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Economic assessment of GHG mitigation policy options for EU agriculture

Interactions between the Agriculture, Forestry and Other Land Use sectors – EcAMPA 4

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Contents

Abstract

The European Climate Law mandates the European Union's climate neutrality objectives by 2050, aligning with the European Green Deal and interim greenhouse gas (GHG) emission reduction targets. The Agriculture, Forestry, and Other Land Use (AFOLU) sectors play a crucial role due to their dual function in sequestering carbon and emitting GHGs. This report assesses the potential contribution of the AFOLU sectors to the EU's 2050 targets using CAPRI model scenarios. Recent model enhancements enable a more integrated analysis of GHG emissions and carbon removals, allowing for a detailed assessment of land-based mitigation options. The scenarios assess increased afforestation, sustainable forest management, protection of peatlands, and pricing of AFOLU GHG emissions and removals. Results indicate that reversing GHG emission trends requires significant action, particularly enhanced soil carbon sequestration and climate-smart agricultural practices. The protection of histosols and land conversion towards grassland and forest areas significantly increase carbon dioxide removals, while lower livestock and crop production reduce methane and nitrous oxide emissions. Policies strengthening forest protection and afforestation further enhance the carbon sink capacity of the AFOLU sectors, potentially achieving negative net emissions by 2050. However, it is important to note that emission leakage (i.e., increases in emissions outside the EU) could limit global net reductions.

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Executive summary

Policy context

The European Union (EU) aims to achieve climate neutrality by 2050 under the European Climate Law and Green Deal. This legally binding commitment requires a substantial reduction of greenhouse gas (GHG) emissions across all sectors, including the Agriculture, Forestry, and Other Land Use (AFOLU) sectors.

To address this, the EU's policy framework, including the Common Agricultural Policy, has placed stronger emphasis on GHG mitigation in agriculture, promoting the adoption of technical and management-based measures. The project "Economic Assessment of GHG Mitigation Policy Options for EU Agriculture" (EcAMPA) evaluates the potential and effectiveness of various mitigation options to inform policy discussions. Using the CAPRI model, the EcAMPA series of reports has assessed production, economic, and environmental impacts of GHG mitigation strategies, including technological mitigation options, emissions trading schemes, and carbon pricing within the AFOLU sectors.

EcAMPA 4 extends its scope to carbon sequestration in forestry, the adoption of advanced farming practices, and the protection and restoration of rich organic soils. It provides a comprehensive analysis of several policy scenarios to enhance CO_2 removals and reduce non-CO_2 emissions. The scenarios presented in this study help identify cost-effective strategies that support the EU's target of at least 55% net GHG reduction by 2030 and climate neutrality by 2050.

Key conclusions

The AFOLU sectors can make a significant contribution to the 2050 climate neutrality objectives set by the EU Climate law. Our findings show that a mix of already existing smart technologies and practices, better forest management, and the targeted preservation and restoration of high organic soils can help the EU Agriculture sector reduce its carbon footprint by 29% (115 Mt CO_2-eq), while enabling the Land Use, Other Land Use Change and Forestry (LULUCF) sectors to increase carbon sequestration by 87% (257 Mt CO_2-eq). This would make the EU AFOLU sectors achieve negative net GHG emissions by 2050.

Main findings

Effectiveness of Combined Mitigation Scenarios: A combined scenario, with a reduction in wood harvest, carbon pricing, and set-aside of high organic content soils could achieve a 29% GHG emission reduction by 2050, with the implementation of carbon pricing playing a dominant role, alongside an additional 87% increase in carbon sequestration in the LULUCF sector.

Technological mitigation options: Among the different technological mitigation options, the highest GHG mitigation impact comes from fallowing of histosols, followed by feed additives, anaerobic digestion, precision farming, and nitrification inhibitors. Adoption rates, cost-effectiveness and mitigation potential vary across Member States.

Emission leakage: The introduction of carbon pricing causes some GHG emission leakage (7%), meaning higher GHG emissions in non-EU countries partially offset emission reductions in the EU. However, a scenario combining different strategies reduces emission leakage (4%), mainly due to enforced protection of histosols.

Agricultural production impacts: The afforestation and fallowing of histosols scenarios marginally affect overall EU food supply by primarily altering land allocation for agriculture. In contrast, a carbon pricing scenario substantially impacts livestock production, particularly beef, sheep, and goat meat (up to 8% decline), as well as crop production, with oilseeds being most affected.

Land use change impacts: Under the afforestation scenario, forest area expands by 3.4% (180 million ha), while within the carbon pricing and combined scenarios forest expansion is slightly higher (183 million ha by 2050). The histosol protection scenario safeguards organic soils, resulting in a modest increase in cropland and grassland to compensate for the set-aside of histosols area.

Producer and consumer prices: Animal products, especially beef, experience the most notable price increases, prompting consumers to shift toward poultry, pig meat, and plant-based proteins. Feed markets also react to these impacts, so that production and prices for cereals, especially barley, also increase

Quick guide

This study is based results from the CAPRI model, which assesses the impacts of various GHG mitigation scenarios related to the Agriculture, Forestry and Other Land Use sectors. CAPRI covers 47 key agricultural products, balancing supply and demand across global markets. It also provides detailed information on land use, such as forests, crops, and grasslands. The model evaluates how policy-induced changes in farming practices can reduce GHG emissions, supporting sustainability strategies in the EU.

1 Introduction

The project 'Economic assessment of GHG mitigation policy options for EU agriculture' (EcAMPA) was designed with the aim of assessing relevant aspects associated with a potential integration of the agriculture sector into the EU climate policy framework. In the context of reducing greenhouse gas (GHG) emissions from EU agriculture, the developments and scenarios examined covered issues related to production effects, the importance of technological mitigation options and the need to consider emission leakage for an effective reduction of global agriculture GHG emissions. In 2012, the JRC published a quantitative assessment of the possible production and economic impacts of the implementation of specific policy options (such as regionally homogeneous or differentiated emissions caps and a specific emissions trading scheme for agriculture) to mitigate GHG emissions in the EU (Pérez Domínguez et al. 2012). The first EcAMPA report (Van Doorslaer et al. 2015) marked the inception of the series, followed by the EcAMPA 2 (Pérez Domínguez et al. 2016) and EcAMPA 3 (Pérez Domínguez et al. 2020) reports. These assessments were done with the Common Agricultural Policy Regional Impact (CAPRI) model (www.capri-model.org).

A key contribution of EcAMPA lies in the analysis of specific GHG mitigation options (i.e. technical and management-based measures) in EU agriculture. These technological options are incorporated into the agricultural economic model CAPRI and tested under several illustrative GHG mitigation policy scenarios (Van Doorslaer et al. 2015, Pérez Domínguez et al. 2016). The endogenous representation of technologies was further extended in EcAMPA 3 (Pérez Domínguez et al. 2020) to cover agriculture carbon dioxide (CO_2) emissions related to the 'Land Use, Land Use Change and Forestry)' (LULUCF). This inclusion allows the evaluation to LULUCF-related CO_2 emissions and removals, considering both GHG accounting and specific technological mitigation options. Moreover, EcAMPA 3 introduced a set of techno-economic marginal abatement cost curves for specific GHG mitigation technologies at regional and EU Member State (MS) level. This allowed for computing the potential of each technology and its associated adoption costs. The results highlighted that these technological options need to be considered in combination and not just be added up individually. Moreover, the regional heterogeneity of biophysical and economic circumstances needs to be considered when determining the cost-effectiveness of mitigation technologies (Pérez Domínguez et al. 2020; Fellmann et al. 2021).

EcAMPA 4 follows the concept of continuously developing and refining the capacity of the CAPRI model in the context of GHG emissions accounting and reflecting mitigation options, and validation of assessment results. This new study focused especially on carbon sequestration in the forestry sector and improving key mitigation technologies such as the fallowing of histosols (i.e. protection of high organic content agricultural soils). In this regard, compared to previous studies a stronger focus is put on the estimation of GHG emissions and removals in the Agriculture, Forestry and Other Land Use (AFOLU) sectors, and on policies aimed at achieving a certain decarbonisation of the sector. Furthermore, EcAMPA 4 expands the modelling of climate change mitigation technologies to include additional farming practices important in the context of the Common Agricultural Policy (CAP).

At the core of this report, we present a set of policy scenarios designed to assess the economic and environmental impacts of various GHG mitigation policy options for the AFOLU sectors. On the one hand, we analyse the potential of specific mitigation measures for augmenting CO_2 removals in the Agriculture and Forestry sectors. On the other hand, we also focus on measures reducing both CO_2 and non-CO_2 emissions from these sectors. These GHG mitigation measures are covered through different scenarios focusing on increased afforestation, reduced wood harvest quantities resulting from adjustments in forest management practices, implementation of protective measures for histosols, and the introduction of carbon pricing incentives within the AFOLU sectors to enhance CO_2 removals and reduce methane (CH_4) and nitrous oxide (N_2O) emissions.

The combination of these GHG emission reduction strategies is modelled to maximise the climate benefits achievable while minimising significant area reallocations. This analytical framework contributes to policy discussions surrounding suitable measures aligned with the goals of the European Green Deal. The scenarios presented enable the analysis of policies related to the AFOLU sectors, 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. The policy scenarios are simulated using the CAPRI model, making use of the 2030 EU Medium-Term Agricultural Outlook (EC 2020) as the baseline for comparison, and further extending it to 2040 and 2050 using additional long-term projections from the GLOBIOM model (IBF-IIASA 2023; Havlík et al. 2014). The analysis then evaluates the impact of expanding the EU's carbon sequestration capacity to achieve climate neutrality by 2050.

The European Climate Law addresses the objective of achieving climate neutrality by 2050, as set out in the European Green Deal, establishing a legally binding commitment for Europe's economy and society to become climate-neutral by 2050. The legislation also sets the intermediate target of reducing net GHG emissions by at least 55% by 2030 compared to 1990 levels. Climate neutrality by 2050 means achieving net zero GHG emissions for EU MS mainly by cutting emissions, investing in green technologies, and environmental protection. The Law also includes a process for setting a 2040 climate target, with a high ambition on net emissions reductions by 2040. The law aims to ensure that all EU policies contribute to this goal and that all sectors of the economy and society play their part.

Despite an overall reduction of total GHG emissions in the EU by a third since 1990, the Agriculture sector has experienced a slower reduction process and has stagnated since 2005 Based on EU countries' current policies and measures, this trend is projected to continue, with only a 1.5% decrease in emissions expected between 2020 and 2040 (European Environmental Agency 2023). Policies and efficiency gains have reduced the emission intensities of some agricultural products, but this process has been counteracted by an increase in agricultural production. Therefore, new policies and an increased uptake of existing measures are needed to further reduce emissions. To accelerate this process, it is important to raise farmers' awareness regarding their responsibilities and the technical possibilities for emission reduction. Technical and financial support for investments and tailored advice at farm level are provided under the CAP. These elements could lead to a faster transition and better implementation of a variety of policy mechanisms. However, it is essential to acknowledge that the responsibility for moving the agri-food sector towards climate neutrality extends not only to farmers but also to consumers (e.g. adopting healthier and low carbon intensive diets) and other agri-food actors (e.g. reducing food waste in the food chain). Certainly, stronger stakeholder engagement is needed for a meaningful progress towards decarbonisation.

2 Methodology

2.1 Model description

CAPRI is an economic optimisation model for the Agriculture sector, encompassing 47 primary and secondary agricultural products. Product quantities are expressed in terms of physical primary product equivalents using the Supply Utilization Accounts (SUAs) of the Food and Agriculture Organization (FAO). It incorporates a global market module, representing a spatial comparative static multi-commodity model. This system is constructed as a square system of supply and demand equations, facilitating the analysis of bilateral trade flows between countries, consolidated into 40 trade blocks.

The inherent structure of the CAPRI model renders it exceptionally well-suited for the comprehensive analysis of GHG emissions. The modelling system has been adapted to facilitate the calculation of GHG emissions from agricultural sources, with a focus on activity-based assessments, as originally detailed by Pérez Domínguez et al. (2006). Subsequently, Pérez Domínguez et al. (2012) employed the CAPRI model to examine the potential production and economic impacts arising from specific policy options aimed at mitigating GHG emissions within the EU.

CAPRI represents a global agricultural sector model with a primary focus on the EU. It is designed for ex-ante impact assessment of agricultural policies and environmental and trade policies. CAPRI comprises two pivotal components: the supply and market modules, which engage in an iterative exchange of model feedback. The supply module receives information on input and output prices from the market module, subsequently generating estimates for the production supply of 65 agricultural primary and processed products within the EU. Crucially, the supply models operate independently, guided by market equilibrium prices obtained through an iterative procedure between these two modules.

CAPRI operates as a comparative static model, tailored specifically for scenario analysis. This entails the simulation of medium- to long-term outcomes for various scenarios at any given temporal point, with no consideration for lagged relationships. Consequently, the simulated results reflect the anticipated situation of the Agriculture sector in the baseline scenario, projecting the ex-ante repercussions of the scenario under investigation (Britz and Witzke 2014).

The AFOLU sectors have been included in the CAPRI model and serve as a crucial driver in both mitigating GHG emissions and enhancing carbon sequestration. Within CAPRI, land allocation in the Agriculture sector is determined by the profit-maximizing decisions made by representative regional farms in the EU supply module. This assumption also includes how agricultural land use responds to non-economic factors such as farmer’s traditions and additional constraints like land tenure laws, CAP regulations, and access to infrastructure. The model includes six endogenous aggregate classes, namely forestry, arable crops, permanent crops, permanent grassland, settlements and other land. The latter category encompasses unproductive grassland, shrubland other natural areas and bare land. Land use classes are connected to each other by means of calibrated land supply elasticities within a multinomial logit framework (i.e. the expansion of one class means the contraction of the others).

2.2 Overview of Agriculture, Forestry and Other Land Use sector emissions covered in CAPRI

Table 1 presents the GHG emissions of the Agriculture sector and Table 2 the emissions of the LULUCF sector, modelled in CAPRI[1]. EcAMPA 4 introduces a new feature compared to previous model versions: the inclusion of CO_2 emissions related to urea.

Table 1. Agriculture reporting items to the UNFCCC and emission sources modelled in CAPRI

	UNFCCC Reporting Agriculture Sector (CRF Sector 3)	**CAPRI Reporting and modelling**	
Methane	***A: Enteric fermentation***	CH4ENT	Enteric fermentation
	B: Manure management	CH4MAN	Manure management
	C: Rice cultivation	CH4RIC	Rice cultivation
Nitrous oxide	***B: Manure management***	N2OMAN	Manure management (stable and storage)
	D: Agricultural soils		
	1. Direct N2O emissions from managed soils		
	1: Inorganic N fertilizers	N2OSYN	Synthetic fertilizer
	2: Organic N fertilizers	N2OAPP	Manure management (application)
	3: Urine and dung deposited by grazing animals	N2OGRA	Excretion on pasture
	4: Crop residues	N2OCRO	Crop residues
	5. Mineralization/immobilization associated with loss/gain of soil organic matter		*Not active in the current version**
	6: Cultivation of histosols	N2OHIS	Histosols
	7. Other *		*Not covered in CAPRI**
	2. Indirect N2O emissions from managed soils		
	1: Atmospheric deposition	N2OAMM	Deposition of ammonia
	2: Nitrogen leaching and run-off	N2OLEA	Emissions due to leaching of nitrogen
	E: Prescribed burning of savannahs		*Not covered in CAPRI*
	F: Field burning of agricultural residues		*Not covered in CAPRI*
Carbon Dioxide	***G: Liming***	CO2LIM	Liming
	H: Urea application	CO2UREA	Emissions from urea application
	I: Other carbon-containing fertilizers		*Not covered in CAPRI*
	J: Other agriculture emissions		*Not covered in CAPRI*

Source: Authors elaboration (adapted from Pérez Domínguez et al. 2020).

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[1] The reader should be reminded that AFOLU emissions are the sum of emissions from the Agriculture sector and emissions from the Land Use, Land Use Change and Forestry sectors.

Table 2. LULUCF reporting items to the UNFCCC and emission sources calculated and reported in CAPRI

	UNFCCC Reporting Sector LULUCF (CRF Sector 4)	CAPRI Reporting and modelling	
Methane	*Land use, Land-use changes and Forestry*	CH4BUR	Biomass burning
		CH4HIS	Cultivation of organic soils
Nitrous oxide		N2OBUR	Biomass burning
		N2OSOI	Soil carbon losses
Carbon Dioxide		CO2BUR	Biomass burning
		CO2BIO	Losses of carbon in biomass and litter
		CO2SOI	Soil carbon losses
		CO2HIS	Cultivation of organic soils

Source: Authors elaboration

2.3 Technological GHG mitigation options

This section briefly describes the technologies used for mitigating GHG emissions in this study and explains the major assumptions taken for their implementation in CAPRI to assess their contributions in GHG mitigation. Most of the technological options discussed here are also presented in the previous studies (EcAMPA 2 and EcAMPA 3). However, to render this report self-contained, we describe briefly the measures as in Pérez Domínguez et al. (2016, 2020).

Table 3 presents the technological GHG mitigation measures that are endogenously determined in CAPRI. Each of those mitigation options are targeting a specific greenhouse gas (N_2O, CH_4 or CO_2). When a certain mitigation option is activated, a reduction in GHG emissions for the corresponding production activities is assumed. Following EcAMPA 2 (Pérez Domínguez et al. 2016) and EcAMPA 3 (Pérez Domínguez et al. 2020) the specific assumptions on mitigation potentials, mitigation costs and degree of adoption of these technologies by region within a certain time frame is partly derived from the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) database (GAINS - IIASA 2013; Höglund-Isaksson 2015, Winiwarter and Sajeev 2015; Höglund Isaksson et al. 2016), the AnimalChange project (Mottet et al. 2015), and systematic literature reviews conducted by the JRC (see Annex 3) and the Scotland's Rural College. For detailed descriptions of these technology-driven mitigation options, see Pérez Domínguez et al. (2016). Additional assumptions for the EU are gathered from internal survey-based research (e.g. winter cover crops and precision farming).

Incorporating these agricultural practices into the CAPRI model facilitates the evaluation of the environmental consequences associated with payments made under Agri-Environmental and Climate Measures (AECMs) within the Rural Development Programs (RDPs). Previous studies (EcAMPA 2 and 3) explicitly modelled these payments as a lump-sum transfer affecting environmental indicators. As we introduce an increasing number of farm practices as mitigation technologies, we gain the ability to differentiate the assessment of environmental impacts. This separation enables us to move from the assessment of environmental effects modelled as a collective lump-sum payment to the evaluation of the environmental impacts tied to individual farm practices.

Table 3. Technological GHG mitigation options included in EcAMPA 4.

	Mitigation options	*Emissions targeted*
Crop Sector		
1.	Better timing of fertilisation	N_2O
2.	Nitrification inhibitors	N_2O
3.	Precision farming	N_2O
4.	Increasing legume share on temporary grassland	N_2O; CO_2
5.	Rice measures	CH_4
6.	Fallowing histosols (abandoning the use of organic soils)	N_2O; CO_2; CH_4
7.	Winter cover crops	CO_2
Livestock sector		
8.	Anaerobic digestion: farm scale	CH_4; N_2O
9.	Low nitrogen feed	CH_4
10.	Feed additives: linseed	CH_4
11.	Feed additives: nitrate	CH_4
12.	Feed additive: 3-Nitrooxypropanol (3NOP)	CH_4
13.	Vaccination against methanogenic bacteria in the rumen	CH_4
Ammonia mitigation options		
14.	Low emission housing	CH_4; N_2O
15.	Covered storage of manure	CH_4; N_2O
16.	Low ammonia manure application	CH_4; N_2O

Source: Authors elaboration

Crop sector related mitigation technologies

This study covers nine technological mitigation options belonging to the crop sector. These options encompass a range of strategies, including those related to fertilisers, conservation tillage practices, and the promotion of legumes and winter cover crops.

The fertilizer-related options, which involve optimizing the timing of fertilization, using nitrification inhibitors, substituting urea, and increasing the share of legumes on temporary grassland and winter cover crops, are purpose fully designed to harness multitude of environmental benefits. These strategies reduce the potential loss of nutrients by enhancing the timing of fertilisation, thereby extending the retention of nitrogen in the form of ammonia (NH_3).

1. *Better timing of fertilisation*

This mitigation option assumes that the timely and optimal application of fertilisers, specifically nitrogenous fertilisers and manure, can bring about various environment benefits. An instance of this is the potential loss and conversion of a significant amount of nitrogen into GHGs when fertilizers are applied during autumn while crops are only planted in spring. This occurs before the crops have the chance to uptake and utilize the nitrogen for their growth. The extent of this loss resulting from inappropriate timing depends on several factors, including soil properties, weather conditions and farm management practices (e.g., fertilizer placement, crop rotation, or tillage system). Although implementing proper fertilizer application implies higher costs for farmers (e.g. increased expenses for frequent soil analyses and splitting fertiliser applications), it can also lead to higher yields and/or reduced fertilizer requirements (Hoeft et al. 2000). Data on how N use efficiency affects GHG emissions are based on a systematic literature review (see annex 3). However, the emission reduction potential associated with the 'timing of fertilisation' is constrained by the actual excess of fertilizer applied. These regional 'over-fertilization' factors are estimated in CAPRI at regional level.

2. *Nitrification inhibitors*

Nitrification inhibitors (NI) are chemical compounds that delay the bacterial oxidation process, especially the conversion of ammonium into nitrite (NO_2) by inhibiting the metabolic activity of Nitrosomonas bacteria. Additionally, they hinder the transformation of nitrite to nitrate (NO_3) by Nitrobacter bacteria for a certain duration. The primary objective of NI employment is to mitigate nitrate leaching by prolonging the retention of nitrogen in the form of NH_3. This mechanism also aids in reducing N_2O emissions resulting from nitrification and denitrification processes (e.g. Akiyama, Yan, and Yagi 2010; Lam et al. 2015; Ruser and Schulz 2015). However, the application of NI remains a topic under debate, due to the detection of traces of dicyandiamide in dairy products in New Zealand (OECD 2013). These traces raise concerns regarding potential negative effects on human health and the environment.

In CAPRI, we used the national shares of urea (based on MITERRA), plus the proportion of nitrogen applied as ammonium (100% of ammonium sulphates and phosphates, and 50% of ammonium nitrates and NPK fertilisers) as the upper limit for application. Data on how the use of NI improves N use efficiency and affects GHG emission factors are based on a systematic literature review (see annex 3). The emission reduction potential of the applying NI is also restricted by the regional over-fertilisation factors estimated in CAPRI (i.e. the excess fertilizer applied over the regional crop needs).

3. *Precision farming and Variable Rate Technology*

Precision agricultural technologies (PATs), including Variable Rate Technology (VRT), remote sensing technologies, Global Positioning Systems (GPS) and Geographical Information Systems (GIS), are helpful to optimize the application of inputs and machinery more precisely and contribute to the reduction of GHG emissions (e.g. Mulla 2013; Kloepfer, Klöble, and Eckel 2015). PATs can generally be applied to both crop and livestock production. In this report, however, we only discuss its application to crop production, defining it as 'an information and technology-based crop management system' (Heimlich 2003). In addition, VRT is separated from the PATs in here, because it is considered as a single precision farming technology with a broader application and reduced implementation costs (see Pérez Domínguez et al. 2016 and Pérez Domínguez et al. 2020 for more details). For the inclusion of precision farming as a mitigation technology option, we assume a potential 36% reduction in N_2O emissions based on the data available at (GAINS 2015). Like in the technologies above, the regional over-fertilisation factors estimated in CAPRI also limit the emission reduction potential of these technologies.

4. *Increasing legume shares on temporary grassland*

Increasing the share of legumes on temporary grassland improves soil carbon content and reduces the requirement for nitrogen fertiliser application by fixing nitrogen in the roots. It is frequently stated that one of the primary benefits of larger legume shares on grasslands is increased carbon sequestration. When the legume share is increased significantly, Lüscher et al. (2017) estimate an additional carbon sequestration of 300 – 500 kg C per ha and year. In CAPRI, we assume that increasing the legume share from the default value of 6.5% to 20% will result in an average 400 kg C per ha per year. The potential gain in carbon sequestration can be reduced proportionally, if the initial share is higher.

5. *Combined measures for rice cultivation*

While rice paddies are a major contributor to CH_4 emissions worldwide, they only make up 0.6% of total GHG emissions in EU agriculture. As a result, technological mitigation options targeting rice cultivation are of limited consequences in the EU. However, these options could still help to reduce agriculture emissions in specific regions of the EU. This mitigation option in CAPRI combines intermittent aeration, rice variety selection, and sulphur application. Since 2013, the parameters and cost assumptions from GAINS have been used.

6. *Fallowing histosols (abandoning the use of organic soils)*

Histosols, also called peat soils, muck soils, Moore (in Germany) and organosols (in Australia), are particularly efficient carbon sinks, because water acts as a barrier for oxygen and supresses the decomposition of peats in flooded areas. Drainage of organic soils (histosols) causes aeration and subsequent decomposition of the peat, resulting in significant CO_2 and N_2O emissions.

Histosol restoration/fallowing is considered an effective GHG mitigation option. CAPRI considers the mitigation option of fallowing histosols by reserving a certain proportion of agricultural land in each MS. The full implementation of the mitigation option would equal the total histosols in the region. This may result in, for example, in Finland idle land may amount to 10% of the Utilised Agricultural Area (UAA), but in Spain, it may amount to 0.5% of the UAA. The opportunity cost of land use (i.e. concurrent uses) is used as the direct costs of this measure. However, there are additional direct costs (e.g. rewetting) and indirect costs (e.g. transaction costs linked to regional land regulation) that farmers must bear to attain a 100% implementation rate of this measure.

For technical reasons, the protection of histosols from former cropland is separated in CAPRI from the set aside activity from former grassland, because the GHG emission coefficients for CO_2 from organic soils utilized for arable cropland and grassland are considerably different. Furthermore, in CAPRI, N_2O emissions from fallowing histosols are attributed to the Agriculture sector, while CO_2 and CH_4 emissions from fallowing histosols are attributed to the LULUCF sectors.

The assumptions have been updated within this study to refine the histosols shares and consider rewetting costs (see section 2.4).

7. *Winter cover crops*

Winter cover crops are included in CAPRI as one of the options to comply with the ‘Ecological Focus Area’ constraint of the CAP greening policy. In this regard, these crops are modelled as an activity with no output and, formally, no requirement of additional land. The area for cover crops is limited to the area not covered by regular crops during the winter season. The costs are implemented simply as 25% of machinery and other input costs from the CAPRI category ‘other fodder on arable land (OFAR)’ and 50% of sowing costs. We use data from the Farm Structure Survey (FSS) on Agricultural Production Methods (SAPM), a survey conducted in 2010 to collect data at the farm level on agro-environmental measures, to calculate the initial application rates of winter cover crops.

Winter cover crops, moreover, are viewed as a promising option for sequestering carbon in agricultural soils. Given that winter cover crops are generally legumes and are left on the fields, these crops would fix 75% of their N needs and deliver the corresponding amount of N to the main (future) crops, implying a comparable drop in N inputs, particularly mineral fertilizers. This results in lower CO_2 emissions from the production of mineral fertilizers, whilst lower N_2O emissions from mineral fertilizer application are countered by greater N_2O emissions from crop residues.

Livestock sector related mitigation technologies

8. *Anaerobic digestion*

Anaerobic digestion (AD) has emerged as a highly effective technology for mitigating GHG emissions associated with livestock manure. More specifically, it has shown notable success in reducing CH_4 emissions from stored manure and N_2O emissions from cattle slurries. In our analysis, we assume that only farms with more than 200 livestock units (LSU) have the economic viability to implement AD as a technological option for emission reduction. Community-based AD has not been considered in our analysis due to the potential for these AD systems to generate additional GHG emissions during the pre-digester storage phase, as the duration and method of manure storage are factors influencing emissions. Moreover, emissions may also arise during the transportation of manure to the community's digester. These supplementary emissions could potentially offset the carbon benefits typically associated with AD, hence warranting their exclusion from our analysis.

The data on LSU comes from the EU farm structure survey of Eurostat[2]. In the case of liquid systems that do not incorporate a natural crust cover, CH_4 losses of 25% are considered in the pre-digester phase of anaerobic digestion process. Leaching losses, on the other hand, are estimated to be 3% during the digester phase. To calculate CH_4 yield, revenues and CO_2 savings resulting from reduced fossil fuel consumption, information from Mottet et al. (2015) was utilized as a reference.

In the modelling approach adopted, the consideration of normal heat and electricity prices is crucial. These prices are determined by using national values published by IIASA, ensuring accuracy and consistency. In terms of farmers' revenues, the total energy production is calculated based on the manure output. Specific subsidies aiming at promoting large-scale biogas production are not considered in this analysis. Furthermore, it is expected that neither the electricity generation nor the biogas production processes will receive any subsidies.

In CAPRI, the costs associated with the implementation and operation of AD plants are determined based on the volume of manure (m_3), which is an endogenous variable. MacLeod et al. (2010) and Mottet et al. (2015) provide detailed information on the functional form of the costs associated with AD.

9. *Low nitrogen feed*

The implementation of low nitrogen feed (LNF) as a technological mitigation option has proven effective in reducing crude protein (CRPR) intake and consequently NH_3 emissions from livestock. This reduction is attributed to the direct relationship between dietary nitrogen input and the subsequent nitrogen excretion via urine and faeces. It has been observed that, on average, approximately one third of the dietary nitrogen intake is converted into animal protein. By providing LNF, the excretion of nitrogen is minimized, which is in turn has a positive impact on N_2O emissions from livestock (Kirchgessner, M., Windisch, and Roth 1994; Luo et al. 2010). Furthermore, LNF may influence both feed intake and the rate of digestibility, which can consequently affect the extent of CH_4 emissions from enteric fermentation and manure management.

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[2] In the Eurostat survey, only the category 100–500 LSU is available. We therefore linearly divided the category 100-500 LSU. For instance, if there are 100 animals in the 100–500 LSU, then one-quarter or 25 are allocated to the category 100–200 LSU and three-quarters or 75 are allocated to the category 200–500 LSU. This is a simplification and may not be accurate due to the asymmetric distribution. This assumption should be revised in the future.

In CAPRI, nitrogen excretion is directly derived from CRPR intake and nitrogen retention, which subsequently affects N_2O emissions associated with nitrogen excretion. Furthermore, it is expected that this mitigation option can be applied to all monogastric livestock and dairy cows during their time indoor, as well as 50% of other ruminants during their indoor periods. The costs associated with implementing LNF are estimated to be approximately 3 Euro per head, based on the crude protein surplus projections from CAPRI and the abatement potential is derived from GAINS. This cost, which represents approximately 5% of the total feed expenditure, has been inflated in comparison to the findings of van Vuuren et al (2015). The endogenous response in CAPRI of the feeding complex, such as substituting cereals for protein feed, may reduce the effective final cost. However, these costs can be reassessed in future analyses.

10. Feed additives: linseed

In animal nutrition, the inclusion of lipids, such as vegetable oils or animal fats, in animal diets serves to enhance energy content and optimize energy utilisation by reducing dry matter intake and increasing digestion. The incorporation of dietary lipids, especially linseed, has been found to enhance feed efficiency and decrease CH_4 emissions from cattle.

In the context of CAPRI, the implementation of the linseed feeding strategy as an emission mitigation option is feasible for the entire EU dairy herd, while being applicable to only 50% of other cattle categories. The intake of linseed is determined by the fat content of the diet, which is estimated endogenously in CAPRI. The addition of linseed is limited to a maximum of 5% of total fat content in dry matter intake. Based on estimations, it is estimated that, for each 1% increase in fat content, there will be a corresponding 5% reduction in CH_4 emissions resulting from enteric fermentation (Mottet et al. 2015).

11. Feed additives: nitrate

The utilization of nitrate as a feed additive can lower CH_4 emissions from enteric fermentation. However, caution must be taken to prevent any negative impact on cattle health. In the context of CAPRI, it is anticipated that this approach can be applied to all dairy cows during lactation and about half of the fattening cattle and replacement heifers during their indoor time. Given a maximum nitrate consumption of 1.5% of total dry matter intake, the expected reduction in CH_4 emission from enteric fermentation and crude protein intake is estimated at 15% and 0.42%, respectively. We assume that both linseed and nitrate can be used as feed additives independently or in combination.

12. Feed additives: 3NOP

3-Nitrooxypropanol (3NOP) is a synthetic compound acting as an enzyme inhibitor that specifically targets the enzyme methyl-coenzyme M reductase (MCR), which catalyses the final step of methanogenesis in microbes inhabiting the digestive system of ruminants. As a feed additive, 3NOP can be added to the feed of dairy and reproductive ruminants (as the additive is not yet approved for beef herds) when the animals are fed in a stable (i.e. not when grazing). For the implementation into the CAPRI model, it is assumed that the feed additive is given to all dairy and suckler cows during the time they spend indoors, for a maximum of 10 months per year. The minimum and maximum doses are 60 and 90 parts per million (ppm) per kg of dry matter intake. The price in

2030 is expected to be in the range of EUR 15-17.5/kg per kg of product.[3] The CH4 mitigation from enteric fermentation depends on the dose and the fat and fibre content in the feed. On average CH4 emissions from enteric fermentation are reduced by around 30 % for an animal which gets the 60 ppm dose.

13. Vaccination against methanogenic bacteria in the rumen

This technological mitigation option refers to the use of vaccines that target methanogens in the rumen, which are responsible for CH_4 production. However, the efficacy of this option as a CH_4 mitigation approach remains inconsistent. Further testing is necessary to establish its viability.

This mitigation option has already been incorporated into CAPRI as part of the ECAMPA project (see EcAMPA 2 and 3 for details). According to GAINS (2015), vaccination against methanogenic bacteria leads to a 5% reduction in enteric fermentation for both dairy and non-dairy cattle and sheep. The associated cost for implementing this technology is assumed to be EUR 10 per animal per year (GAINS) (Höglund-Isaksson 2015).

Ammonia related mitigation technologies

Mitigation measures aiming at reducing NH_3 emissions have also implications for non-CO_2 emissions. The implementation of these measures in CAPRI is based on the Miterra-Europe model (Velthof 2007) and the data from the GAINS model (Klimont and Brink 2004), but most emission change factors were replaced by the results of a systematic literature review (see annex 3), while reference values were replaced by data from national GHG inventories as far as available. NH_3 mitigation measures are implemented in CAPRI as endogenous options, following the same approach as for GHG mitigation measures (Pérez Domínguez et al., 2016). All available options for NH_3 mitigation primarily focus on manure management and application. Klimont and Winiwarter (2011) and Reis et al (2015) provide information on the costs associated with implementing these technologies.

The following measures have been incorporated in this study:

14. Low emission housing

This measure involves the use of flushing systems and other measures to directly transport manure into storage facilities. As this measure involves covered storage, it cannot be combined with the ‘covered storage’ option listed below.

15. Cover storage of manure

The measure aims to reduce the exposure of stored manure to air and offers low and high efficiency variants. Low efficiency systems utilize floating foils or polystyrene, while high efficiency systems employ concrete, corrugated iron or polyester caps. The cover of field storage is a mandatory requirement in Poland, Finland and Sweden, and it has been evolved as a farm practice.

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[3] The commercial product is Bovaer® 10, with approximately 10% of 3NOP content. Cost and emission reduction factors have been provided by DSM Nutritional Products Ltd., the company that has developed 3NOP and is the only one producing it. Model assumptions are based on bilateral communication with DSM (since 2022 DSM-Firmenich).

16. Low ammonia application

These measures aim at minimizing the surface exposure of manure applied to fields by placing manure under soil cover or vegetation. Like storage measures, there are low and high efficiency variants. The low efficiency variant includes slit injection, trailing shoes, slurry dilution, band spreading for liquid slurry, and integration of solid manure into the soil by ploughing it the day after application. The high efficiency variant entails immediate ploughing after application, deep and shallow injection of liquid manure, and immediate ploughing after the application of solid manure.

2.4 Protecting and restoring organic soils

In the context of the EcAMPA 4 study, regional shares of organic soils in CAPRI have been updated at the NUTS 2 level based on detailed geographical information as described in Annex 2. A major improvement in this study is the refinement of regional organic soil shares, a factor previously emphasised in earlier EcAMPA studies. This refinement is crucial because it directly influences the implementation of the mitigation option of protecting (i.e. fallowing) histosols. The allocation of agricultural land in each MS for this purpose depends on the regional distribution of histosols under cropland and grassland use. For instance, in regions with a high histosols share, such as Finland, a full implementation of the 'fallowing histosols' mitigation option may result in an additional idle land equivalent to 10% of the total UAA, whereas it may amount to 0.5% of the UAA in Spain (Pérez Domínguez et al. 2020).

Another key enhancement in EcAMPA 4 is the explicit consideration of restoration costs, such as rewetting, which were omitted in earlier EcAMPA studies. The cost of restoring organic soils in Europe varies significantly depending on site characteristics, including whether the peatlands are upland or lowland. The costs associated with each restoration technique can show considerable variability, depending on several factors such as the type of machinery required and the accessibility of the peatland area. Capital costs can fluctuate spatially, being relatively high for severely degraded sites and comparatively lower for lightly degraded sites (Moran et al. 2013). For instance, (COWI, Ecologic Institute, and IEEP 2020) estimate restoration costs in the EU to range between € 4,900 and € 6,240 per hectare, A broader assessment across European countries reveals restoration costs ranging from € 2,135 to € 7,335 per hectare. Notably, Ireland and Finland exhibit relatively lower restoration costs, whereas the Netherlands and Germany report higher restoration costs. Table 4 provides a more detailed overview of restoration costs across EU countries.

Table 4. Overview of average restoration costs for histosol sites in some European countries (Euro per ha)

	Cost Range (€ per ha)	Source
Restoration costs (EU)	€ 4,900/ha - € 6,240/ha	(COWI, Ecologic Institute, and IEEP 2020)
Germany	€ 3,000/ha - € 5,000/ha (incl. land purchase)	(Förster 2010)
Poland	€ 800/ha - € 3,100/ha (incl. topsoil removal)	(Klimkowska et al. 2010)
Netherlands	€ 10,000/ha - € 30,000/ha (incl. topsoil removal)	
Great Britain	€ 235/ha - € 11,700/ha	(Moxey and Moran 2014)
Finland	€ 800 €/ha	(Rana et al. 2024)
Ireland	€ 750/ha	(Dietzel and Maes 2015)
Austria	€ 31,000/ha	(Andersen et al. 2017)
United Kingdom	€ 1,200/ha	

Source: Authors elaboration

Fallowing histosols can yield significant climate benefits, primarily by halting carbon emissions from drained peatlands. This study quantifies the benefits, assessing the impact of fallowing histosols with restoration costs, based on the distribution of organic soils across the EU MS as derived from a meta-analysis of the literature. In the scenarios (see Table 5 in section 3), histosols are assumed to provide maximum carbon benefits through full rewetting, incorporating restoration costs.

In CAPRI, the mean investment cost estimates provided by COWI (2020) are adopted, considering a 30-year horizon and a 1% interest rate. This leads to an estimated restoration cost of approximately 216 € per hectare per year for the default scenario of protecting histosols. This specification of restoration costs prevents double counting of endogenous opportunity costs (i.e., land rents), which were reported as restoration expenses in previous CAPRI studies, leading to potential accounting overlaps with land purchase costs. Moreover, it distinguishes topsoil removal costs when calculating restoration expenses. However, topsoil removal is a practice not limited to carbon mitigation but also applied in biodiversity conservation efforts, such as restoring a previous oligotrophic state. Therefore, these costs should not be solely attributed to carbon mitigation efforts. Furthermore, we explore an alternative scenario specification in which histosols are left fallow without undergoing rewetting (no restauration costs). In this case, 50% of the benefits observed in the default specification are assumed. Since histosols are unevenly distributed across Europe, our analysis is specifically centred on countries with significant histosols area.

It is important to stress the fact that restoration costs can be large and not uniform across MS, so this is a limitation in this study. A more detailed analysis could be done with additional data on costs. Several EU-funded projects are currently investigating these aspects, focusing on sustainable land-use and management practices and policies in agriculture and forestry, as well as the role of EU land use policies in supporting the EU's climate neutrality target (see www.lamasus.eu).

2.5 Forest carbon stock assessment

This study makes use of estimated carbon emission factors (EFs) derived from the Carbon Budget Model (CBM) (Pilli et al. 2016; Blujdea et. al. 2022, Pilli et al. 2024). These factors replace emission factors (EFs) employed in previous studies, such as EcAMPA 2 (Pérez Domínguez et al. 2016) and EcAMPA 3 (Pérez Domínguez et al. 2020) which relied on data conforming to the Common Reporting

Format (CRF) from the UNFCCC. In those studies, the UNFCCC-CRF data were accessible for the ex-post period, and it was assumed to remain constant when estimating the LULUCF sector's capacity to sequester CO_2 from the atmosphere.

Within the UNFCCC framework, EFs are expressed as per hectare (ha) carbon (C) or CO_2 effects and are then multiplied by corresponding areas to calculate the total emissions. In our study, the CBM data provides harvest factors expressed as C per hectare for harvested trees and projected EFs based on the provided harvest factor information. This approach is also applicable to harvest factors obtained from external sources, such as the POTEnCIA model. Additionally, the CBM's carbon flows can be used for the following purposes:

- Estimating gain and loss factors for living biomass,
- Deriving EFs for dead wood and litter, and
- Calculating soil organic carbon in mineral soils.

To establish a functional relationship between emission and harvest factors, linear regression coefficients have been estimated and the outcomes have been compiled in a format consistent with UNFCCC data. During this process, the empirical validity of the estimated regression coefficients was assessed. For example, the forest management coefficients used to project CO_2 emissions and removals from land-use changes and forest management activities due to carbon losses in biomass for the countries covered by CBM. However, for countries not included in CBM, future harvest factors are assumed to remain unchanged.

CBM-based emission factors (EFs) reflect a slight increase in the forest sink on the EU level between 2015 and 2030, as observed in the studies by Pilli et al. (2017) and Capros et al. (2021). Nonetheless, this change varies across countries. For instance, a few MS like Slovenia, Austria, Spain, Belgium and Luxembourg, are projected to sequester more CO_2 in 2030 compared to 2015, whereas Portugal and the Netherlands are expected to reduce their sequestration in biomass per hectare.

It is important to note that while we incorporate CBM-based forest management coefficients and EFs, the CAPRI model does not explicitly simulate wood markets. Consequently, carbon effects associated with varying wood harvests are not modelled, as the model does not currently incorporate a carbon price mechanism that would in part influence forest management decisions.

3 Scenarios

This section introduces a set of scenarios designed to evaluate the economic impacts that may arise from various GHG mitigation policy options within the Agriculture and LULUCF sectors. These scenarios are designed to provide a robust framework for the analysis of future policies and their potential implications on these sectors. They consider a range of factors, including carbon pricing mechanisms and external mitigation factors, to simulate the impacts of the proposed policy changes. The aim is to provide a clear understanding of how different policy options could influence the adoption of GHG mitigation technologies, farming practices, and ultimately, changes in land use.

These scenarios are categorized into two major groups:

- Mitigation strategies for enhancing CO_2 removal within the LULUCF sector, and
- Mitigation options to reduce CO_2 and non-CO_2 emissions within the LULUCF and Agriculture sectors.

In recent years, the carbon content in EU soils has been increasingly threatened due to intensified agricultural practices and the negative impact of the climate change (e.g. higher frequency of droughts). The overarching objective of these scenarios is to assess the potential impact of policies enhancing EU's carbon sequestration capacity, thereby facilitating the achievement of climate neutrality by 2050. Immediate action is required to reverse the current trend, encompassing measures such as planting or maintaining trees, the implementation of more sustainable forest management practices (including harvesting), and the enhancement of soils' sequestration capacity, particularly concerning the protection of organic soils.

3.1 Increased afforestation

Forests currently cover around 40% of the EU's total land area and the expansion of forested area is essential for mitigating climate change by absorbing and storing CO_2. Sweden, Finland, Spain, France, Germany and Poland have the highest forest cover in the EU, accounting for two thirds of the forested landscape. The EU has seen steady growth in forest cover due to natural regeneration and afforestation efforts. However, the full potential of forests to sequester carbon is not being realized due to the slow growth rate of young forest.

To address this, an Afforestation scenario (Affor) has been developed to simulate the long-term impact of increased forest cover on terrestrial carbon stocks. This scenario offers an exploratory interpretation of active afforestation initiatives by increasing the current annual afforested area. Unlike previous scenarios developed in CAPRI where there is no active demand for forest cover expansion, this scenario actively designates land for afforestation.

The EU's diverse geography and climatic conditions required a tailored approach to assess the potential for expanded forest cover. A spatially explicit land-use model was employed to consider factors like suitability, land use competition, and territorial policy constraints, including Natura2000 (Barbosa et al. 2023). The goal of this scenario is to enhance terrestrial carbon sequestration by expanding forested regions by 2030. We, therefore, assume the afforestation of 7.5 million hectares (Mha). This additional afforested land is achieved through both active planting and natural regeneration and is maintained up to 2050. Implementing this scenario will contribute to the growth of EU forest cover, enhance the EU's land carbon sink and stock, and support EU's commitment to achieving its biodiversity targets and GHG emission reduction, as set out in the European Climate Law.

The EU has developed a new forest strategy that advocates for sustainable reforestation and afforestation practices. This new forest strategy has recognized the central and multifunctional role of forests to achieving a sustainable and climate-neutral economy by 2050.

3.2 Sustainable forest management

In recent years, the capacity of the LULUCF sector to remove CO_2 from the atmosphere has been decreasing, primarily due to rising wood harvests, pests, continued emissions from organic soils and natural disturbances (e.g. fire and windstorms), particularly in central European countries. In response to this challenge, this Forest Management (FM) scenario aims to evaluate the potential of reduced wood harvest in forests to enhance carbon storage in European forests. A reduction in wood harvest will directly lead to an increase in carbon sequestration. This fact is based on the principle that forests, by virtue of their photosynthetic processes, absorb CO_2 from the atmosphere and store it within their biomass and soil (Rougieux et al. 2024). By reducing forest harvest rates, we can preserve existing carbon stocks and allow forests to continue accumulating more carbon, thereby enhancing the carbon sink capacity of forests. However, the age of the forest affects the growth rate of the forest, which changes non-linearly with time. Specifically, the carbon sink capacity of very young stands is limited. Conversely, the senescence of trees in old stands can also limit their carbon sink capacity, as older trees often experience declining growth rates and increased mortality. To isolate the effects of harvest reduction on carbon storage, this scenario incorporates a controlled environment, free from external interventions that could influence forestland areas or growth rates. Specifically, we exclude carbon taxes or subsidies that might bring incentives or disincentives to forest management practices. Additionally, we assume that no significant external disturbances, such as extreme events or forest fires, affect the overall forest health and productivity of forests. We introduce a forest management approach specially designed to enhance carbon storage in forest ecosystems. This approach emphasizes reducing wood harvest by 10%, a reduction that could have a substantial impact on carbon sequestration without compromising the sustainability of forest management.

To quantify the anticipated increase in carbon storage, we employ a dedicated module in CAPRI that incorporates emission factors (EFs) from the Carbon Budget Model (CBM). CBM coefficients reflecting a 10% reduction in harvesting were regionalized at MS level and provide a robust basis for assessing the carbon sink potential under the FM scenario. We assume that forest growth rates remain consistent with historical data.

It is important to note that this scenario does not consider the potential financial implications of reduced harvests on forestry net returns. This exclusion is intentional, as we seek to isolate the purely biophysical effects of harvest reduction on carbon sequestration. We acknowledge that lower wood harvest could impact forestry profits, but this financial aspect is beyond the scope of this study. Future studies could further explore the financial impacts of this scenario and its broader implications for sustainable forest management practices. Furthermore, we also acknowledge that our analysis did not account for the carbon storage potential of the harvested wood products.

3.3 Protection of organic soils

Pristine peatlands globally represent significant carbon reservoirs. However, the drainage of organic peat soils for agricultural purposes can trigger peat decomposition, leading to substantial emissions of CO_2 and N_2O. This mitigation scenario (HisX) involves fallowing or restoring the available histosols used for crop cultivation and grassland in each EU NUTS 2 region. For instance, in regions characterized by a high prevalence of histosols, such as Finland, if the government (or farmers) would decide to ban agricultural production on histosols to protect them and prevent GHG emissions, this would imply that for example, in Finland, a 100 % implementation rate of the mitigation option 'fallowing histosols' may result in idle land equal to 10 % of the UAA, whereas in Spain, this is perhaps 0.5 % of the UAA (see Pérez Domínguez et al. 2020). It is, however, important to account for restoration expenses, including activities like rewetting of drained peatlands, which were not considered in previous EcAMPA studies.

As outlined in section 2.4, according to COWI (2020), the average cost of peatland restoration across the EU varies between €4,900/ha and €6,240/ha, depending on factors such as restoration sites characteristics (e.g., upland or lowland peatlands), machinery type used, and accessibility of the peatland area. We considered the mean investment cost as reported by COWI (2020) together with a 30-year timeframe and a 1% interest rate, yielding an annual restoration cost of approximately 216 € per hectare. Technically, this scenario is denoted as *HisX* since it foresees a mandated (or exogenous) protection of all histosols, so that the adoption of this mitigation options is not subject to an economic decision process. Having said that, the associated restoration costs needed to achieve the reported emission reductions are included.

3.4 Inducing sectoral emission reductions through carbon pricing

This carbon pricing scenario (CP) focuses on the emissions reduction objectives outlined in the new Commission proposal aimed at revising the LULUCF regulation with the goal of achieving climate neutrality. To achieve this, we consider separate emission reduction targets for both the LULUCF and Agriculture sectors through the implementation of separate mechanisms: carbon taxes for CO_2 emissions and carbon subsidies for CO_2 removals. We employed a "reasonable" carbon pricing methodology for non-CO_2 GHG emissions, as defined in Frank et al. (2019). This approach involves a projection of 250 USD per metric ton of CO_2 equivalent by the year 2070, following an exponential carbon price trajectory. This corresponds to 60 and 100 euros per ton of CO_2 equivalent in 2040 and 2050[4], respectively. However, in the context of the LULUCF sector, we assume that only a marginal carbon price level (equivalent to 2.5% of the non-CO_2 carbon price) is sufficient to incentivise desired changes. Consequently, this results in a notably lower carbon price, amounting to 1.5 and 2.5 euros per metric ton of CO_2 equivalent. A previous study of Gocht et al. (2020) has indicated that higher carbon prices can lead to substantial afforestation effects by 2050, surpassing even those observed in the exogenous afforestation scenario (denoted as "Affor scenario). The introduction of distinct carbon prices for the Agriculture and LULUCF sectors allows for the simulation of a flexibility mechanism between these two sectors, either through ad-hoc rules or cost-effectiveness considerations.

3.5 Combined set of mitigation strategies

The last scenario presented in this report (Combi) combines components from the scenarios previously described, with the following considerations:

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[4] Carbon prices are expressed in 2020 values and inflated with a long-run inflation rate of 1.9 to 2030, 2040, and 2050. Thus, we ignore the current short-run surge of inflation in Europe in this calculation.

- It excludes the components from the Affor scenario, which is distinguished by a predefined target to expand forest area. This specific aspect has been omitted due to the significant impact it exerts on spatial reallocations within the CP scenario, ensuring a more balanced and realistic representation in the Combi scenario.
- It is assumed that the forest harvest is reduced as in the FM scenario and remains unaffected by carbon prices.
- The histosols protection component is implemented in the most ambitious variant, entailing full restoration efforts across all organic soil areas, i.e. maximum application of the measure fallowing histosols (as in the HisX scenario), and
- Carbon prices play an important role in guiding all other economic adjustments in the Agriculture and LULUCF sectors (as in the CP scenario).

3.6 Scenario overview

The primary objective underlying the five scenarios is to offer insights into the possible contribution of the AFOLU sectors to climate neutrality. We evaluate the impact of these policy scenarios concerning GHG mitigation relative to the reference scenario (REF). The REF scenario presents the development of EU agricultural production and associated GHG emissions based on current market trends, the existing policy framework, and voluntary adoption of mitigation technologies. Table 5 provides a summary of the scenarios simulated in this study, highlighting their key determinants.

Table 5. GHG mitigation scenarios in EcAMPA 4

Scenario	***Forest area [Mha]***	***Forest management [in %]***	***Protection of histosols***	***Carbon Price on non-CO_2 emissions [€]***	***Simulation year***	***Carbon Price on CO_2-eq emissions & removals [€]***
Affor	7.5				2050	
FM		10% reduction in harvesting			2050	
HisX			Histosols protection with restoration costs		2050	
CP				100	2050	2.5
Combi		10% reduction in harvesting	Histosols protection with restoration costs	100	2050	2.5

Source: Authors elaboration

4. Scenario results

In this section, the results of the REF and various GHG mitigation policy scenarios are presented. Among the mitigation options assessed, carbon pricing emerges as the most efficient instrument to reduce EU agriculture GHG emissions. However, it is important to note that this could potentially lead to increased emission leakage (i.e. higher emissions in other world regions), therefore, having a limited impact on the reduction of net global emissions. Scenario results are compared to the REF scenario, thereby illustrating the ex-ante economic impacts of these mitigation policies. Furthermore, we provide a comprehensive description of the evolution of EU agriculture, including aspects such as agricultural production, price dynamics and changes in land use.

4.1 Impacts on GHG emissions

According to the REF scenario, the EU is expected to witness a 4.4% reduction in agriculture emissions by year 2050, relative to the base year 2020[5] (see Figure 1). The REF scenario estimates that GHG emissions from EU agriculture will reach 390 million tonnes (Mt) CO_2-eq in 2050, which is about 7% higher than what is projected by the EEA (2023)[6]. The disparities between the REF and FAO projections mostly come from variances in the underlying emission factors, since activity data are shared. In CAPRI, emission factors for a projected year are determined with consideration for historical trends, thus accounting for technological advancements. In contrast, FAO calculations maintain emission factors associated with crop and livestock production activities constant.

Regarding forest management practices, any anticipated reductions in operations are expected to yield similar results in agriculture non-CO_2 emissions to those projected by the REF scenario (Figure 1). This is primarily because reductions in forest management activities in the FM scenario do not significantly impact CH_4 and N_2O emissions. This could mainly be the outcome of no substantial changes in livestock herds in this scenario (see Annex 1), as animals are the primary sources of CH_4 and N_2O emissions. Consequently, this indicates that, in alignment with the findings of Roebroek et al. (2023), decreasing forest management intensity (decreasing harvest) cannot be regarded as a viable alternative for mitigating non-CO2 emissions. Nevertheless, the FM scenario results in an additional carbon sequestration of 63 Mt CO_2-eq (calculated as the difference between -358 in the FM and -295 in the REF, see Figure 3). This is primarily due to the lower wood harvests (a 10% reduction) relative to the REF scenario.

A similar impact is observed from an afforestation strategy viewpoint. The Affor scenario results in an almost negligible reduction in agriculture GHG emissions, which is primarily attributed to a marginal shift in land use from agriculture to forestry, which in turn has some minor impacts on reducing CH_4 and N_2O emissions due to slight production shifts in the livestock and crop sectors (see Figure 2).

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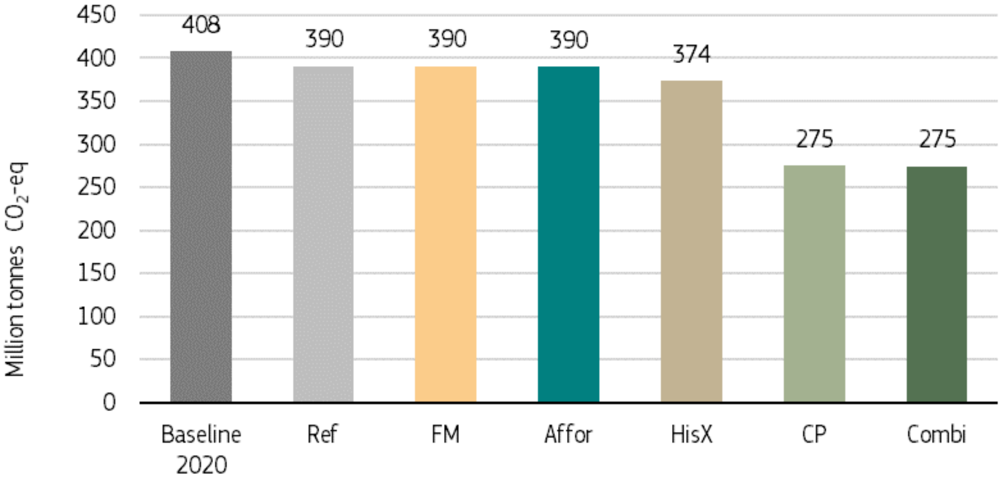
[5] CAPRI estimates 408 Mt of CO_2-eq emitted in the EU in year 2020 from the Agriculture sector. However, according to the European Environment Agency inventories, emissions from agriculture for the same year are reported to be 382 Mt CO_2-eq (EEA 2022).

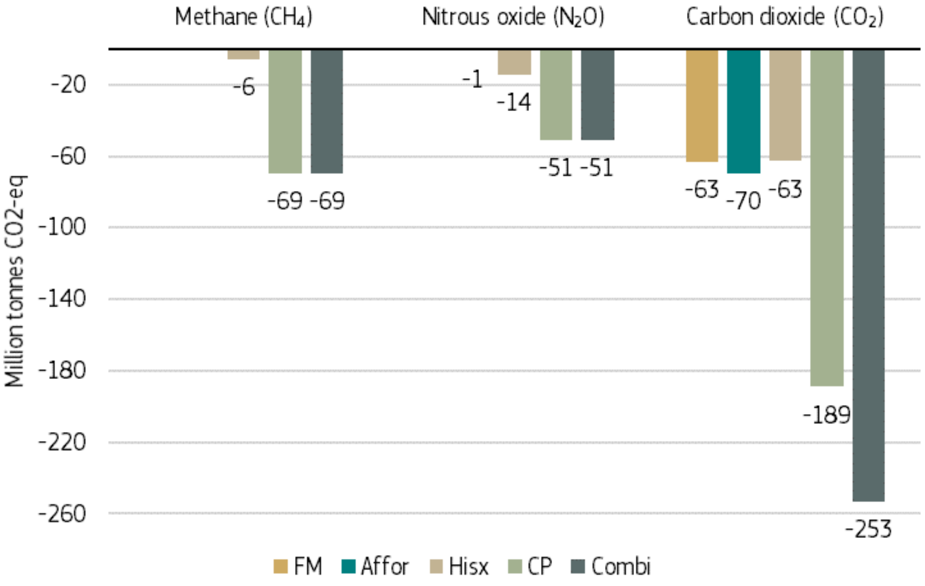
[6] The European Environment Agency projects EU agriculture emissions to reach 362 Mt CO_2-eq by 2050.

Figure 1. EU Agriculture GHG emissions in 2050[7]



Source: CAPRI results

Figure 2. EU AFOLU GHG emissions by source in 2050 (absolute difference to REF)



Source: CAPRI results

However, while the Affor scenario does not yield a substantial reduction in non-CO_2 emissions, it does contribute to the enhancement of terrestrial carbon stocks through the expansion of forested areas. Figure 2 illustrates a reduction of 70 Mt CO_2 emissions compared to the REF, a positive effect on the overall carbon balance within the LULUCF sectors as also reflected in Figure 3. This

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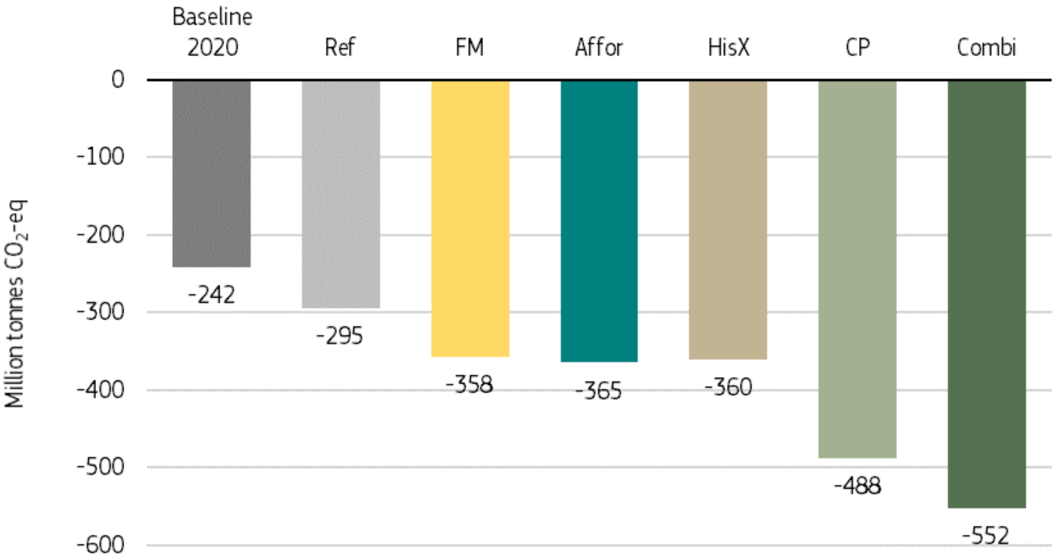
[7] These are mainly non- CO_2 emissions. Agriculture emissions are presented in Table 1. Agriculture reporting items to the UNFCCC and emission sources modelled in CAPRI

improvement is primarily driven by increased forested areas and underscores the pivotal role of afforestation in this context. The most significant contribution stems from a 63 Mt additional carbon sequestration through the further reduction of CO_2 emissions from biomass and litter, while an increase in soil carbon sequestration contributes an additional 6.9 Mt. It is important to note that in the FM and Affor scenarios, carbon prices were not factored in, indicating a lack of incentives for alterations in forested areas. Furthermore, it is worth noting that the forest sector is not explicitly modelled in CAPRI, and as such, the economic aspects of the forest sector are not considered in this analysis.

Figure 3. EU LULUCF GHG emissions in 2050[8]



Source: CAPRI results

In the HisX scenario, the practice of fallowing histosols has been enforced to its maximum potential and emerges as a strategy with the potential to significantly reduce GHG emissions within the agriculture sector. This approach results in a 4.2% reduction in agriculture emissions compared to the REF scenario (see Figure 1). Within the LULUCF sector, the practice of fallowing histosols is projected to trigger direct savings of 82 Mt CO_2 emissions in the EU (only accounting mitigated CO_2 and CH_4 emissions of fallowing histosols). However, these savings are partly offset by losses of carbon in biomass and soils resulting from the expansion of agricultural area use (about +118 thousand hectares, k ha) because of shifts in agricultural production activities, resulting from the fallowing of the histosols area. Consequently, the net gains in total emission reductions in the LULUCF sector are reduced to 65 Mt CO_2 (Figure 3), which still corresponds to an increase of approximately 22% in the net carbon sequestration (see Figure 3).

In the Agriculture sector, the reduction of 16 Mt CO_2-eq emissions (Figure 2) is the result of direct emission savings due to the fallowing of histosols and indirect effects due to production shifts. Approximately 75% of the reduction in agriculture emissions arise directly from reduced N_2O

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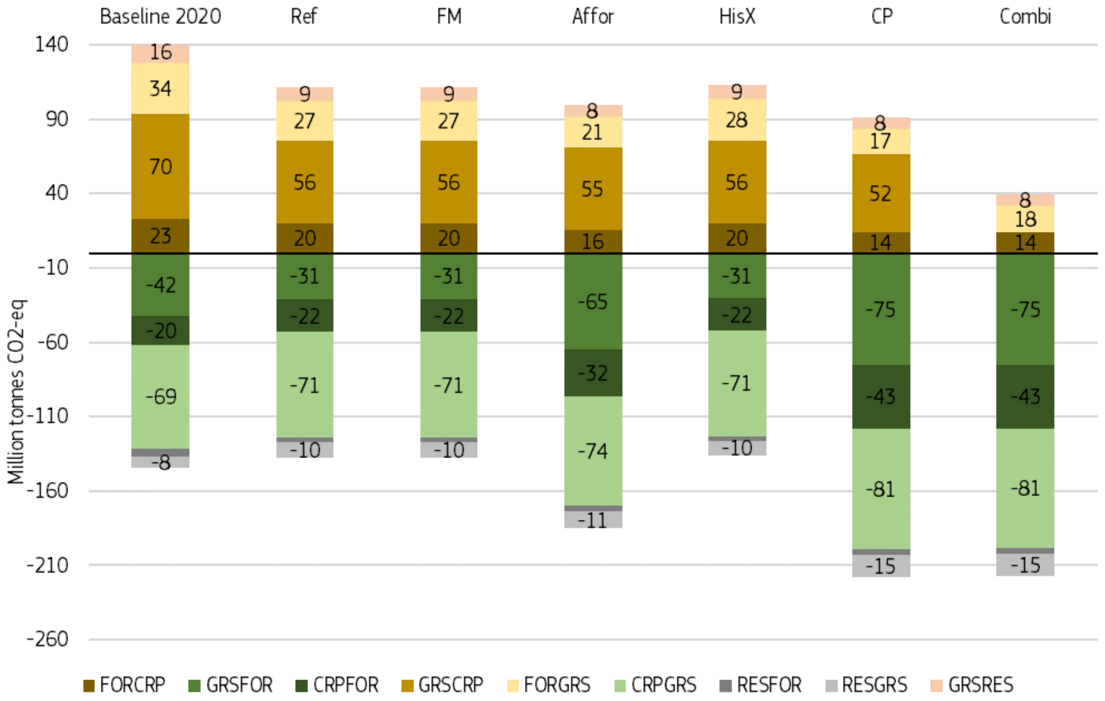
[8] LULUCF emission are presented in the Table 2. LULUCF reporting items to the UNFCCC and emission sources calculated and reported in CAPRI

emissions from histosols, while the rest is partially attributable to lower emissions from livestock, particularly a reduction in CH_4 emissions from enteric fermentation (contributing to 10% of the reduction of agriculture emissions under this scenario). Decreases in the livestock sector arise especially due to a reduction in fodder area as a direct consequence of taking grassland out of production, which has adverse effects on livestock production levels.

In the CP scenario, the gains within the LULUCF sector predominantly result from land use changes towards forest and grassland areas (see Figure 4). In the REF scenario, the LULUCF sector is projected to experience a 53 Mt CO_2-eq net increase of sequestered carbon between 2020 and 2050 (Figure 3). The simulated carbon price is projected to increase LULUCF emission savings from 295 Mt CO_2-eq in the REF scenario to 488 Mt CO_2-eq in the CP scenario by 2050 (see Figure 3). Within the LULUCF sector, the key contributing factor lies in the sequestration of carbon in biomass and litter, which is closely associated with afforestation activities. In the Agriculture sector, the emission reduction is 115 Mt CO_2-eq (-29 %; Figure 1), with the primary contributor to the emissions reduction being the decrease in CH_4 emissions from enteric fermentation (contributing to 48% of the total reduction in agriculture emissions).

Figure 4. EU LULUCF GHG emissions and removals per land use change sector in 2050

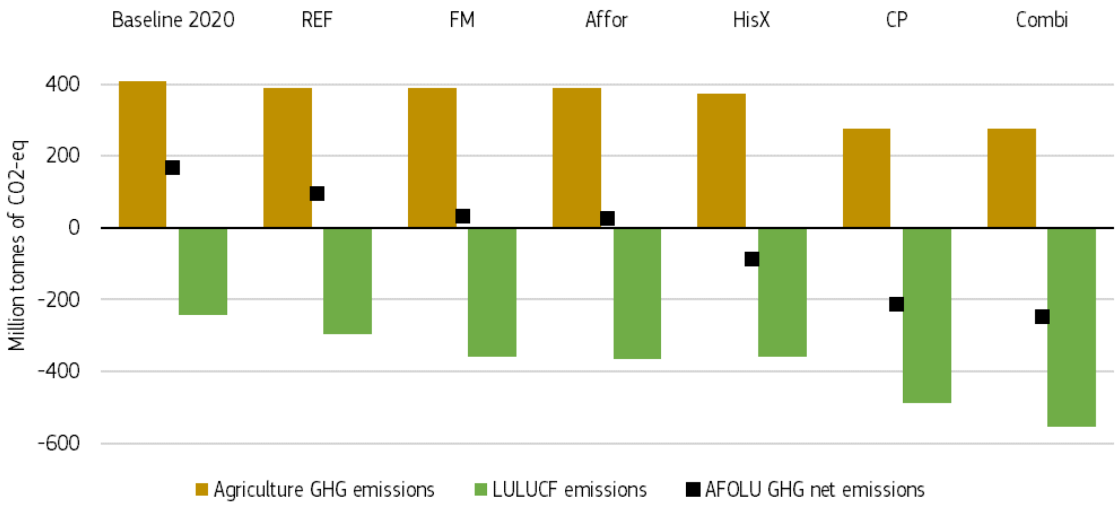


Source: CAPRI results. Legend: FORCRP: forest to cropland; CRPFOR: cropland to forestland; GRSFOR: grassland to forestland; RESFOR: residual land to forestland; GRSCRP: grassland to cropland; RESFOR: residual to forest; RESCRP: residual to cropland; CRPOGRS: cropland to grassland; RESGRS: residual land to grassland; FORRES: forestland to residual land; GRSRES: grassland to residual land.

As illustrated in Figure 3, the Combi scenario exhibits even a higher potential than the CP scenario to reduce CO_2 emissions stemming from LULUCF-related activities, amounting to a total of 552 Mt CO_2-eq annually sequestered. This is a remarkable 88% reduction in LULUCF emissions compared to the REF scenario. In contrast, the FM, Affor and HisX scenarios are anticipated to exert minimal influence on the reduction of emissions related to LULUCF related activities. This is attributed to the fact that these mitigation strategies do not substantially deviate from the dynamics observed in the

REF scenario, as delineated in Figure 3. Among the array of policy elements considered in the Combi scenario, the carbon price emerges as the most efficient method for reducing CO_2 emissions from LULUCF activities (Figure 2). The main land use change elements explaining these effects are the conversion of cropland and residual land into grassland (96Mt CO_2-eq), grassland, cropland and residual land into forested areas (118 Mt CO_2-eq). These land conversion activities account for approximately half of the total reduction (see Figure 4). However, it is imperative to note that the conversion of grassland into cropland can potentially become a source of CO_2 emissions, comprising 52 of the CO_2 emissions stemming from LUC activities. As anticipated, the Combi scenario, encompassing also the components of the FM, CP and HisX scenarios, demonstrates considerable effectiveness in reducing GHG emissions within the EU Agriculture sector, but this is debited to the impact of the carbon price on non-CO_2 emissions, which shows to have almost the same impacts on agriculture emissions as under the CP scenario. Overall, agriculture emissions in the EU decrease by 29% compared to the REF in 2050. It becomes evident that the livestock sector contributes significantly to both CO_2 and non-CO_2 emissions, surpassing the emissions generated by other agricultural activities. The Combi scenario shows that combining strategies across agriculture and land use can substantially mitigate or even reverse GHG emissions in the AFOLU sectors as shown in Figure 5. The Combi scenario shows the greatest benefits in terms of GHG mitigation, with the lowest net emissions (most negative), followed by CP and HisX.

Figure 5. EU Agriculture and LULUCF GHG emissions and total AFOLU net emissions in 2050



Source: CAPRI results

The livestock sector plays a pivotal role in reducing CH_4 emissions, while the crop sector significantly contributes to the reduction of N_2O emissions. This decrease in GHG emissions is primarily driven by a reduction in cattle herd size, consequently reducing CH_4 production via enteric fermentation. Subsequently, N_2O emissions from crop production and the application of synthetic fertilizers also witness a decline. By 2050, EU aggregate production levels of beef meat, pig meat, and raw milk are projected to experience respective reductions of 8%, 3%, and 1% (see Annex 1). This results in a substantial reduction in GHG emissions. Furthermore, improvements in GHG efficiency within crop and livestock production practices also contribute to the overall reduction of GHG emissions by 2050.

Scenario results show considerable variation among MS. Compared to the baseline 2020, several MS, such as Belgium, Bulgaria, Czech Republic, Greece, Italy, Lithuania and Slovak Republic experience a decline in projected GHG emissions in the REF by 2050 (see Table 6). Agriculture emissions decrease in the CP and Combi scenarios across all MS due to the carbon price, but the relative impact varies, which depends on a mixture of production structures, the relative importance of the livestock sector, and the capability to adopt technological GHG mitigation options. In the HisX scenario, some MS show a slight increase in agriculture GHG emissions as they have generally a relatively lower share of histosols area and can rather benefit from some induced production changes in other MS, which leads to a certain increase in emissions.

Table 6. EU GHG Agriculture sector emissions by EU Member State in 2020 and 2050 (percentage difference to REF)

	Total Mt CO2eq		***Change to REF 2020 [in%]***	***Change to REF 2050 [in %]***				
	REF 2020	***REF 2050***	***REF 2050***	***FM***	***Affor***	***HisX***	***CP***	***Combi***
EU	408.0	390.2	-4.4	0	-0.1	-4.2	-29.5	-29.6
Austria	7.2	6.4	-12.2		0.1	-0.5	-23.1	-23.1
Belgium	10.3	8.9	-13.7		-0.2	-1.1	-25.9	-25.9
Bulgaria	5.8	5.7	-2.2		-0.9	-4.8	-23.0	-23.0
Croatia	3.4	3.5	4.7		-2.0	0.1	-27.8	-27.8
Cyprus	0.6	0.6	7.2		-0.1	-0.4	-26.3	-26.3
Czech Republic	7.4	6.5	-11.7		0.4	0.5	-29.2	-29.1
Denmark	13.8	14.4	4.2		0.0	-3.6	-34.3	-34.3
Estonia	1.9	2.0	8.0		-1.7	-22.7	-45.8	-45.8
Finland	6.0	6.0	-1.0			-14.0	-39.6	-39.6
France	76.9	69.8	-9.3		-0.1	-1.2	-25.7	-25.7
Germany	66.4	61.5	-7.4		0.0	-8.5	-32.2	-32.1
Greece	7.7	6.9	-10.2		-0.2	-3.5	-18.6	-19.4
Hungary	7.6	7.6	-0.7		0.6	1.1	-22.1	-22.0
Ireland	28.7	32.4	13.0			-3.8	-32.4	-32.4
Italy	30.6	26.8	-12.1			-0.4	-30.2	-30.2
Latvia	3.1	3.0	-2.3		-1.2	-16.8	-39.1	-39.1
Lithuania	4.7	4.2	-10.7		-0.6	-10.8	-34.8	-34.8
Malta	0.1	0.1	-6.6		-0.1	-0.1	-32.7	-32.7
Netherlands	20.2	20.4	1.0		0.1	-8.4	-32.0	-33.8
Poland	32.4	30.9	-4.6		-0.3	-11.3	-36.3	-36.3
Portugal	7.6	9.0	17.8		-0.9	-0.4	-34.1	-34.1
Romania	15.5	17.1	10.2		-0.3	-1.1	-18.6	-18.6
Slovak Republic	2.7	2.4	-13.7		-1.8	-0.1	-23.6	-23.6
Slovenia	1.4	1.4	-1.1		0.0	-2.2	-31.7	-31.7
Spain	38.1	35.1	-7.9		-0.1	0.2	-27.0	-27.0
Sweden	8.1	7.8	-2.7		0.2	-5.5	-31.7	-31.6

Source: CAPRI results

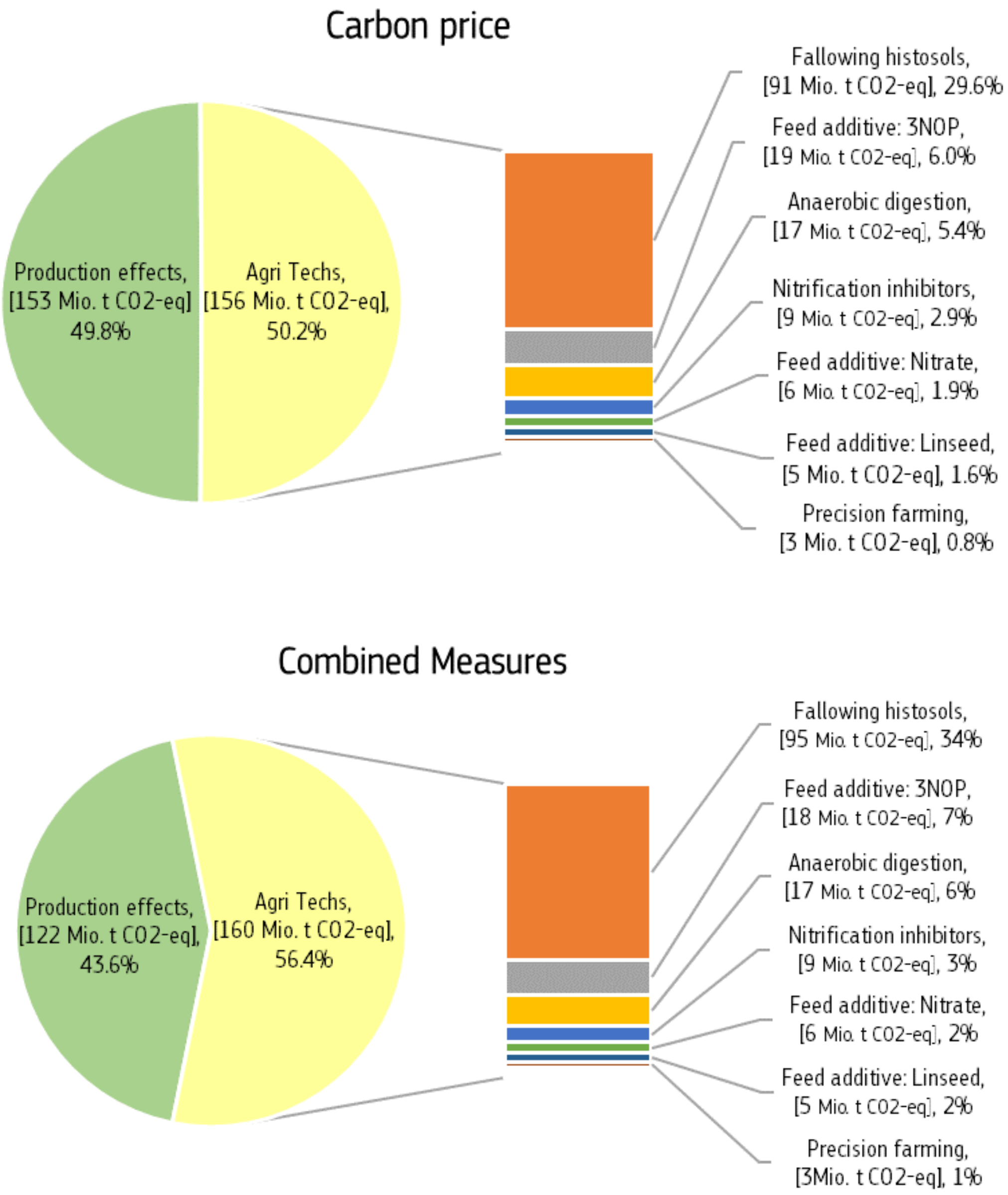
4.2 Impacts on the adoption of technological GHG mitigation options

In this section, we assess the contribution of technological (i.e. technical and management-based) options for mitigating GHG emissions within the AFOLU sectors. In the REF scenario, a widespread adoption of mitigation technologies by farmers is not taken place due to various factors, notably a lack of profitability and incentives. In here, we assess the contribution of each technology to the mitigation of GHG emissions (and the increase of carbon removals) while emphasizing the maximization of profits as a key criterion for the adoption of each technology. This approach implies that farmers would adopt mitigation technologies to avoid paying the carbon price, if the incremental revenue generated by their adoption surpasses their cost (Pérez Domínguez et al. 2016, Fellmann et al. 2021).

As it was the case in EcAMPA 2 and EcAMPA 3, our assessment reveals that the GHG emission reductions achieved by changes in agriculture production (quantities and mix) surpasses the GHG reduction achieved by the sole application of agriculture mitigation technologies. This is evident in the CP and Combi scenarios (Figure 6).

In the HisX scenario, fallowing of histosols is the only technological option applied, and here the total emissions reduction (N_2O, CH4, and CO_2) is solely due to the fallowing of histosols. In fact, the maximum application of “fallowing histosols” as enforced in the HisX scenario, leads to a mitigation of approximately 95 Mt CO_2-eq, whereas the overall reduction in this scenario is lower (approx. 82.3 Mt CO_2-eq), which reflects that the fallowing of histosols leads to production adjustments and related emissions (of about 12.2 Mt CO_2-eq). The maximum application of fallowing histosols is also enforced in the Combi scenario, but the strong potential for emission reduction of fallowing histosols is also visible in the CP. In the CP scenario, where this measure is voluntarily applied based on the carbon price, fallowing histosols remains the most attractive measure, still applied almost to its maximum potential, leading to the mitigation of 91 Mt CO_2-eq. Although the CP and Combi scenarios encompass the application of all the technological mitigation options outlined in Table 3, the carbon price leads to considerable negative impacts on crop and livestock production levels. These changes in production activities contribute about 50% and 44% of the total mitigation achieved in the CP and Combi scenarios, respectively (Figure 6). Notably, in the CP and Combi scenarios, the mitigation options within the livestock sector, including options such as the feed additives 3-NOP, nitrate and linseed, as well as anaerobic digestion and nitrification inhibitors, exhibit significant impact on mitigating GHG emissions. Within the crop sector, the protection of histosols has the highest contribution and additional measures employed to reduce emissions include nitrification inhibitors and precision farming.

Figure 6. Production effects and contribution of technological GHG mitigation options to EU GHG mitigation in 2050 (absolute values in million tonnes of CO_2-eq and contribution share in percentage)

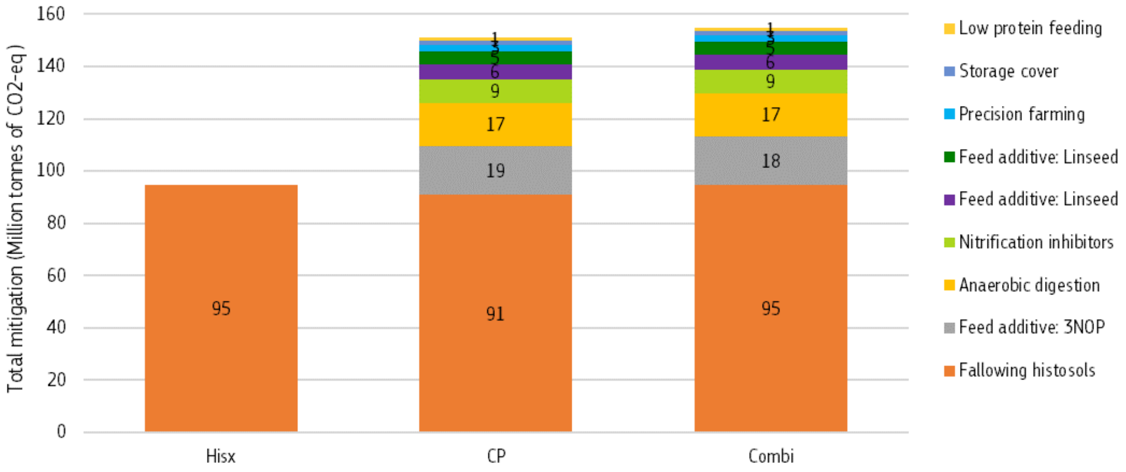


Source: CAPRI results

Figure 7 presents an overview of the individual contributions of various technological and management-related options to the overall mitigation achieved across different scenarios. When protection of histosols is enforced to its maximum adoption potential, it can mitigate up to 95 Mt CO_2-eq of emissions (HisX and Combi scenarios). This option has also substantial mitigation outcomes within the CP scenario (91 Mt CO_2-eq), where fallowing histosols is not enforced, but a result of the carbon price. In the CP and Combi, the feed additive 3NOP (19 Mt CO_2-eq) and anaerobic digestion (17 Mt CO_2-eq) show the highest mitigation potentials after fallowing histosols, and nitrification inhibitors (9 Mt CO_2-eq) and the feed additives nitrate (6 Mt CO_2-eq) and linseed (5 Mt CO_2-eq), as well as precision farming (3 Mt CO_2-eq) considerably contribute to mitigation. The adoption of the technological mitigation options depends on their cost-effectiveness under the carbon price assumed (in this case 100 Euro €/t CO_2-eq). Thus, even though certain mitigation options like the feed additives may be costly to be implemented in all regions to their maximum possible share, as indicated in Pérez Domínguez (2020) and Fellmann et al (2021), they still are cost-effective options in many regions. Conversely, for example precision farming, which may initially be regarded as a relatively low-cost measures with high mitigation potential, shows rather limited adoption, which is also related to the assumption that the emission reduction potential of precision farming is restricted by the regional over-fertilisation factors estimated in CAPRI. Among the fertilizer-related measures, the adoption of nitrification inhibitors stands out as the most cost-effective option, debited to lower costs than precision farming.

The overall trend of technology adoption and assessment of the mitigation capabilities of different technological options within the EU is generally reflected also at MS level. However, certain variations can be observed in terms of the individual contributions made by each technological option towards the total level of mitigation achieved at the MS level (see EcAMPA 3).

Figure 7. EU mitigated GHG emissions per technology in 2050



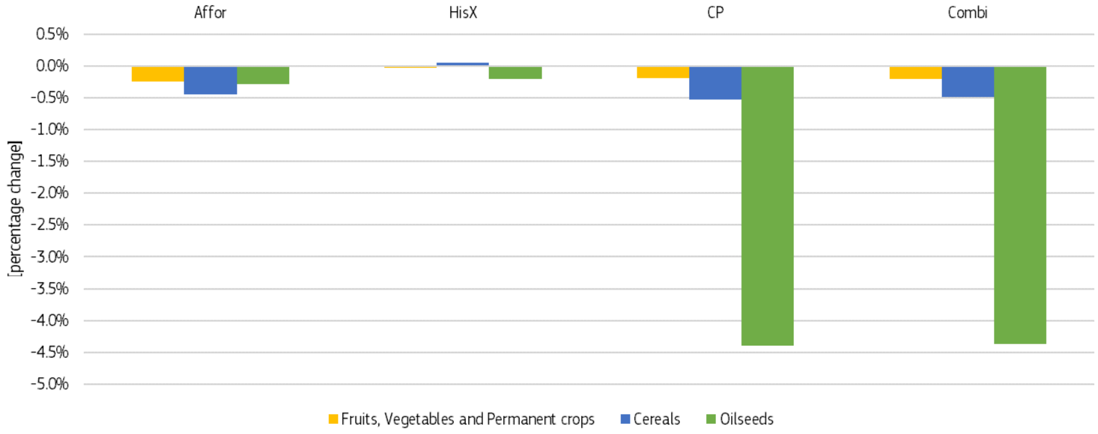
Source: CAPRI results

4.3 Impacts on production

The implementation of mitigation options within the EU can have implications for domestic food supply. In the Affor and HisX scenarios, changes in agricultural land use serve as the main drivers, while the CP scenario influences food commodity supply based on carbon footprint and associated carbon prices. The FM scenario has no implications neither on land allocation nor on land productivity. Consequently, these three scenarios (FM, Affor, and HisX) exhibit only relatively small impacts on EU food supply, as illustrated in Figure 8 and Figure 9. These scenarios primarily affect food production through adjustments in land allocation for agricultural activities. Furthermore, no noticeable impact on changing the land use pattern was observed (see Section 4.4).

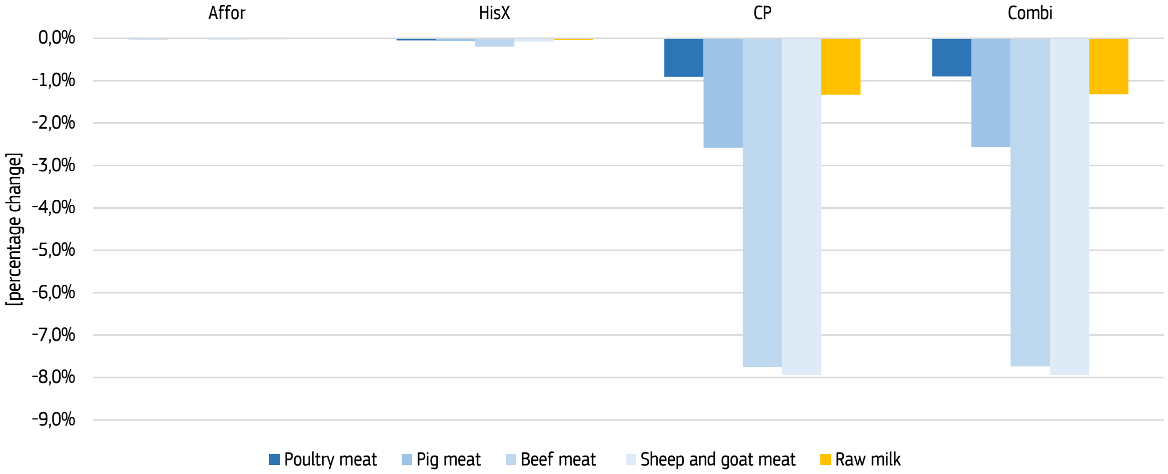
However, the CP scenario directly affects the production methods for food commodities, particularly in the case of high carbon footprint products like livestock-based commodities, which also impacts production of plant-based commodities for feed (Figure 9). Specifically, the implementation of the carbon price in the CP and Combi scenarios has the greatest effect on beef, and sheep and goat meat supply, declining by up to 8%, due to the associated substantial carbon emission intensities. In the crop sector, EU oilseeds production (predominantly rapeseed) is relatively most affected by the carbon price. However, in absolute terms, the impacts on cereals production are similar, with a more pronounced decrease in wheat, but increases in EU barley production.

Figure 8. EU crop production in 2050 (percentage difference to REF)



Source: CAPRI results

Figure 9. EU livestock production in 2050 (percentage difference to REF)



Source: CAPRI results

The data presented in the Annex 1 Tables 8-11 shows the impact of the scenarios on production of major food commodities, namely beef, dairy, pig meat and cereals, at MS level. In the CP and Combi scenarios, the reduction in beef production primarily arises from a smaller herd size. The impact of the carbon price is particularly pronounced in Bulgaria, Estonia, Greece, Hungary and Latvia (Annex1, Table 8). Conversely, the effects are relatively smaller in Italy and Slovak Republic, as these countries exhibit higher beef production efficiency (i.e., productivity) compared to the average level observed in the EU[9]. This demonstrates that increased productivity can help keep higher production levels under carbon price scenarios, since production becomes more emission efficient. The impact of the scenarios on the production of other animal-based foodstuffs, such as dairy products and pig meat (-1.4% and 2.6%, respectively), is noticeably less substantial than on beef production. In the case of dairy production, the lower production impact compared to beef production is due to the generally higher profitability of EU dairy production, whereas for pig meat it is due to lower emission intensities than for ruminants. Bulgaria and Latvia experience the most noticeable impacts on beef livestock production in comparison to other countries. Croatia and Ireland, in turn, show the largest impacts on dairy cattle production. In the absence of alleviation strategies, these countries may witness a greater outflow of livestock cattle for milk and beef production. Spain, Poland and Belgium appear to be the most affected by the decline in pig meat production (see Annex 1, Table 10). Regarding cereals (as shown in Annex 1, Table 11), results indicate that most countries exhibit a slight decline in both area and production levels across the scenarios, although a few exceptions, such as Portugal and Ireland, demonstrate increases in production.

4.4 Impacts on land use

The patterns of land conversion involving afforested areas remain relatively consistent across the REF, FM and HisX scenarios (Figure 10). However, the CP and Combi scenarios demonstrate notable differences in land use patterns, driven by the implementation of a carbon price (the Combi scenario does not include the exogenous expansion of forest area of the Affor scenario). In the Affor scenario, the changes in forest area across each NUTS 2 region are integrated as exogenous inputs into the CAPRI model. Consequently, the introduction of additional forest area resulting from enhanced afforestation or reduced deforestation triggers an endogenous response and adjustment in other land use types, which is dependent on the land supply elasticities and the magnitude of the shock.

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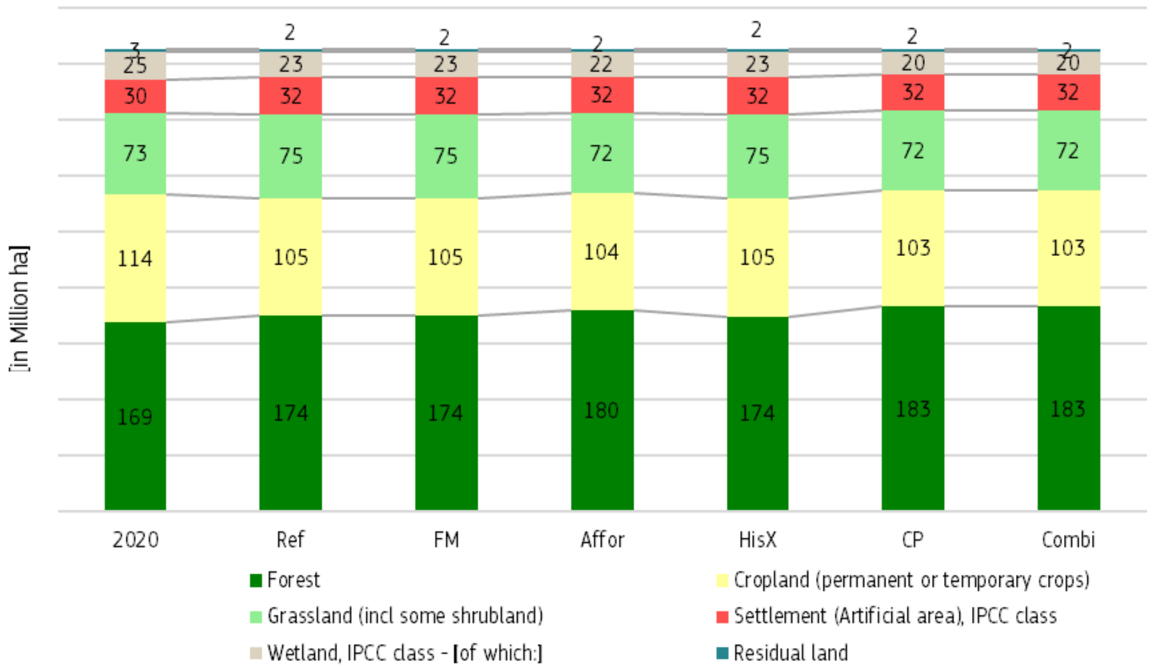
[9] Beef productivity in Italy, Malta and Slovak Republic is anticipated to 2.5, 2.0 and 4.8 t per ha in 2050, respectively, whereas the EU average productivity is calculated to 0.9 t per ha (Source: authors' calculation based on information in Annex 1 Table 3).

Figure 10. EU Land use area in 2050



Source: CAPRI results

The Affor scenario aims to significantly expand forest areas by 2050, resulting in 180 million ha, representing a 3.4% increase compared to the REF scenario (Table 7). Most of these new forest areas are expected to emerge from converted grassland, followed by cropland, and residual land. This outcome is the direct result of the externally defined scenario target, which calls for a substantial afforestation effort involving the plantation of 7.5 million hectares (Mha). Forest expansion under the Affor varies significantly among the MS (Figure 13). Bulgaria, Poland, Romania and Spain show a strong increase in forestland (in between 600 – 800 thousand hectares). Consequently, the highest reduction of cropland and grassland areas under this scenario occurs is those countries (Figure 13).

Table 7. EU Land use area in 2050 (absolute and relative differences to REF)

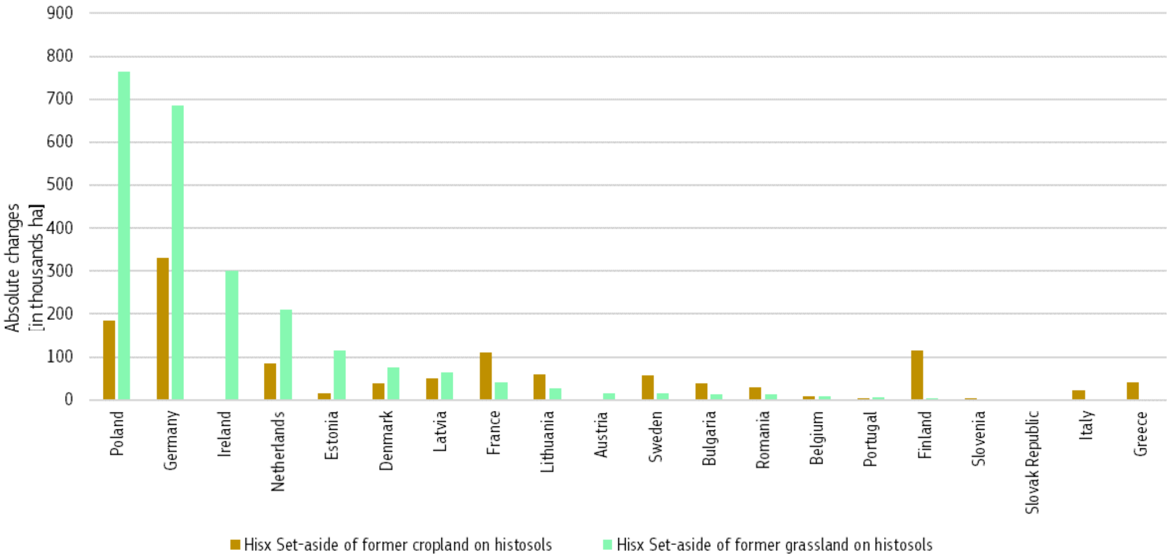
	REF	***Changes in Affor***		***Change in Hisx***		***Changes in CP***		***Change in Combi***	
	[Mio. ha]	***[kha]***	***[%]***	***[kha]***	***[%]***	***[kha]***	***[%]***	***[kha]***	***[%]***
Forest	*174.4*	+5,564.5	+3.2	-172.7	-0.1	+8,964.1	+5.1	+8,925.3	+5.1
Cropland	*105.1*	-1,161.1	-1.1	+115.5	+0.1	-2,337.1	-2.2	-2,314.1	-2.2
Grassland	*75.3*	-3,233.8	-4.3	+36.8	+0.1	-3,578.1	-4.8	-3,565.3	-4.7
Wetland	*22.9*	-652.4	-2.9	+20.4	+0.1	-2,427.0	-10.6	-2,423.2	-10.6
Settlement area	*32.3*	-370.9	-1.2	-3.3		-262.5	-0.8	-264.8	-0.8
Residual land	*2.3*	-146.4	-6.4	+3.3	+0.1	-359.4	-15.6	-357.9	-15.6

The FM scenario involves an externally determined increase in wood harvest from existing forest without any loss or expansion of forested areas. This scenario has minimal changes across all land uses. In contrast, the HisX scenario aims to safeguard organic soils by ceasing their use for agricultural production. The HisX Scenario has modest increases in cropland (115.5 thousand ha) and grassland (36.8 thousand ha), with a reduction in forestland (172.7 thousand ha). Within the

EU, the HisX scenario results in a 3,357 thousand ha increase in protected histosol area, 2,362 thousand ha obtained from grassland and 1,194 from cropland (see Figure 11 for these changes at MS level). The reduction of grassland primarily affects the utilisation of these soils for fodder production, most pronounced for extensive grasslands. Consequently, this has a direct effect on livestock production activities, leading to the substitution of fodder with bulk feeds (i.e. cereals) or the reduction of animal numbers, with beef production most affected.

As shown in Figure 11, the protection of histosols in grassland is particularly important in Poland, Germany, Ireland, and the Netherlands, largely due to the higher concentration of histosols within their grasslands. Additionally, the protection of histosols in cropland is also projected to be important, particularly in Germany and Poland. The effect of fallowing histosols and restoration costs (mainly rewetting) can also be seen in the CP and Combi scenarios, as fallowing of histosols is widely used due the introduction of the carbon price.

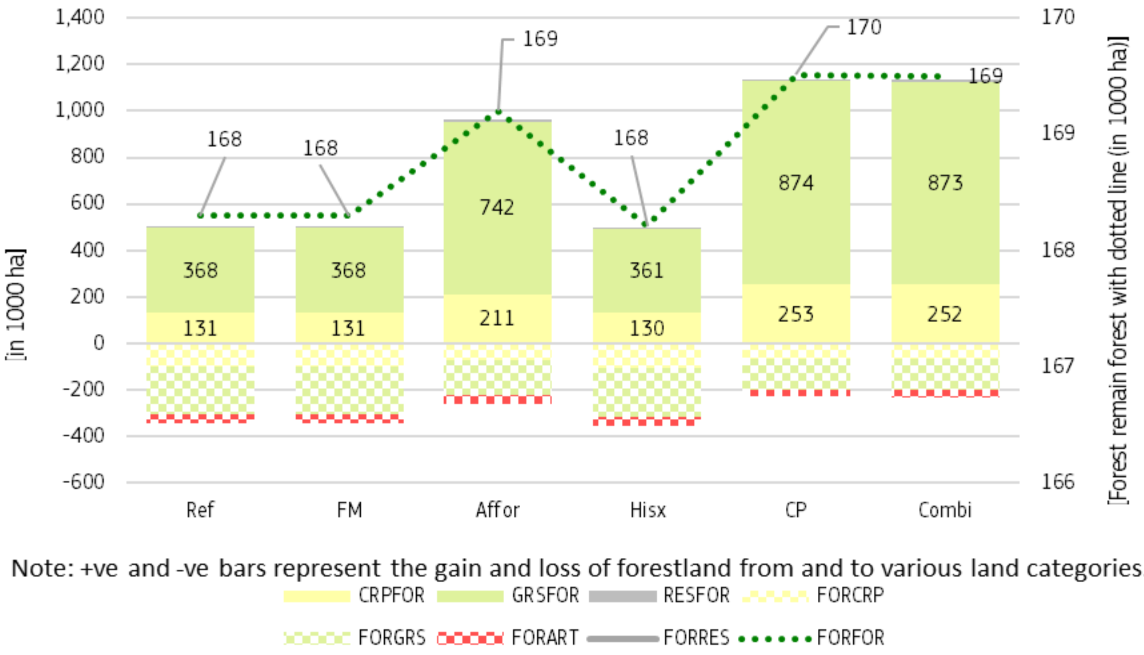
Figure 11. EU set-aside of histosols on grassland and cropland under the HisX scenario in 2050 (absolute difference to REF)



Source: CAPRI results

Within the Combi scenario, forest area is expected to reach 183 Mha in 2050, representing a 5.1% increase compared to the REF scenario. This outcome closely aligns with the impact projected in the CP scenario (see Figure 12 and Figure 13).

Figure 12. EU forest land and land conversion from- and to- forest land in 2050 (absolute difference to year 2020)



Source: CAPRI results.

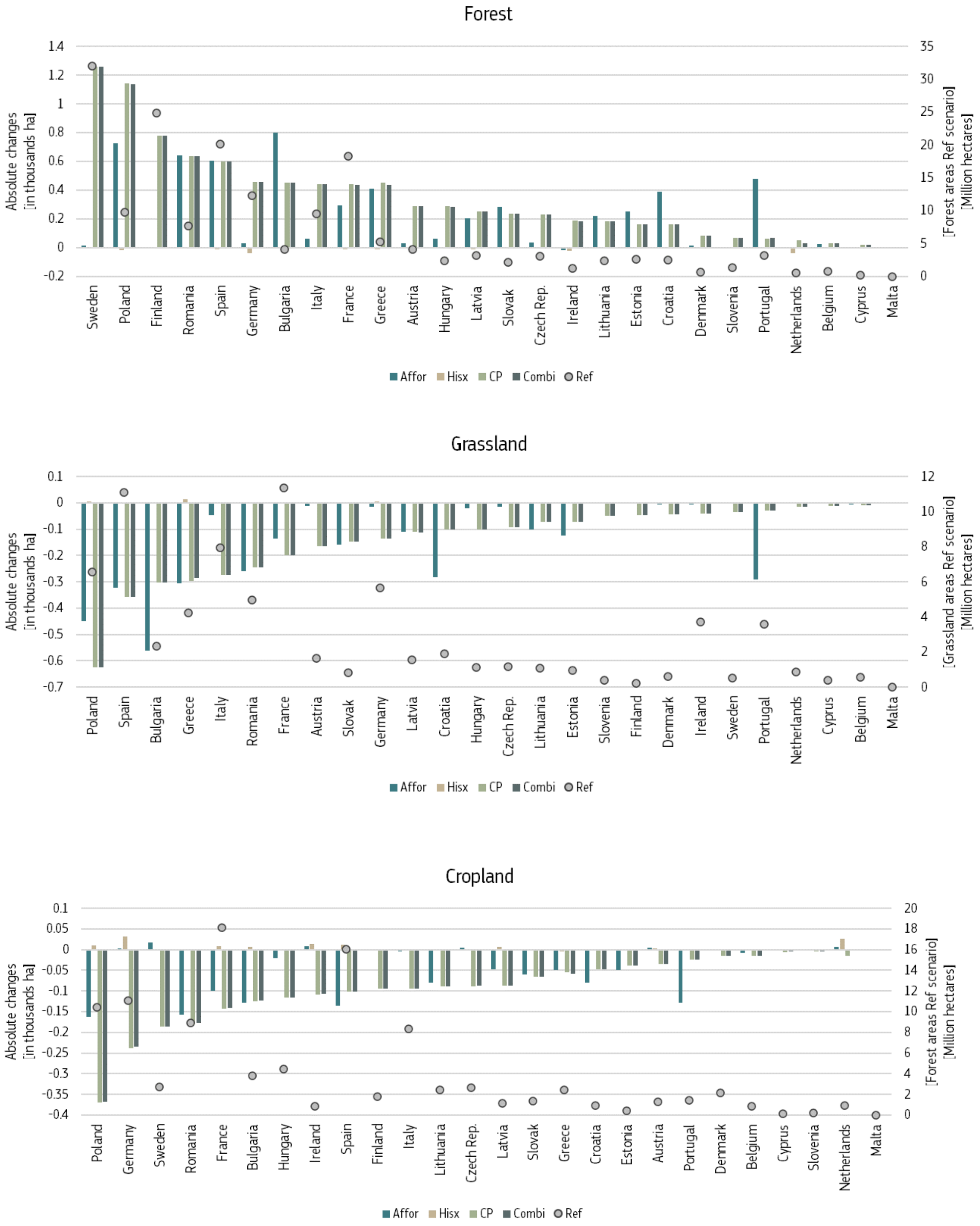
Note: +ve and –ve bars represent the gain and loss of forestland (FOR) from and to various land categories. CRPFOR, GRSFOR, and RESFOR represent FOR gains from cropland (CRP), grassland (GRS), artificial land (ART), and residual land (RES), whereas FORCRP, FORGRS, FORART, and FORRES indicate FOR losses to CRP, GRS, ART, and RES, respectively.

The Combi and CP scenarios show the most significant decreases in cropland, grassland, and wetlands. Notably, the CP scenario, which is also a component of the Combi scenario, appears to be more effective in expanding forest land. Due to the implementation of carbon prices on agricultural production under the CP and Combi scenarios, the primary sources for additional forest land are the conversions of grassland and cropland to forest land (see Figure 12).

Sweden and Poland experience a significant increase in forest area (1,260 and 1,140 thousand ha, respectively) (Figure 13). This is due to an increase in the transformation of non-forest areas, originally designated for livestock grazing or remaining unused with shrub cover, into forestland. Most of the overall expansion in forestland results from the cumulative sum of additional land transitions to forestland and the forested areas that remain unchanged (represented by the dotted line in see Figure 12).

Regarding the changes in the cropland and grassland areas, the Figure 13 shows significant variations at EU MS level. Countries like Poland, Germany and Spain see the largest grassland reductions in scenarios involving afforestation and land-use shifts (Figure 13).

Figure 13. EU forest land, cropland and grassland by EU Member states in 2050 (absolute and percentage difference to REF)



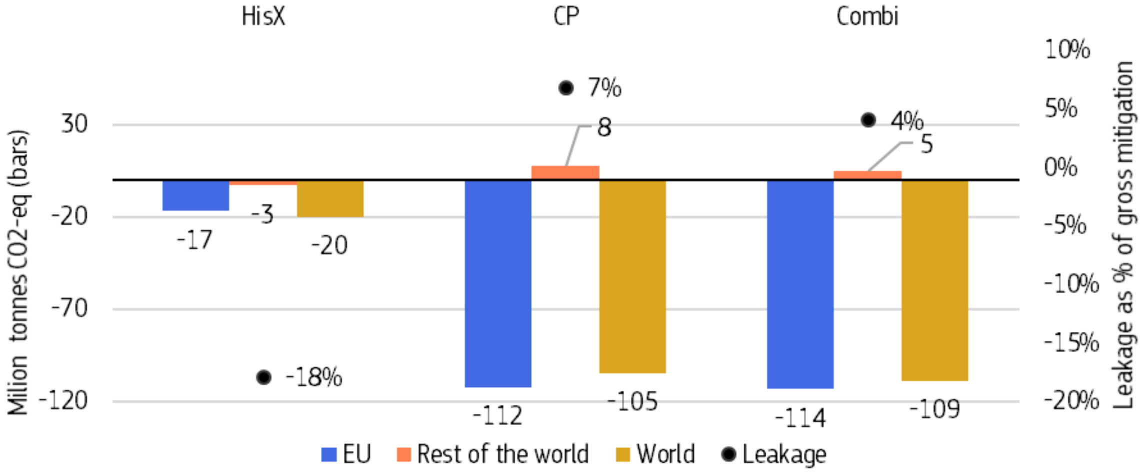
Source: CAPRI results

4.5 Impacts on GHG emission leakage

This report analyses the effectiveness of GHG mitigation measures in reducing emissions within the EU Agriculture sector. However, changes in the EU under different scenarios may have impacts also on production structures outside the EU, and hence on non-EU GHG emissions. Accordingly, we also assess whether emission savings in the EU might be offset by emission increases in non-EU countries (i.e. emission leakage). Within this chapter we only concentrate on emissions related to the Agriculture sector, as CAPRI does not account for LULUCF emissions and savings in non-EU countries.

Figure 14 presents the agriculture GHG emission changes in the EU and the rest of the world (ROW), including the share of the EU's gross mitigation "leaked" to the ROW. Results indicate variation across the three scenarios, clearly linked to the magnitude of the production decreases in the EU. While the HisX scenario indicates an emission decrease also in ROW, the CP and Combi scenarios show a partial shift of emissions to ROW, with 7% and 4% respectively of the mitigated emissions in the EU being "leaked" to the ROW. However, in the HisX scenario a negative leakage effect of 18% compared to REF is observed, i.e. there are net emission reductions in the ROW. As explained in previous sections, the fallowing of histosols affects more grasslands than croplands. Consequently, in the HisX scenario, domestic livestock production is affected through the more expensive fodder. Total EU UAA is expected to increase (although relatively slightly) and some crop production is shifted towards fodder crops. Producer and consumer prices slightly increase, leading to some reduction in the consumption of livestock products in the EU, especially beef, and sheep and goat meat. Imports also decrease and in general production of these products also decreases in the ROW, leading to a net decrease in non-EU emissions and, therefore, to this "negative emission" leakage effect. However, the effect in absolute terms is minor compared to the CP and Combi scenarios (see Figure 14).

Figure 14. EU and global Agriculture GHG emissions in 2050 (absolute difference to REF) and global emission leakage (percentage of gross mitigation)



Source: CAPRI results

Emission leakage occurs when emission reductions within the EU are partly offset by emission increases in the rest of the world (non-EU regions), either due to EU export substitution or increased imports by the EU (Nordin et al. 2025). As mentioned above, the carbon price emerges as the primary driver of reduction in livestock production activities, leading to a considerable decrease in overall agriculture emissions in both the CP (-112 Mt CO_2-eq) and the Combi (-114 Mt CO_2-eq) scenarios. The production decrease in the EU due to the implementation of a carbon price results in increased agricultural production in the ROW and hence emission leakage. Emission leakage is characterized by diminished competitiveness among domestic producers due to the carbon price

Böhringer et al. 2012; Nordin et al. 2025), i.e. within the EU, farmers are at risk of facing reduced competitiveness due to higher production costs. As a consequence, prices increase and there is a subsequent decline in demand for domestic products, which is then filled by cheaper imported alternatives (Böhringer, Carbone, and Rutherford 2012, Nordin et al. 2025). The implementation of carbon pricing alone would lead to a leakage equivalent to 7% of the EU's gross mitigation (7.7 Mt of CO_2-eq per year). In their study, Stepanyan et al. (2023) observed a notable rise in carbon leakage, reaching up to 15% towards the ROW. The observed variations in carbon leakage are likely attributed to differences in model assumptions, particularly pertaining to carbon prices and the level of adoption of mitigation technologies[10].

4.6 Impacts on prices and human consumption

Producer prices increase following the supply reductions in the scenarios. Therefore, they are most pronounced in the scenarios with carbon prices (Figure 15). Also related to the underlying GHG emission intensities, ruminant producer prices are the most affected commodities. For instance, Beef prices are expected to increase 13.7% in the Combi scenario, while sheep and goat meat prices exhibit an increase of 10.6%. These production effects in the livestock sector also have a direct effect on feed markets, so that cereals production and prices also increase. For instance barley prices increase in the Combi scenario by 6.5%.

Consumer prices follow the increase in producer prices, but relative changes are lower due to high consumer margins (6.8% for beef and 5.7% for sheep and goat meat in the Combi scenario).

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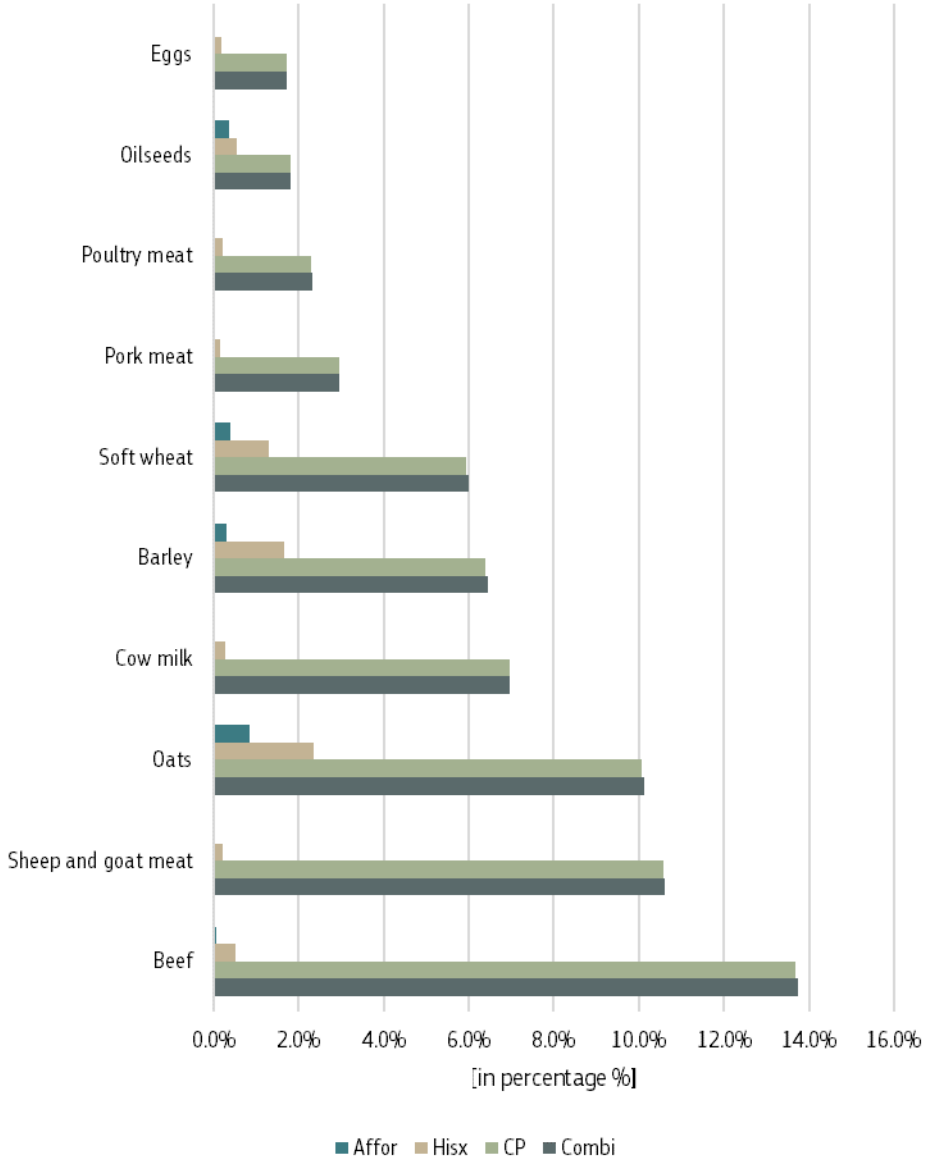
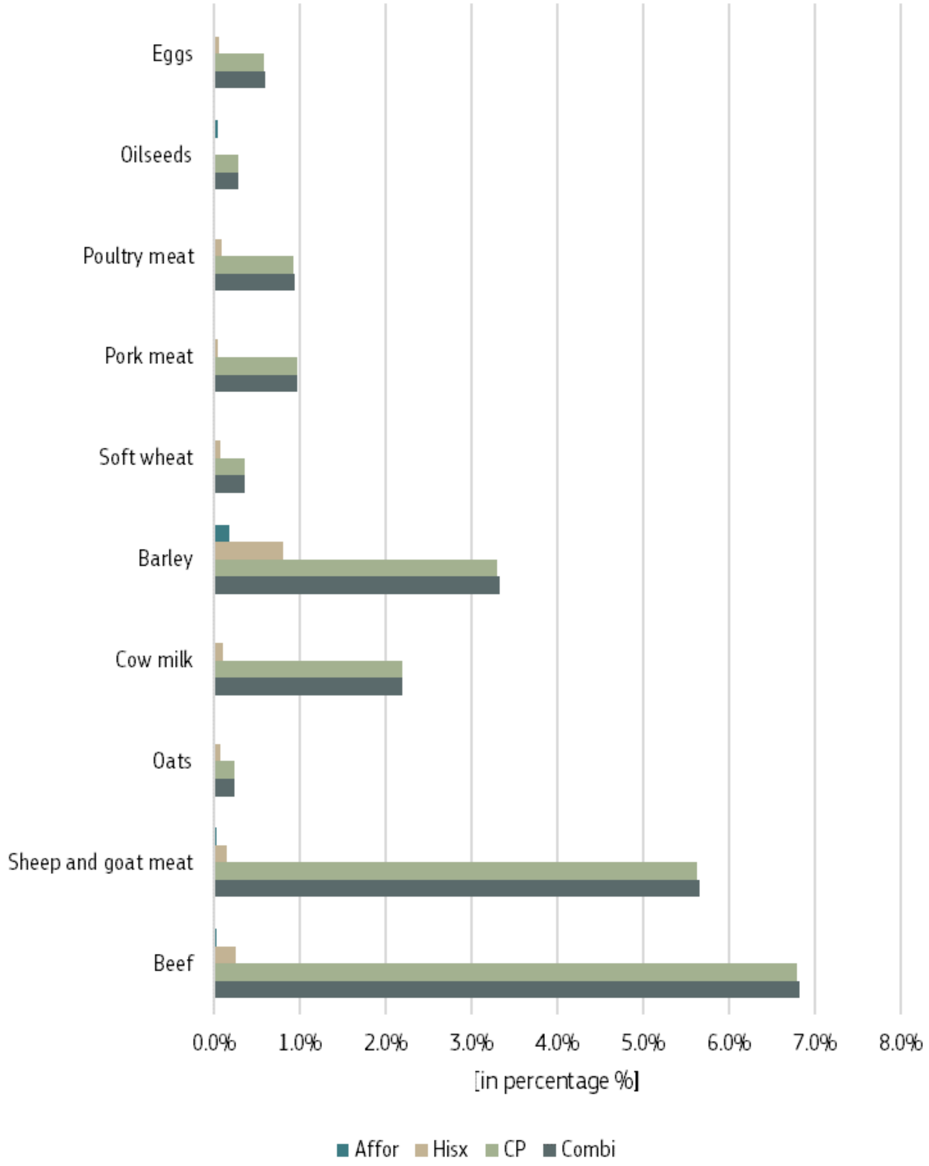
[10] Stepanyan et al (2023) assumes a carbon tax equivalent to 100€/t CO_2-eq to agricultural activities in the EU with the effect of mitigation technologies.

Figure 15. EU producer prices by commodity in 2050 (percentage difference to REF)



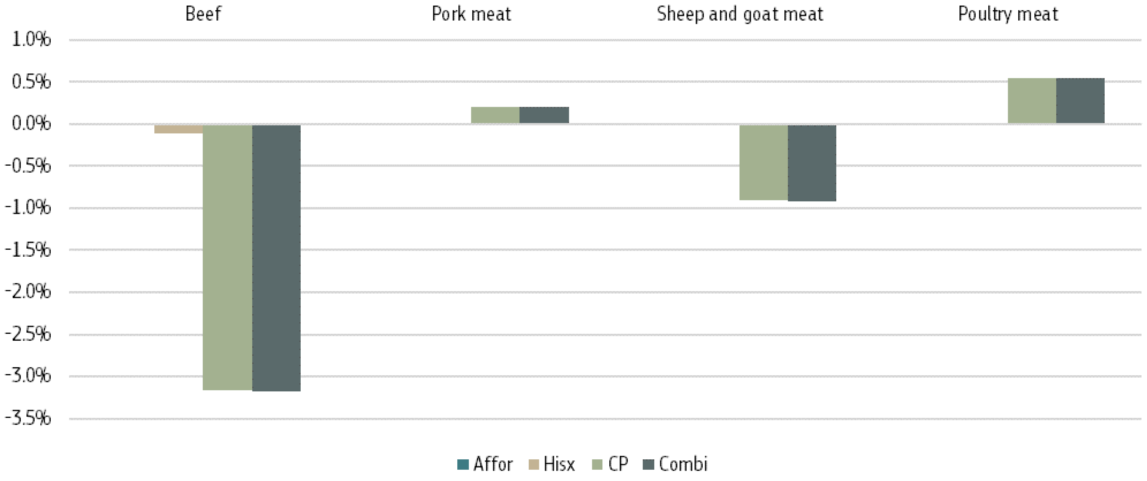
Source: CAPRI results

Figure 16. EU consumer prices by commodity in 2050 (percentage difference to REF)



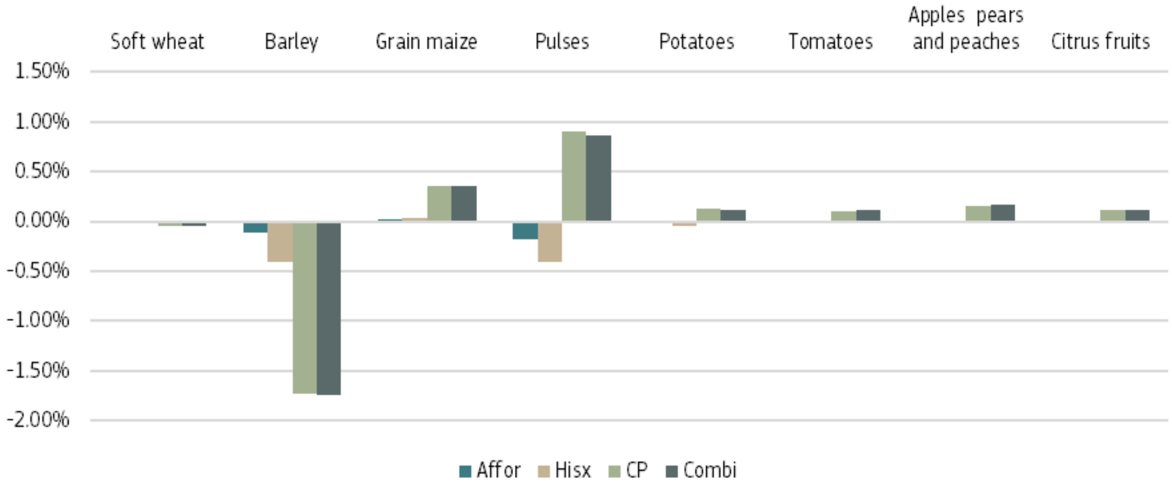
The price increases observed in animal products, particularly beef, trigger a shift in consumer preferences within the EU. As illustrated in Figure 17, consumers respond to the price increases by substituting beef with other (relatively cheaper) meat options, such as poultry and pig meat. Moreover, an increase in the consumption of plant-based protein products is observed, such as pulses and maize (Figure 18). These changes in consumption patterns indicate a certain potential of GHG mitigation strategies to not only reduce emissions but also to exert some pressure on consumer preferences moving away from ruminant products (in this case due to the higher GHG emission intensity underlying the production of these commodities).

Figure 17. EU human consumption of animal products in 2050 (percentage difference to REF)



Source: CAPRI results

Figure 18. EU human consumption of crop products in 2050 (percentage difference to REF)



Source: CAPRI results

5. Conclusions

The AFOLU sectors can significantly contribute to achieving the EU's 2050 climate neutrality goals, as set out in the EU Climate Law. The assessment shows that technological (i.e., technical and management-based) GHG mitigation options—particularly the protection of carbon rich soils in cropland and grassland—can reduce emissions at least as effectively as changes in agricultural production alone, especially in scenarios involving carbon pricing. Other relevant GHG mitigation options include anaerobic digestion, feed additives, precision farming, and nitrification inhibitors. However, adoption rates for these technologies can greatly vary across regions and EU Member states due to cost-effectiveness constraints.

Mitigation measures within the EU can also impact domestic food supply, particularly when policies including carbon pricing in the AFOLU sectors are implemented. Carbon pricing schemes could place significant pressure on the livestock sector and feed markets due to increased production costs. In contrast, policies involving afforestation, improved forest management and histosol protection are expected to have minimal effects on food production, mainly due to land use changes. Histosol protection is especially critical in certain EU Member States, where these soils are concentrated in grasslands and cropland areas. This reinforces their importance for both emission mitigation and ecosystem conservation.

The adoption of carbon pricing in agriculture may result in notable carbon leakage, as increased EU imports and decreased exports shift emissions abroad. This means that part of the emission reductions in the EU triggered by these GHG mitigation policies is offset by increases in emissions in the ROW. The analysis shows that in the CP and Combi scenarios, 7% and 4%, respectively, of mitigated emissions in the EU are “leaked” to the ROW This highlights the complex interplay between domestic emission reductions and global emission shifts.

Carbon pricing policies also lead to shifts in consumer preferences away from emission-intensive products such as beef and sheep and goat meat, and towards poultry, pig meat and protein-rich crops. This indicates potential synergies between climate policy and dietary diversification, supporting the development of more sustainable food systems.

One limitation of the study is that, in carbon pricing scenarios, the impact on agricultural income depends heavily on who bears the cost of the carbon price. While the modelled carbon pricing generates substantial tax revenues for governments, this aspect is not addressed in the report. If governments were to reinvest a portion of this revenue to support farmers in adopting technological GHG mitigation measures, it could substantially reduce the financial burden on EU farmers and moderate the supply response. Such technologies enable emissions reductions while sustaining higher levels of agricultural production.

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List of abbreviations and definitions

AFOLU	Agriculture, Forestry and Other Land Use
CAP	Common Agricultural Policy
CAPRI	Common Agricultural Policy Regional Impact Analysis
CBM	Carbon Budget Model
CH_4	Methane
CO_2	Carbon Dioxide
CO_2-eq	Carbon Dioxide equivalents
CP	Carbon price (scenarios of the combined measures approach)
CRF	Common Reporting Format
DG CLIMA	Directorate General ‘Climate Action’
EcAMPA	Economic assessment of GHG mitigation policy options for EU agriculture
EEA	European Environment Agency
EF	Emission Factor
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FM	Forest management
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies (model/database)
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
LUC	Land Use Change
LULUCF	Land Use, Land Use Change and Forestry
MS	Member State(s)
Mt	Million tonnes
N	Nitrogen
NI	Nitrogen Inhibitors
N_2O	Nitrous Oxide
NO_2	Nitrite

NO_3	Nitrate
NUTS	Nomenclature of Territorial Units for Statistics
OECD	Organisation for Economic Co-operation and Development
POTEnCIA	Policy Oriented Tool for Energy and Climate Change Impact Assessment
REF	Reference scenario
ROW	Rest of the World
UAA	Utilised Agricultural Area
UNFCCC	United Nations Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
VRT	Variable Rate Technology

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Annexes

Annex 1. Detailed scenario production effects by EU Member State

Table 8. Beef herds and production per EU Member State (percentage difference to REF)

	Ref		**FM/Affor**		**Hisx**		**CP/Combi**	
	Herd size	**Supply**	**Herd size**	**Supply**	**Herd size**	**Supply**	**Herd size**	**Supply**
	[1000 hds]	**[Mio t.]**	**Difference to the Ref [in %]**					
EU	**15933**	**14.2**	**0**	**0**	**-0.3**	**-0.2**	**-13.9**	**-8.0**
Austria	376	0.6					-7.2	-5.7
Belgium	509	0.2			-0.1		-13.2	-7.9
Bulgaria	113				-0.4	-0.1	-34.6	-16.2
Croatia	124	0.1				-0.1	-27.6	-8.9
Cyprus	5				-0.4	-0.4	-7.1	-5.2
Czech Republic	220	0.1			-0.2	-0.1	-24.4	-9.9
Denmark	74	0.1			-0.3	-0.1	-20.9	-12.0
Estonia	48				-3.1	-1.0	-39.2	-13.4
Finland	190	0.2			-0.4	-0.2	-10.4	-8.3
France	5059	3.4			-0.1		-11.3	-5.7
Germany	1193	1.7			-1.0	-0.7	-8.4	-7.9
Greece	160	0.1			-0.5		-30.3	-7.9
Hungary	187	0.1			-0.3	-0.1	-33.5	-13.3
Ireland	2056	2.0			-0.9	-0.5	-20.6	-13.5
Italy	487	1.2					-4.0	-3.4
Latvia	59				-0.9	-0.6	-30.2	-26.3
Lithuania	75				0.1		-22.0	-8.6
Malta	1				-0.8	-0.5	-8.3	-7.1
Netherlands	205	0.1			-2.5	-1.0	-12.8	-6.9
Poland	1421	1.2			-0.4	-0.3	-16.1	-12.5
Portugal	689	0.3			-0.2		-18.9	-7.0
Romania	66	0.1			0.1	0.1	-7.7	-7.0
Slovak Republic	13				0.2	0.1	-4.4	-1.8
Slovenia	121	0.1					-12.0	-6.5
Spain	2080	1.5			0.1		-11.3	-4.4
Sweden	402	0.4			-0.1		-8.5	-5.4

Source: CAPRI results

Table 9. Dairy herds and production per EU Member State (percentage difference to REF)

	Ref		FM/Affor		Hisx		CP/Combi	
	Herd size	**Supply**	**Herd size**	**Supply**	**Herd size**	**Supply**	**Herd size**	**Supply**
	[1000 hds]	**[Mio. t]**	**Difference to the Ref [in %]**					
EU	**18542**	**157**	**0**	**0**	**0**	**0**	**-1.4**	**-1.3**
Austria	484	3.5					-0.9	-0.9
Belgium	387	4.0					-0.8	-0.7
Bulgaria	164	0.9					-2.1	-1.9
Croatia	94	0.6					-4.1	-4.2
Cyprus	36	0.3			-0.1	-0.1		
Czech Republic	349	3.6					-1.1	-1.0
Denmark	611	6.3					-1.8	-1.8
Estonia	63	0.8			-0.2	-0.2	-1.7	-1.6
Finland	225	2.4					-1.5	-1.4
France	3078	25.8					-0.4	-0.4
Germany	3733	33.4			-0.2	-0.1	-1.9	-1.7
Greece	61	0.6			0.1	0.1	2.6	2.7
Hungary	148	1.8					-1.4	-1.3
Ireland	2043	13.7			-0.1	-0.1	-3.3	-3.2
Italy	1874	12.7					-1.0	-0.9
Latvia	90	0.8			-0.1	-0.1	-2.4	-2.3
Lithuania	175	1.6					-0.7	-0.6
Malta	6					-0.1	-1.2	-1.0
Netherlands	1543	17.4			-0.1	-0.1	-1.0	-0.9
Poland	1510	12.6			-0.1		-1.9	-1.8
Portugal	181	1.9					-0.2	-0.2
Romania	743	3.1					-0.7	-0.6
Slovak Republic	96	0.9					-1.9	-1.8
Slovenia	84	0.6					-1.1	-1.0
Spain	512	5.5					0.5	0.6
Sweden	250	2.3					-1.1	-1.1

Source: CAPRI results

Table 10. Pig herds and production per EU Member State (percentage difference to REF)

	Ref		**FM/Affor**		**Hisx**		**CP/Combi**	
	Herd size	**Supply**	**Herd size**	**Supply**	**Herd size**	**Supply**	**Herd size**	**Supply**
	[1000 hds]	**[Mio. t]**	**Difference to the Ref [in %]**					
EU	**254498**	**23**	**0**	**0**	**-0.1**	**-0.1**	**-2.6**	**-2.6**
Austria	3487	0.4			-0.1	-0.1	-2.1	-2.1
Belgium	8800	0.9					-3.6	-3.6
Bulgaria	764	0.1					0.1	0.1
Croatia	1998	0.1					-3.0	-3.0
Cyprus	809	0.1			-0.9	-0.9	-2.4	-2.4
Czech Republic	1328	0.1					-0.3	-0.3
Denmark	24077	1.8					-2.3	-2.3
Estonia	693	0.1			-0.1	-0.1	-0.7	-0.7
Finland	1784	0.2			-0.1	-0.1	-3.0	-3.0
France	23726	2.4					-2.7	-2.7
Germany	51139	4.6			-0.2	-0.2	-1.7	-1.7
Greece	997	0.1					-2.2	-2.2
Hungary	3369	0.4					-1.5	-1.5
Ireland	3346	0.3			-0.1	-0.1	-1.4	-1.4
Italy	10860	1.5					-2.2	-2.2
Latvia	426						-2.0	-2.0
Lithuania	752	0.1					-1.1	-1.1
Malta	36				-0.3	-0.3	-2.7	-2.7
Netherlands	25159	1.8			-0.1	-0.1	-2.4	-2.4
Poland	15425	1.7					-3.6	-3.6
Portugal	6496	0.4			-0.1	-0.1	-2.2	-2.2
Romania	3540	0.4					-1.2	-1.2
Slovak Republic	432				0.1	0.1		
Slovenia	474	0.1					-1.7	-1.7
Spain	62296	5.3			-0.1	-0.1	-3.6	-3.6
Sweden	2285	0.3					-1.6	-1.6

Source: CAPRI results

Table 11. Cereals area and production per EU Member State (percentage difference to REF)

	Ref		**FM**		**Affor**		**Hisx**		**CP/Combi**	
	Area	**Supply**	**Area**	**Supply**	**Area**	**Supply**	**Area**	**Supply**	**Area**	**Supply**
	[1000 ha]	**[Mio. t]**	**Difference to the Ref [in %]**							
EU	**47084**	**288.1**	**0**	**0**	**-0.9**	**-0.5**	**-0.7**	**0**	**-1.8**	**-0.5**
Austria	628	4.0			0.3	0.6	0.3	1.9	-0.5	1.4
Belgium	339	2.9			-1.3	-0.9	-1.2	-0.4	3.8	4.7
Bulgaria	1618	11.7			-2.7	-1.9	0.2	0.7	-2.4	-0.8
Croatia	450	3.2			-9.8	-9.1	0.5	0.8	-4.3	-4.7
Cyprus	30	0.1			1.5	2.1	0.8	1.2	-24.9	-33.3
Czech Republic	1235	7.7			1.1	1.4	1.3	1.8	-5.8	-5.3
Denmark	1055	7.0			0.1	0.2	-2.4	-1.5	0.4	0.8
Estonia	324	1.4			-13.8	-11.0	-4.9	-2.4	-14.3	-14.7
Finland	855	3.8			0.3	0.4	-3.9	-3.4	-2.2	-0.4
France	8674	65.0			-0.4	-0.2	-0.1	0.6	0.4	2.3
Germany	5390	41.5			0.1	0.2	-3.8	-2.9	-5.9	-4.4
Greece	488	1.9			-3.2	-2.7	-2.4	-0.7	-6.8	-3.3
Hungary	2038	15.2			1.7	2.0	3.1	3.7	1.7	3.4
Ireland	324	2.9			1.3	1.4	3.2	4.5	18.5	21.6
Italy	2378	14.1				0.1	0.4	0.8	-1.2	-0.2
Latvia	642	2.9			-2.8	-2.5	-2.1	-1.7	1.5	2.1
Lithuania	1183	5.2			-4.4	-3.1	-3.1	-1.7	-5.2	-5.1
Malta	0							0.3	-8.9	-8.7
Netherlands	131	1.1			1.4	1.5	-8.5	-7.9	7.0	2.5
Poland	6454	30.6			-1.4	-0.9	-1.6	-0.8	-5.4	-5.0
Portugal	148	0.4			-3.9	-4.2	1.9	3.8	58.1	49.0
Romania	5373	36.7			-1.5	-1.1	0.1	0.5	-1.7	
Slovak Republic	622	3.7			-1.5	-1.9	0.4	0.9	-2.3	-2.0
Slovenia	50	0.3			0.7	1.1	-2.6	-2.7	-2.2	-3.2
Spain	5762	19.6			-0.7	-0.5	0.8	1.8	1.9	2.5
Sweden	892	5.3			0.4	0.4	-1.2	0.1	-10.2	-7.4

Source: CAPRI results

Annex 2. Regional distribution of managed cropland and grassland on organic soils in CAPRI

The assessment of greenhouse gas emissions using the CAPRI model requires information on the regional distribution (primarily at the NUTS2 level) of managed croplands and grasslands on organic soils. Currently, there is no dataset providing this information at the required spatial resolution and extent across Europe. Therefore, the share of managed cropland and grassland on organic soils for CAPRI regions was derived using three key datasets.

The spatial distribution of organic soil area was extracted from the Harmonized World Soil Database (HWSD). The HWSD spatial data set delineates distinct “Mapping Units (MU)”, each characterized by one or more ”Soil Typological Units (STU)”. Information regarding organic carbon content is provided at the STU level, encompassing one dominant STU and up to eight secondary STUs in a MU. While the share of the STU within a MU is known, its spatial location within a MU is unknown. For the calculation of the share of organic soils in a MU, all dominant and secondary STUs are considered. The analysis is restricted to topsoil data (0-30 depth) for the STUs. A STU is classified as organic / non-organic soils following the IPCC/FAO (Eggleston et al., 2006) definition[11]. In practice, all STUs identified as "organic soils" within the HWSD for Europe exhibited organic carbon content exceeding 30%. The share of organic soil within a MU is determined by summing the shares of all STUs classified as organic soil within that MU.

Spatially explicit information on cropland and grassland is available from remote sensing land use/land cover data sets such as CORINE land cover data. However, the given cropland and grassland areas do not necessarily align with the statistical data on managed cropland and grassland in the CAPRI model’s underlying data base for NUTS2 regions. Particularly for grassland areas in transition zones between natural and managed grasslands (e.g. Mediterranean and boreal regions) larger discrepancies are observed. Therefore, calculations are based on the CAPRI disaggregated dataset (Koeble et al. 2025) which includes cropland and grassland areas at the level of Farm Structure Units (FSU). FSUs vary in size from 1 km² to 100 km² and are sub-units of the CAPRI regions and of the MUs of the HWSD. The FSU level cropland and grassland areas are consistent with the CAPRI data at regional level.

Neither the HWSD's organic soil data nor the cropland/grassland data within an FSU are spatially explicit below their respective mapping units (MU for HWSD, FSU for cropland and grassland). While we know the share of organic soil within a MU, we lack information on its precise spatial location and the distribution of different land uses on the organic soil area. Additionally, not every land use class occurs on organic soils with the same probability. For example, cropland is less likely to be found on organic soils compared to grassland, due to soil management challenges such as excessive wetness that hinders machinery access, and the unsuitability of organic soils for certain crop species. To incorporate country-specific environmental and management factors that affect the occurrence of managed cropland and grassland on organic soils, we utilize the data from the

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[11] Soils are organic if they satisfy the requirements 1 and 2, or 1 and 3 below: 1. Thickness of 10 cm or more. A horizon less than 20 cm thick must have 12 percent or more organic carbon when mixed to a depth of 20 cm; 2. If the soil is never saturated with water for more than a few days, and contains more than 20 percent (by weight) organic carbon (about 35 percent organic matter); 3. If the soil is subject to water saturation episodes and has either: (i) at least 12 percent (by weight) organic carbon (about 20 percent organic matter) if it has no clay; or (ii) at least 18 percent (by weight) organic carbon (about 30 percent organic matter) if it has 60 percent or more clay; or (iii) an intermediate, proportional amount of organic carbon for intermediate amounts of clay.

countries' annual GHG reporting under the UNFCCC (data for the year 2019, submitted in 2021, https://unfccc.int/ghg-inventories-annex-i-parties/2021). In the common reporting format (CRF) tables, countries report total area of organic soil, area of different land uses (cropland, grassland, wetland, forest, settlements, other) on organic soil, and the area of cultivated/managed organic soil (without differentiation of land uses). It is assumed that in the case of cropland, the organic soil is always managed. This is not necessarily true for grasslands, which can include also natural grasslands. Therefore, the area of managed grasslands on organic soils is calculated as the difference between total managed organic soil and cropland area on organic soil. The land use/cover on the remaining organic soil area (not covered by managed cropland and grassland) is summarized as “other land use” on organic soil. This information serves to estimate the probability of a certain land use to occur on organic soils at country level.

Based on the information extracted from the three data sets, the share of managed croplands and grasslands on organic soils in the CAPRI NUTS2 regions is calculated. First, weights (sum of weights -= 1) for each land use class are derived from the UNFCCC information at country level:

$wco_{ms}^{U} = \frac{soc_{ms}^{U}}{soc_{ms}^{U}+sog_{ms}^{U}+sof_{ms}^{U}}$ weighting factor for cropland

$wgo_{ms}^{U} = \frac{sog_{ms}^{U}}{soc_{ms}^{U}+sog_{ms}^{U}+sof_{ms}^{U}}$ weighting factor for grassland

$wfo_{ms}^{U} = \frac{sof_{ms}^{U}}{soc_{ms}^{U}+sog_{ms}^{U}+sof_{ms}^{U}}$ weighting factor for other land use

where:

$soc_{ms}^{U} = \frac{OC_{ms}^{U}}{C_{ms}^{U}}$ share of managed cropland on organic soil area (OC_{ms}^{U}) in total cropland area (C_{ms}^{U}) in country (ms) according to UNFCCC data

$sog_{ms}^{U} = \frac{OG_{ms}^{U}}{G_{ms}^{U}}$ share of managed grassland on organic soil area (OG_{ms}^{U}) in total grassland area (G_{ms}^{U}) in country (ms) according to UNFCCC data

$sof_{ms}^{U} = \frac{OF_{ms}^{U}}{F_{ms}^{U}}$ share of other land use on organic soil area (OF_{ms}^{U}) in total other land use area (F_{ms}^{U}) in country (ms) according to UNFCCC data

Some countries report zero organic soils in their submissions to the UNFCCC but the soil map indicates organic soil area in the country. In these cases, the weighting factors for all land uses are set to 1.

In a second step, for each country, these weights are applied to distribute the land use classes at the level of our smallest spatial unit (the FSU polygon) over the organic soil area (based on the HWSD) within this spatial unit:

$OC_{p}^{s} = \frac{O_{p}^{S} * C_{p}^{S} * wco_{ms}^{U}}{C_{p}^{S} * wco_{ms}^{U} + G_{p}^{S} * wgo_{ms}^{U} + F_{p}^{S} * wfo_{ms}^{U}}$ weighted cropland area on organic soils (OC_{p}^{s}) in FSU polygon (p) ∈ of country (ms)

$OG_{p}^{s} = \frac{O_{p}^{S} * G_{p}^{S} * wgo_{ms}^{U}}{C_{p}^{S} * wco_{ms}^{U} + G_{p}^{S} * wgo_{ms}^{U} + F_{p}^{S} * wfo_{ms}^{U}}$ weighted grassland area on organic soils (OG_{p}^{s}) in FSU polygon (p) ∈ of country (ms)

$OF_{p}^{s} = \frac{O_{p}^{S} * F_{p}^{S} * wfo_{ms}^{U}}{C_{p}^{S} * wco_{ms}^{U} + G_{p}^{S} * wgo_{ms}^{U} + F_{p}^{S} * wfo_{ms}^{U}}$ weighted other land use area on organic soils (OF_{p}^{s}) in FSU polygon (p) ∈ of country (ms)

Where:

O_p^S organic soil area based on HWSD in FSU polygon (p)

C_p^S cropland area based on disaggregated CAPRI data in FSU polygon (p)

G_p^S grassland area based on disaggregated CAPRI data in FSU polygon (p)

F_p^S other land use area based on disaggregated CAPRI data in FSU polygon (p)

Finally, the share of, for example, cropland on organic soils at CAPRI NUTS2 regional level is calculated as the sum of cropland area on organic soils in all FSU polygons (p) in region (r), divided by the sum of total cropland area in all FSU polygons (p) in region (r):

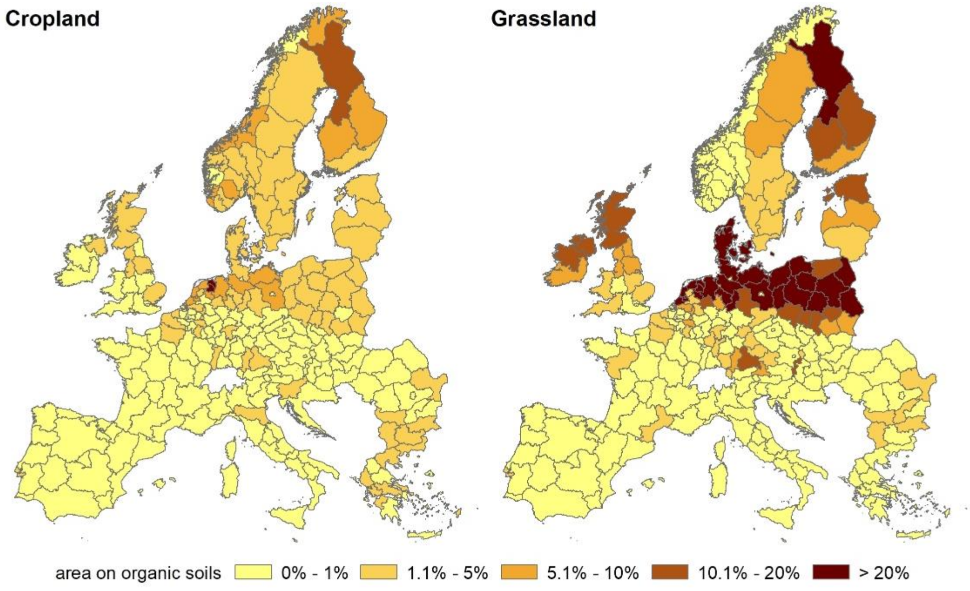
$soc_r^S = \frac{\sum_{p \in r} OC_p^S}{\sum_{p \in r} C_p^S}$ share of cropland on organic soils in CAPRI NUTS2 region (r)

$sog_r^S = \frac{\sum_{p \in r} OG_p^S}{\sum_{p \in r} G_p^S}$ share of grassland on organic soils in CAPRI NUTS2 region (r)

$sof_r^S = \frac{\sum_{p \in r} OF_p^S}{\sum_{p \in r} F_p^S}$ share of other land use on organic soils in CAPRI NUTS2 region (r)

The results for cropland and grassland on organic soils for CAPRI NUTS2 regions are presented in **Figure 19.** Regional shares of organic soils on cropland and grassland areasFigure 19.

Figure 19. Regional shares of organic soils on cropland and grassland areas



Source: CAPRI model

Annex 3. Knowledge synthesis on agriculture GHG mitigation measures

We performed a systematic literature review and a meta-analysis, aimed at evaluating the effectiveness of various emission-mitigation measures applicable to livestock production and agricultural systems. The goal was to identify robust quantitative effects for potential implementation into the CAPRI model.

The synthesis focused on ammonia, methane, nitrous oxide emissions, and nitrate leaching/run-off and was structured using the PICO framework (Populations, Interventions, Controls, Outcomes). It defined specific intervention-control pairs across different agricultural compartments to assess mitigation effectiveness relative to baseline or common practices. The following mitigation technologies were covered:

- Manure Storage: Both liquid (e.g., covers, acidification, cooling, digestion) and solid manure (e.g., covers, compaction, additives, composting).
- Manure Land Application: Techniques for liquid and solid manure (e.g., injection, incorporation timing), timing of application, precision techniques, use of digested manure, and nitrification inhibitors.
- Mineral Fertilizers: Use of nitrification inhibitors and improved application timing.
- Soil-Land Management: Effects of no-tillage, minimum tillage, and mulch tillage under different fertilization regimes.

The systematic literature search was conducted between May and October 2019 across four major databases (Web of Science, Scopus, Cordis, Google Scholar) plus references from existing reviews. The search targeted experimental studies (peer-reviewed and grey literature) comparing mitigation interventions to controls, without language, date, or geographic restrictions.

A multi-stage screening process based on predefined inclusion/exclusion criteria (focus on quantitative comparisons, exclusion of modelling-only studies) was followed, adhering to PRISMA guidelines. This resulted in the selection of 21 published meta-analyses and 178 individual studies for data extraction. We re-compiled existing evidence from published datasets and re-extracted missing information from original primary literature papers. Quantitative effect sizes were extracted, primarily using the Response Ratio (RR = 1 - Treatment/Control), comparing the mitigation treatment (T) to the control (C). The logarithm of RR (logRR) was used for analysis to meet statistical assumptions.

For the meta analyses linear mixed models were employed, treating the data source ('study') as a random effect to account for between-study variability. Categorical variables (e.g., manure type, climate) were included as fixed effects. Intra-study variance was considered negligible relative to inter-study variance. The study quality was not formally assessed at this stage, and lab, pilot, and field studies were treated equally. Data from individual studies were used to complement and expand databases from meta-analyses.

Results were presented as mean effect sizes (back-transformed RR) with 95% Confidence Intervals (CIs), estimated using REML or bootstrapping. Statistical significance was based on non-overlapping 95% CIs. A specific set of rules was applied to determine if an effect size was sufficiently robust for inclusion in the CAPRI model:

- Criterion 1: Included if the 95% CI did not overlap zero and |mean / CI width| > 0.33.

- Criterion 2: If CI overlapped zero, included if |mean / (CI width - overlap)| > 2.
- Criterion 3: If neither 1 nor 2 met: Interpreted as 'no effect' (value 0 implemented) if sample size (n) ≥ 6; interpreted as 'lack of evidence' (not implemented) if n < 6.

Table 1 presents a subset of results of the literature review[12], which was directly used for the modelling of mitigation technologies in CAPRI. Some values had to be transformed to fit the CAPRI nitrogen flow model. The column "Mean" shows the relative change factor of the respective emission category, which relate to the total nitrogen input into the storage system. The last column indicates whether we used the "Mean" (Increase/Decrease), assumed no effect, or data were not sufficient to draw any conclusions (unclear).

Table 12. Findings from the knowledge synthesis and agriculture GHG mitigation measures

Technology	**Comparator**	**Emission category**	**Mean**	**CI low (95%)**	**CI high (95%)**	**No obs.**	**Effect**
Manure storage techniques							
Natural Crust (liquid)	No cover	NH3	-41%	-46%	-35%	40	Decrease
		N20	+1392%	+5840%	+2200%	13	Increase
		Runoff					Unclear
		CH4	+10%	-8%	+29%	16	No effect
Low efficiency covers in liquid systems: (floating foils, polystyrene foam, porous inert materials)	No cover	NH3	-73%	-81%	-61%	53	Decrease
		N20	+346%	-11%	+202%	6	Increase
		Runoff					Unclear
		CH4	-25%	-63%	+54%	16	No effect
High efficiency covers in liquid systems: (tension caps, concrete, polyester, corrugated iron, wooden lids)	No cover	NH3	-86%	-91%	-78%	34	Decrease
		N20	-35%	-76%	+79%	14	No effect
		Runoff					Unclear
		CH4	-11%	-58%	+87%	15	No effect
High efficiency covers in solid systems: direct cover with plastic foil	No cover	NH3	-65%	-80%	-40%	19	Decrease
		N20	-54%	-80%	+9%	13	Decrease
		Runoff	-17%	-32%	-2%	11	Decease
		CH4	-3%	-65%	+170%	12	No effect
Manure application techniques							
Low efficiency techniques for liquid manure: Trailing hose, surface spreading + incorporation 24h, slit injection	Surface spreading	NH3	-51%	-65%	-32%	192	Decrease
		N20	+31%	-6%	+83%	34	Increase
		Runoff/ Leaching	+24%	-9%	+69%	23	Increase
		CH4	+98%	-3%	+305%	8	Increase
High efficiency techniques for liquid manure: Deep and shallow injection	Surface spreading	NH3	-93%	-95%	-90%	40	Decrease
		N20	+140%	+58%	+265%	24	Increase
		Runoff/ Leaching	-5%	-34%	+38%	15	No effect
		CH4	+488%	+163%	+1214%	6	Increase
Low efficiency techniques for solid manure: Incorporation within 24h	Surface spreading	NH3	-63%	-82%	-25%	16	Decrease
		N20					Unclear
		Runoff/ Leaching					Unclear
		CH4					Unclear
High efficiency techniques for solid manure: Incorporation within 4h	Surface spreading	NH3	-78%	-87%	-61%	50	Decrease
		N20	-45%	-64%	-16%	33	Decrease
		Runoff/ Leaching	-26%	-64%	+53%	4	Unclear
		CH4					Unclear
Better timing of manure application: growing		NH3	+66.5%	+2.3%	+170.9%	26	Increase
		N20	-32.2%	-57.2%	+7.3%	24	Decrease

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[12] The full list of references used in the literature review could be provided upon request.

Technology	Comparator	Emission category	Mean	CI low (95%)	CI high (95%)	No obs.	Effect
season vs non-growing season, non-rainy season vs rainy season		Leaching	-79.6%	-90%	-59%	4	Decrease
Manure treatment							
Manure acidification	Raw manure	NH3	-79%	-86.5%	-67.2%	49	Decrease
		N2O	-77.7%	-94.6%	-6.8%	11	Decrease
		CH4	-85.7%	-93.6%	-68.2%	33	Decrease
Anaerobic digestion	Raw slurry	NH3	+14%	-37.8%	+109.3%	24	No effect
		N2O	-21.8%	-71%	+111.3%	10	No effect
		CH4	-76.8%	-87.3%	-57.9%	27	Decrease
Application of digestate	Raw slurry	NH3	-13.8%	-46.4%	+38.5%	23	No effect
		N2O	-22.8%	-41.7%	+2.3%	48	Decrease
Nitrification inhibitors							
NI with mineral fertilizers	No NI	NH3	+14%	-6%	+38%	15	Increase
		N2O	-17.9%	-20.5%	-15.1%	41	Decrease
		Leaching	-51.1%	-53.5%	-48.4%	37	Decrease
NI with manure	No NI	NH3	+27%	+20%	+36%	12	Increase
		N2O	-39%	-42.1%	-30.6%	18	Decrease
		Leaching	-43%	-63%	-36%	101	Decease
NI with mineral fertilizers or manure	No NI	NUE	+10.2%	+6.7%	+11.5%	202	Increase
		yield	+5%	+4%	+7%	57	Increase
Soil management							
No tillage (mineral)	Conventional tillage	CH4	-15.9%	-26.4%	-3.7%	65	Decrease
		CO2	-11.3%	-5.5%	+0.76%	139	Decrease
		N2O	+10.4	+2.4%	+18.9%	299	Increase
		Leaching	+23.7%	+3.1%	+62.5%	108	Increase
		Runoff (slopes)	-52.9%	-65.9%	-24.9%	129	Decrease
		Runoff (general)	-6.7%	-30.8%	+26.3%	39	No effect
No tillage (manure)	Conventional tillage	Leaching	+38.4%	+20.5%	+58.9%	26	Increase
		Runoff (general)	-9.4%	-26.3%	+17.9%	4	unclear
Conservation tillage	Conventional tillage	Leaching	-87.7%	-91.2%	-81.8%	50	Decrease
		Runoff (slopes)	-46.2%	-65%	-14%	192	Decrease
Mulching, soil cover with plant material	Conventional tillage	Leaching	+6.2%	-4.3%	+44.3%	30	No effect
		Runoff (general)	-33.2%	-64.5%	-15.3%	63	Decrease

Source: Authors elaboration

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