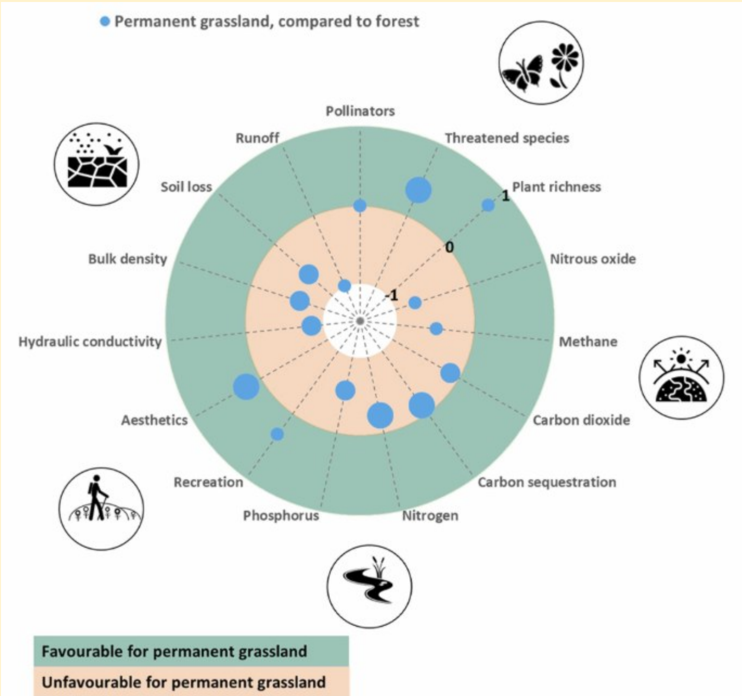
Meanwhile, the *Agora* scenario provides an illustration of how preserving permanent grasslands and maintaining their ecological functionality could be achieved alongside greater reductions in beef production – and, consequently, greater emission reductions in the agricultural sector – than those projected in the *TYFA* scenarios. It should be noted that the number of livestock required to meet population-level consumption patterns is strongly influenced by underlying yield and consumption level assumptions. In the *Agora* scenario, despite an increase in the share of grass in dairy cattle feed, average milk yield per cow rises by approximately 7%, from around 7,200 litres in 2020 to nearly 7,700 litres in 2045 – an estimate acknowledged as ambitious (Agora Agriculture, 2024b, p.32). In contrast, the *TYFA* scenario assumes a decline in productivity associated with extensification, with milk yields falling to approximately 5,335 litre per head.

Box 3: Grasslands: climate mitigation and other benefits

The *TYFA* scenario assert strongly the benefits of maintaining permanent grasslands with ruminant livestock, arguing that a climate-led approach, which prioritises a decrease in ruminant livestock production results in a reduction in permanent grassland areas, which are either tilled in order to be cultivated or afforested in order to store carbon.

There clearly are trade-offs in shifting land use away from grassland maintenance. A meta-analysis by Schils et al. (2022) compared the performance of different land use types on a range of ecosystem services indicators (see Fig. 1) and found that permanent grasslands generally support higher levels of biodiversity and cultural ecosystem services than forests, particularly in terms of indicators related to threatened species. In contrast, forests tend to perform better in regulating services such as erosion and flood control, while findings on water purification showed no consistent advantage for either land use type.

Fig. 1: Comparison between land use types for indicators of ecosystem services: permanent grassland compared to forest[13]



Source: Schils et al. 2022

Although no reference counterfactual scenario is constructed in the *TYFA* study, the cultivation of grasslands or afforestation, including for wood production, are suggested to be inevitable alternatives to preserving permanent grassland through livestock grazing. *TYFA-GHG*, which assumes a greater reduction in cattle, without diminishing the area under permanent grasslands, introduces anaerobic digestion using grassland grasses while indicating that the consequences of cutting grass from grassland for biogas production instead of having ruminants on them is also likely to negatively impact upon their biodiversity. In *TYFA*, alternative grassland management approaches which may be designed with a stronger biodiversity focus than afforestation, such as e.g., rewilding, fall conceptually under the category of arable land under ecological infrastructures, with no further detail on ecological land use.

As the *TYFA* authors note, the climate benefit associated with carbon sequestration in grasslands in their scenario is not a given, despite the prioritisation of permanent grassland maintenance. This is due to the central role of nitrogen transfers from the grazing animals to crop production in the cultivated areas in the scenario. In order to avoid inefficiencies, and close nitrogen cycles at the finest territorial level possible, such a system requires a re-territorialisation of livestock systems in cropland areas. This, in turn, implies selectively redeploying these grasslands (and therefore the associated herbivore production) in areas currently used for field crops. In other words, while some grasslands will be converted to croplands in grass-dominated landscapes, some croplands will conversely return to grassland in arable land dominated landscapes. In practice this process may involve significant releases of SOC into the atmosphere, and the rate of carbon sequestration in croplands converted to grassland would be slower than that of emissions from grasslands turned into croplands (Poux & Aubert, 2018).

It is also important to note that, despite the frequently highlighted potential of grasslands for carbon sequestration, it cannot be regarded as

[13] The meta-analysis did not account for total ecosystem carbon sequestration, which is typically greater in forests due to long-term accumulation of aboveground biomass (Schulze et al., 2009). Consequently, this component is not captured in the relative CO_2-related outcomes presented in the radar chart.

a viable strategy for offsetting non-CO_2 emissions from livestock. The capacity of soils to sequester carbon is inherently limited and declines over time. SOC storage reaches a saturation point, which varies depending on initial soil properties and local agroecological conditions, with the rate of sequestration diminishing as soils approach this equilibrium. Crucially, SOC sequestration is reversible: the carbon stored in soils can be re-released through changes in land use or management practices.

Even under optimistic assumptions regarding the capacity and duration of SOC sequestration in grasslands, substantial reductions in livestock emissions remain necessary. Wang et al. (2023) estimate that offsetting the ongoing methane and nitrous oxide emissions from the global ruminant sector would require sequestration of approximately 135 Gt CO_2 – nearly double the current global carbon stock in managed grasslands. In several world regions, this would necessitate increases in grassland carbon stocks ranging from 25% to 2,000%, underscoring the infeasibility of relying on grassland carbon sequestration to neutralise the warming impact of emissions from existing ruminant systems.

7. DISCUSSION AND POLICY IMPLICATIONS

As a result of the implementation of different assumptions across the analysed scenarios, the remaining domestic emissions from the EU agricultural sector range between 150 Mt CO_2e in 2045/2050 (in the *Agora* scenario) and 275 Mt CO_2 e in 2050 (EcAMPA 4 CP scenario), representing, respectively, a 59% and 25% reduction relative to emission levels reported in 2023.

These results should be interpreted in light of the differing starting points and methodological approaches of the analysed scenarios, which shape their respective assumptions. Although not all scenarios are explicitly designed to maximise emission reductions, they offer valuable insights into how specific – both implicit and explicit – assumptions influence the estimated mitigation potential and shape differing views on the agricultural sector's contribution to residual emissions at the point of carbon neutrality.

Table 7: Scenario overview

Core approach	Source	Scenario	End date	Remaining emissions from agriculture (Mt CO2e)	GHG reduction compared to 2023 emissions
Assessment of agriculture's possible contribution to climate neutrality, alongside the delivery of other sustainability objectives set out in (largely non-binding) EU policy frameworks; incorporate a techno-economic assessment of mitigation potential under different carbon pricing and technology assumptions in the context of shifting societal preferences with respect to food.	**Agora Agriculture (2024)**	**Agora Agriculture**	2045/2050	**150**	59%
	2040 target IA (EC, 2024a)	**LIFE**	2050	**194**	47%
Assessment of the feasibility of a large-scale transition to an "agro-ecological Europe", with phase-out of synthetic inputs and EU protein self-	**TYFA (Aubert, Schwoob & Poux, 2019)**	**TYFA-GHG**	2050	**203**	44%

sufficiency as key pillars, focusing on biophysical constraints and meeting nutritional needs.	**TYFA (Poux & Aubert, 2018)**	**TYFA main**	2050	**243**	33%
Techno-economic assessment of mitigation potential under different carbon pricing and technology assumptions, in the context of relatively static consumer preferences.	**2040 target IA (EC, 2024a)**	**S2**	2050	**249**	32%
	2040 target IA (EC, 2024a)	**S3**	2050	**249**	32%
	EcAMPA 4 (Pérez Domínguez et al., 2025)	**CP scenario**	2050	**275**	25%

The wide range of outcomes is steered by a diversity of starting points and assumptions introduced to the models. Key input variables include assumptions about possible change in consumer behaviour, the implementation of carbon pricing, and choice and cost of mitigation technologies, as well as other modelling design choices based on priorities assigned to other environmental objectives.

The role of changing consumption patterns

Scenarios that assume the possibility of a demand shift away from animal protein, alongside deploying mitigation technologies in the sector, show the most ambitious levels of emission reductions. A lower domestic demand for food products with a high GHG footprint, such as meat and dairy, and a parallel reduction in livestock populations in the EU, can offer a range of sustainability and economic benefits, while supporting climate change mitigation.

Under the right conditions, a reduction in domestic demand can have a positive impact on the trade balance in key products, as shown in the *Agora* and *TYFA* scenarios. In both scenarios, the EU's trade deficit in feed grains, oilseeds, and other protein feedstocks declines due to reduced demand for animal feed. The EU also maintains its position as a net exporter of cereal and increases the trade surplus in dairy as consumption falls more than production, allowing the EU dairy sector to retain its comparative advantage on the world stage.

Beyond trade balance and self-sufficiency improvements, this shift also aids the environmental integrity of the EU's climate mitigation efforts. The *Agora* and *TYFA* scenarios comprehensively demonstrate how through changes in production and consumption, the EU could drastically reduce its imports of protein feed (by 55-100%), alleviating pressure on land outside the EU, with potential benefits for global food security, biodiversity conservation, and climate change mitigation.

The broader environmental and adaptation benefits manifest also domestically as a result of the change in consumption and production mix, as made explicit across all three scenarios that introduce nutrition-based changes. The main drivers of these benefits are a decline in livestock densities, decreases in nitrogen surpluses reducing eutrophication and acidification, as well as the provision of landscape features or semi-natural habitats on agricultural land.

Finally, all of the scenarios incorporating exogenous dietary changes respond, in part, to well-documented nutritional imbalances in current EU dietary patterns, where the average consumption of calories, ruminant meat, sugar, salt, and saturated fats exceeds recommended levels, while intake of whole grains, fruits, vegetables, legumes, and nuts remains inadequate (EEA, 2024). The modelled dietary shifts are therefore expected to yield positive outcomes linked to reduced risk of chronic illnesses such as cardiovascular diseases or certain cancers, as well as broader public health benefits as a result of reduced air pollution, antimicrobial resistance and zoonotic disease risk mitigation, among others (Koch et al., 2023; Westhoek et al., 2014; Crippa et al., 2022; ECDC et al., 2024; UNEP, 2020). These positive outcomes complement the inherent health co-benefits of climate mitigation, such as reduced health risks associated with extreme heat and other climate-related stressors.

In scenarios that prioritise supply-side climate mitigation without assuming significant shifts in consumer preferences beyond the baseline, achieving substantial emission reductions alongside a broad range of co-benefits appears further out of reach. The *EcAMPA 4 CP* scenario, for instance, shows only minor shifts in consumer food choices, suggesting that pricing measures applied at the production level alone are unlikely to induce dietary shifts that could otherwise be seen as desirable e.g. from a health perspective.

However, the modelling outcomes are strongly influenced by assumptions about the price elasticity of demand – that is, how responsive consumers are to price changes. As noted by CONCITO (2025), the *CAPRI* model relies on price elasticities of meat which appear conservative when compared with estimates from other studies (e.g., Bouyssou et al., 2024; Femenia, 2019; Gallet, 2012; Wirsenius et al., 2011). If the modelling underestimates the extent to which consumers adjust their consumption in response to price changes, pricing policies could, in practice, lead to greater dietary shifts, reducing projected levels of carbon leakage, and enhancing overall mitigation effectiveness beyond what the *EcAMPA* results suggest.

The role of technological mitigation options

To achieve the most ambitious GHG emission reductions, scenarios with the highest ambition pair changes in the production mix, which is typically the most significant mitigation driver, with the use of mitigation technologies. Scenarios that explicitly implement mitigation technologies (all except *TYFA*) model their related emission reductions based on cost-effectiveness. This is directly linked to the assumed carbon price and the estimated cost of implementing these technologies.

Although all these scenarios use the CAPRI model, there are some variations in the suite of mitigation technologies considered and their supporting parameters, including implementation costs. For crop production, the use of nitrification inhibitors in synthetic fertiliser application is consistently identified as the biggest driver of emission reductions, with significantly higher mitigation potential than that of precision application methods, which have poorer cost/benefit outcomes. For the livestock sector, the biggest technological mitigation potential is consistently associated with 3-NOP feed additives, followed by anaerobic digestion. Notably, the use of these technologies requires a certain level of intensification and consolidation due to the need for frequent administration of additives and the economies of scale for anaerobic digestion. Overall, while technology measures reliant on economies of scale can lower emissions in the short term, they may delay or inhibit transitions towards systems that improve animal welfare and perform well on a wider range of environmental indicators.

CAPRI modelling incorporates some of the existing constraints on the deployment of mitigation technologies, especially where these are of a cost or technical nature. For instance, the mitigation potential of fertilisation management is limited by regional nitrogen surpluses, estimated using regional over-fertilisation factors, while the administration of feed additives is limited to animals in feedlots, by livestock type. These parameters rely on available farm activity data, which introduces an inherent level of uncertainty. Other limitations and trade-offs may also exist beyond these technical constraints, without being captured.

As the *TYFA*, *Agora*, and *LIFE* scenarios demonstrate, the extensification of production can also be part of a climate mitigation strategy for the agricultural sector. Importantly, however, this approach may not lower the emissions intensity of products (for example, emissions per litre of milk) and therefore relies on an overall decrease in animal numbers in order to ensure climate mitigation outcomes. The analysed scenarios show that a shift to more extensive modes of production in some localities as part of a sustainable land use strategy can, in addition to mitigating climate change, play an important role in the transformation of the EU's agricultural system, particularly given its contribution to biodiversity, animal welfare, and climate resilience.

Food production

Decreased consumption of animal products drives reductions in livestock populations across all scenarios that incorporate dietary change, although the extent of decline in different livestock types - cattle, pigs, and poultry - varies by scenario. These differences reflect the underlying approaches: scenarios that prioritise direct emission reductions from EU agriculture show larger declines in cattle herds, whereas the two *TYFA* scenarios, which emphasise the role of ruminants in maintaining the nitrogen cycle, show greater reductions in poultry populations.

Results for plant production vary more widely across the scenarios. In some cases, fruit and vegetable production increases – driven by demand-related assumptions – while in others it declines, even where higher fruit and vegetable intake is assumed. Mixed outcomes are also observed for cereals and oilseeds, although production of the latter generally increases or remains stable.

The differing effects of increased demand on domestic supply are likely partly attributable to assumptions about the persistence of existing barriers to the competitiveness of EU production. For example, while the *Agora* study models an increase in fruit and vegetable production, it also notes that EU producers face comparatively high labour and energy costs, combined with a limited growing season. The authors emphasise that, to enable increases in production at the scale presented in the scenario, leaps in technology and capacity building will be needed to ensure sustainable production.

It is worth noting that more pronounced changes in production levels – beyond those projected in the Agricultural Outlook – are not reflected in scenarios S2 and S3 of the Commission's Impact Assessment. By design, these scenarios keep food production aligned with currently forecast trajectories, even in the presence of carbon pricing. Consequently, the entire reduction in agricultural emissions relative to the outlook projections is achieved solely through the adoption of mitigation technologies, without any reduction in livestock output. As Matthews (2024) observes, maintaining unchanged food production while increasing carbon prices would require significant changes in relative prices and consequently farm incomes within the models; however, such adjustments are not accounted for in the Impact Assessment.

Socio-economic impacts on farmers and consumers

The analysed scenarios do not provide significant detail or insight into the socio-economic impacts of the modelled reductions and thus cannot be used to draw detailed conclusions on these aspects.

The economic rationale required for actors to align their decisions with a scenario's intended direction is implicitly addressed in scenarios that incorporate carbon pricing. These assume that farmers will adopt mitigation measures whose implementation costs per unit of carbon saved are lower than the assumed carbon price level. While real-world decision-making is far more complex – and implementation costs vary widely across localities and contexts – such scenarios nevertheless convey plausible trajectories for GHG emissions that consider economic factors at both the economy-wide and farm levels. They also, to varying degrees, reflect assumptions about what carbon price levels might be acceptable to stakeholders and what levels of production effects (e.g., reductions in herd size or output volume) might be considered tolerable. (As noted in the previous section, this does not appear to be the case for the core 2040 target IA scenarios, which do not account for the potential production impacts of relatively high carbon prices of EUR 290 and above.)

Carbon pricing features in all scenarios except *TYFA*, which instead focuses on the agronomic and biophysical feasibility of sustaining agroecological production systems at EU scale. The economic dimensions of such a transition fall outside the scope of *TYFA*'s analysis. However, the projected trends – such as reduced stocking rates and lower milk and meat yields per livestock unit – would, within the existing economic system and agri-food markets, likely exert downward pressure on farm incomes.

While preserving grassland multifunctionality is clearly desirable from a societal perspective, it cannot currently be assumed to be economically rational at the level of individual farms, where short- and medium-term management decisions are often driven primarily by business profitability. In many cases, land conversion or abandonment – both key drivers of permanent grassland loss – are linked to the underlying lack of economic viability of maintaining grassland-based systems (see e.g. Pe'er et al., 2014). Given that low profitability presently drives trends counter to *TYFA*'s assumptions – and that intensification continues in some regions, such as Eastern Europe (Török et al., 2020) – significantly stronger policy instruments or major shifts in consumer prices would be required first to enable extensification and then to sustain it by counteracting ongoing economic pressures toward intensification.

The impacts of the analysed mitigation pathways on consumers will depend on the development of dietary preferences and the pass-through of mitigation costs down the value chain. While changes in consumer prices may be expected, they are likely to be steered by global price developments as much as by moderate increases in EU producer prices as part of a decarbonisation effort. Notably, the significance of shocks resulting from climate change should not be understated, with the resulting price volatility likely to be mitigated by holistic mitigation efforts and a lower reliance on agricultural inputs in the EU.

In sum, the incomes of farmers and consumer prices are shaped by multiple parameters, themselves driven by markets and policies. While it is clear that the analysed scenarios would have major and complex socio-economic impacts, these should not be considered as inescapable. Indeed, proactive and responsive policy measures can and should be designed to ensure a fair and inclusive transition.

High-level public policy implications

Recognising that pursuing mitigation pathways with the lowest residual emissions represents the safest and most responsible course of action for limiting climate change and minimising or reversing temperature overshoot (Lamb, 2024), there is a clear rationale for policy to prioritise creating the enabling conditions that would make such pathways achievable. Policymakers should therefore focus on identifying, facilitating, and scaling the key elements of the scenarios that deliver the greatest emission reductions. These scenarios also demonstrate that, under the right conditions, ambitious mitigation trajectories can generate multiple co-benefits – including improved public health outcomes, enhanced food self-sufficiency, and broader environmental gains beyond climate mitigation – thereby strengthening the rationale for policy intervention.

A key area for renewed policy focus concerns dietary transitions and the wider food environment. The analysis indicates that achieving deeper agricultural emission reductions relies on a wider shift towards diets less reliant on animal products. At the same time, this shift in consumption can play an effective role in addressing trade-offs that may arise from supply-side actions taken in isolation, including by mitigating carbon leakage and fostering improved trade balances in key commodities. Reviving policy discussions on sustainable diets, pricing mechanisms, and consumer environments is therefore warranted. At various governance levels, dietary transitions aligned with nutritional guidelines and planetary boundaries can be supported through a combination of measures, including reforming food pricing and taxation to better reflect environmental costs, adjusting subsidies and fiscal incentives, regulating marketing to encourage sustainable choices, and shaping food environments – both in retail and public procurement – to make healthy, low-carbon options more accessible and attractive.

The required changes in production mix, particularly the likely structural shifts in the livestock sector, necessitate a transparent public debate and should be viewed not only as a climate policy imperative but also a broader opportunity to future-proof agriculture production. Transitioning toward a smaller but higher-value livestock industry, integrated more closely with circular bioeconomy models and ecosystem service provision, can enhance rural resilience and diversify income sources for farmers through a shift toward multifunctional production systems.

It is also essential to design early public policy interventions that support a fair and inclusive transition, including for those leaving the sector. Although the scenarios analysed offer limited insights into the distribution of socio-economic impacts, the transformations required will inevitably have significant implications that must be managed with caution. The transition will not progress uniformly across different regions or production types and will consequently impact livelihoods, labour demand, and community structures within rural areas to varying degrees. A fair balance must be struck by applying the "polluter pays" principle, as recommended by the European Court of Auditors (2022), while providing targeted public support to those with limited means and capacity to adopt new technologies and practices. This support should include public investment in a robust and easily accessible system of agronomic advice tailored to the needs of a sustainable transition.

The reviewed scenarios have inherent limitations in analysing transition barriers, as market equilibrium models are fundamentally constrained in their ability to capture structural and behavioural dynamics that shape real-world transitions. While modelers strive for accurate reflection of implementation costs of lower-emission production methods, other adoption barriers – whether cost-related or not – persist. These may include transaction costs related to data collection, management and reporting that allow for the verification of sustainability credentials, the need for new or overhauled value chains for key commodities, existing market demand and power dynamics, and other considerations which need to be identified and addressed as part of the policy process.

To ensure alignment across these elements, the agricultural sector requires a comprehensive and coherent long-term vision that defines its structure and trajectory to 2040, 2050, and beyond. From a climate perspective, this vision should consider overall emission reduction needs at the sector level, the composition of residual emissions by source (e.g. livestock, fertiliser application), and production modes within a well-defined, science-based climate transition pathway that provides long-term policy certainty. Crucially, the climate pathway must sit within an integrated approach that accounts for human health, animal welfare, climate resilience, biodiversity and other environmental dimensions, so that emission reductions are achieved in ways that reinforce, rather than undermine, broader sustainability goals.

REFERENCES

Ainsworth, E. A., Yendrek, C. R., Sitch, S., Collins, W. J., & Emberson, L. D. (2012). Ozone effects on crop yields and interactions with climate change. *Plant, Cell & Environment, 35*(2), 253–265. https://doi.org/10.1111/j.1365-3040.2011.02426.x

Alexandratos, N., & Bruinsma, J. (2012). *World agriculture towards 2030/2050: The 2012 revision*. Food and Agriculture Organization of the United Nations. https://www.fao.org/3/ap106e/ap106e.pdf

Allen, M. R., Lynch, J., Cain, M., & Frame, D. (2022). *Climate Metrics for Ruminant Livestock: Programme Briefing (July 2022)*. Oxford Martin Programme on Climate Pollutants. https://oms-www.files.svdcdn.com/production/downloads/reports/ClimateMetricsforRuminentLivestock_Brief_July2022_FINAL.pdf

Agora Agriculture. (2024). *Agriculture, forestry and food in a climate neutral EU: The land use sectors as part of a sustainable food system and bioeconomy*.

Arendt, R. (2024). Residual carbon emissions in companies' climate pledges: Who has to reduce and who gets to remove? *Climate Policy, 24*(9), 1195–1210. https://doi.org/10.1080/14693062.2024.2358989

Arneth, A., Sitch, S., Pongratz, J., Stocker, B. D., Ciais, P., Poulter, B., ... Zaehle, S. (2010). Terrestrial biogeochemical feedbacks in the climate system. *Nature Geoscience, 3*(8), 525–532. https://doi.org/10.1038/ngeo905

Aubert, P.-M., Schwoob, M.-H., & Poux, X. (2019). Agro-ecology and carbon neutrality in Europe by 2050: What are the challenges? IDDRI, Issue Brief N°05/19.

Avnery, S., Mauzerall, D. L., Liu, J., & Horowitz, L. W. (2011). Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic costs. *Atmospheric Environment, 45*(13), 2284–2296. https://doi.org/10.1016/j.atmosenv.2010.11.045

Bodirsky, B. L., Popp, A., Lotze-Campen, H., & Dietrich, J. P. (2020). Resource-use efficiency and food security: The role of sustainable intensification. *Environmental Research Letters, 15*(8), 084025. https://doi.org/10.1088/1748-9326/ab8f7e

Boch, S., Prati, D., & Socher, S. A. (2020). Land-use intensity and biodiversity in European grasslands: A meta-analysis. *Biological Conservation, 241*, 108305.

Bouyssou, C. G., et al. (2024). Food for thought: A meta-analysis of animal food demand elasticities across 87 countries. *Food Policy, 122,* 102346. https://doi.org/10.1016/j.foodpol.2023.102346

Buck, H. J., Carton, W., Lund, J. F., et al. (2023). Why residual emissions matter right now. *Nature Climate Change, 13,* 351–358. https://doi.org/10.1038/s41558-022-01592-2

Butler, T. M., Lawrence, M. G., Taraborrelli, D., & Lelieveld, J. (2020). Methane's role in ozone formation and impacts on air quality and climate. *Environmental Research Letters, 15*(7), 073002. https://doi.org/10.1088/1748-9326/ab8334

Cain, M., Lynch, J., Allen, M. R., Fuglestvedt, J. S., Frame, D. J., & Macey, A. H. (2019). Improved calculation of warming-equivalent emissions for short-lived climate pollutants. *npj Climate and Atmospheric Science, 2,* 29. https://doi.org/10.1038/s41612-019-0086-4

Campbell, B. M., Beare, D. J., Bennett, E. M., Hall-Spencer, J. M., Ingram, J. S. I., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J. A., & Shindell, D. (2017). Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecology and Society, 22*(4), 8. https://doi.org/10.5751/ES-09595-220408

Clark, M. A., Domingo, N. G. G., Colgan, K. K., Thakrar, S. K., Tilman, D., Lynch, J., Azevedo, I. L., & Hill, J. D. (2020). Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. *Science, 370*(6517), 705–708. https://doi.org/10.1126/science.aba7357

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., ... Thornton, P. (2013). Carbon and other biogeochemical cycles. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 465–570). Cambridge University Press.

Climate Watch. (2024). Historical GHG emissions dataset. World Resources Institute.

Cole, D. R., & McCoskey, S. K. (2013). Sustainable intensification and the economics of agricultural land use. *Agricultural Economics, 44*(3), 271–281. https://doi.org/10.1111/agec.12035

COMEAP. (2015). *Associations of long-term average concentrations of nitrogen dioxide with mortality: A report by the Committee on the Medical Effects of Air Pollutants.* UK Department of Health.

Costa, C. Jr., Wollenberg, E., Benitez, M., Newman, R., et al. (2022). Roadmap for achieving net-zero emissions in global food systems by 2050. *Scientific Reports, 12*, 15064. https://doi.org/10.1038/s41598-022-19184-7

Costa, C. Jr., Wironen, M., Racette, K., & Wollenberg, E. (2021). Global warming potential (GWP*): Understanding the implications for mitigating methane emissions in agriculture. *CCAFS Info Note*. CGIAR.

Crippa, M., et al. (2022). Health and environmental impacts of dietary risks in Europe: A systematic analysis. *The Lancet Planetary Health, 6*(3), e172–e182. https://doi.org/10.1016/S2542-5196(22)00003-4

EEA. (2023). *Transforming Europe's food system — Assessing the EU policy mix*. EEA Report No. 14/2022. https://www.eea.europa.eu/en/analysis/publications/transforming-europes-food-system

EEA. (2024). Annual European Union greenhouse gas inventory 1990–2022 and inventory document 2024: First submission under the Enhanced Transparency Framework of the Paris Agreement. EEA/PUBL/2024/046.

EC. (2024a). *Impact Assessment Report: Securing our future Europe's 2040 climate target*. SWD/2024/63 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52024SC0063

EC. (2024b). *EU agricultural outlook, 2024–2035*. European Commission, DG Agriculture and Rural Development.

European Commission. (2023). *EU agricultural outlook for markets and income 2023–2035*. European Commission, Directorate-General for Agriculture and Rural Development. https://agriculture.ec.europa.eu/system/files/2024-01/agricultural-outlook-2023-report_en_0.pdf

European Centre for Disease Prevention and Control, European Food Safety Authority, & European Environment Agency. (2024). *Antimicrobial resistance in the EU/EEA: A One Health perspective*. ECDC Technical Report. https://www.ecdc.europa.eu/en/publications-data/antimicrobial-resistance-eueea-one-health-perspective

European Environment Agency (EEA). (2024). *Annual European Union greenhouse gas inventory 1990–2022*.

Femenia, F. (2019). A meta-analysis of the price and income elasticities of food demand. *German Journal of Agricultural Economics, 68*(2), 77–98. https://doi.org/10.52825/gjae.v68i2.2127

Feyen, L., Hristov, J., & Toreti, A. (2020). Analysis of climate change impacts on EU agriculture by 2050. *JRC PESETA IV Final Report*. European Commission. https://doi.org/10.2760/121115

Franke, A. C., van der Werf, W., & van Ittersum, M. K. (2022). Climate change impacts on European agriculture: A meta-analysis of crop yield responses. *Field Crops Research, 276,* 108314. https://doi.org/10.1016/j.fcr.2021.108314

Gallet, C. A. (2012). A meta-analysis of the price elasticity of meat: Evidence of regional differences. *Business and Economic Research, 2*(2), 14–25. https://doi.org/10.5296/ber.v2i2.2115

Garnett, T. (2014). Three perspectives on sustainable food security: Efficiency, demand restraint, food system transformation. What role for life cycle assessment? *Journal of Cleaner Production, 73,* 10–18. https://doi.org/10.1016/j.jclepro.2013.07.045

Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., … Godfray, H. C. J. (2013). Sustainable intensification in agriculture: Premises and policies. *Science, 341*(6141), 33–34. https://doi.org/10.1126/science.1234485

Habel, J. C., Schmitt, T., & Müller, P. (2013). Conservation of European grassland butterflies: A review. *Journal of Insect Conservation, 17*(1), 1–12. https://doi.org/10.1007/s10841-012-9483-4

Heck, V., Gerten, D., Lucht, W., & Popp, A. (2018). Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change, 10,* 1050–1055. https://doi.org/10.1038/s41558-018-0323-7

Hörtenhuber, S. J., Seiringer, M., Theurl, M. C., Größbacher, V., et al. (2022). Implementing an appropriate metric for the assessment of greenhouse gas emissions from livestock production: A national case study. *Animal, 16*(10), 100638.

Hristov, J., Pérez Domínguez, I., & Fellmann, T. (2020). Analysis of climate change impacts on EU agriculture by 2050. *JRC PESETA IV Final Report*. European Commission. https://joint-research-centre.ec.europa.eu/system/files/2020-05/pesetaiv_task_3_agriculture_final_report.pdf

IPCC. (2021). *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Jens Friis Lund, N., Markusson, N., Carton, W., & Buck, H. J. (2023). Net zero and the unexplored politics of residual emissions. *Energy Research & Social Science, 98,* 103035. https://doi.org/10.1016/j.erss.2023.103035

Kate Dooley, C., Holz, C., Kartha, S., Klinsky, S., Roberts, J. T., Shue, H., ... Winkler, H. (2021). Ethical choices behind quantifications of fair contributions under the Paris Agreement. *Nature Climate Change, 11*(4), 300–305. https://doi.org/10.1038/s41558-021-01000-3

Klein, A. M., Vaissière, B. E., Cane, J. H., Steffan-Dewenter, I., Cunninghan, S. A., Kremen, C., & Tscharntke, T. (2007). Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences, 274*(1608), 303–313. https://doi.org/10.1098/rspb.2006.3721

Korosuo, A., et al. (2023). The role of forests in the EU climate policy: Are we on the right track? *Carbon Balance and Management, 18,* 15. https://doi.org/10.1186/s13021-023-00234-0

Lesschen, J. P. (2021). Consequences of an alternative emission metric. *Nature Food, 2,* 918–919.

Luderer, G., Vrontisi, Z., Bertram, C., et al. (2018). Residual fossil CO2 emissions in 1.5–2 °C pathways. *Nature Climate Change, 8,* 626–633. https://doi.org/10.1038/s41558-018-0198-6

Lynch, J., Cain, M., Pierrehumbert, R., & Allen, M. (2020). Demonstrating GWP: A means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. *Environmental Research Letters, 15,* 044023. https://doi.org/10.1088/1748-9326/ab7ab5

Macleod, C. J. A., McDowell, R. W., & McLaren, R. G. (2013). The role of permanent grasslands in providing ecosystem services. *Agriculture, Ecosystems & Environment, 181,* 1–10. https://doi.org/10.1016/j.agee.2013.07.002

Matthews, A. (2024, February 24). What does the Commission's proposed 2040 climate target mean for agriculture? *CAP Reform*. https://capreform.eu/what-does-the-commissions-proposed-2040-climate-target-mean-for-agriculture/

Moore, F. C., & Lobell, D. B. (2015). The fingerprint of climate trends on European crop yields. *Proceedings of the National Academy of Sciences, 112*(9), 2670–2675. https://doi.org/10.1073/pnas.1409606112

Myers, S. S., Zanobetti, A., Kloog, I., Huybers, P., & Schwartz, J. (2014). Increasing CO2 threatens human nutrition. *Nature, 510*(7503), 139–142. https://doi.org/10.1038/nature13179

Pe'er, G., et al. (2014). EU agricultural reform fails on biodiversity. *Science, 344*(6188), 1090–1092. https://doi.org/10.1126/science.1253425

Ponisio, L. C., M'Gonigle, L. K., Mace, K. C., Palomino, J., & Tsang, D. (2015). Diversification practices reduce organic to conventional yield gap. *Proceedings of the Royal Society B: Biological Sciences, 282*(1799), 20141396. https://doi.org/10.1098/rspb.2014.1396

Poux, X., & Aubert, P.-M. (2018). An agroecological Europe in 2050: Multifunctional agriculture for healthy eating. Findings from the Ten Years For Agroecology (TYFA) modelling exercise. IDDRI-AScA, Study N°09/18.

Ravishankara, A. R., Daniel, J. S., & Portmann, R. W. (2009). Nitrous oxide (N_2O): The dominant ozone-depleting substance emitted in the 21st century. *Science, 326*(5949), 123–125. https://doi.org/10.1126/science.1176985

Scheper, J., Holzschuh, A., Kuussaari, M., Potts, S. G., Rundlöf, M., Smith, H. G., & Bommarco, R. (2013). Environmental factors driving the effectiveness of European agri-environmental measures in mitigating pollinator loss – A meta-analysis. *Ecology Letters, 16*(6), 912–920. https://doi.org/10.1111/ele.12128

Smith, H. B., Vaughan, N. E., & Forster, J. (2024). Residual emissions in long-term national climate strategies show limited climate ambition. *One Earth, 7*(5), 867–884. https://doi.org/10.1016/j.oneear.2024.04.009

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., … Willett, W. (2018). Options for keeping the food system within environmental limits. *Nature, 562*(7728), 519–525. https://doi.org/10.1038/s41586-018-0594-0

Taub, D. R., & Wang, X. (2008). Effects of elevated CO2 on the protein concentration of food crops: A meta-analysis. *Global Change Biology, 14*(3), 565–575. https://doi.org/10.1111/j.1365-2486.2007.01511.x

Wang, Y., et al. (2023). Risk to rely on soil carbon sequestration to offset global ruminant emissions. *Nature Communications, 14*(1), 4345. https://doi.org/10.1038/s41467-023-43452-3

Westhoek, H., et al. (2014). Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. *Global Environmental Change*, *26*, 196–205. https://doi.org/10.1016/j.gloenvcha.2014.02.004

William, F. L. (2024). The size and composition of residual emissions in integrated assessment scenarios at net-zero CO2. *Environmental Research Letters, 19,* 044029. https://doi.org/10.1088/1748-9326/19/4/044029

Wirsenius, S., et al. (2011). Greenhouse gas taxes on animal food products. *Climatic Change, 108*(1–2), 159–184. https://doi.org/10.1007/s10584-010-9971-x

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