Incentives for Climate Change Mitigation across the Agri-food Value Chain

Input paper #2 - Effectiveness[1]

1 Introduction

1.1 Purpose and scope of the paper

The theme of this paper, and its corresponding technical workshop is “effectiveness.” The aim of this paper and corresponding workshop is to explore the previously presented policy options, and discuss their potential effectiveness in achieving GHG reductions and increasing carbon removals in the agri-food sector.

This paper aims to facilitate discussions in the workshop regarding the potential for different types of policy options for reducing different sources of farm gate emissions and increasing removals, such as emissions from livestock production (enteric fermentation, manure management), the use of synthetic fertilisers, the use of organic fertilisers, and LULUCF emissions from croplands and grasslands used for agricultural purposes.

Since the policy options considered have points of obligation which are off-farm, the mitigation potential of off-farm actions, such as changing recipes for manufactured foods, innovating the composition of fertilisers, and marketing strategies to facilitate changes in consumer behaviour, are also considered. Effectiveness should also consider changes to consumer behaviour, particularly in facilitating dietary changes towards more sustainable diets.

In focusing on the potential of the policy options considered in this document to reduce emissions and increase removals, the means of incentivising needed actions, practices, and innovations for each of the policy options should be considered, including what types of behaviours could each of the options provide an impetus for, and to what extent would different actors uptake such actions. What are some of the limitations of each of the policy options, and are there trade-offs between these policy options for climate mitigation? What design features could enhance or hinder climate mitigation for the policy options?

Designing the options to ensure high environmental integrity should also be considered. Considerations of environmental integrity must also focus on co-benefits and risks for biodiversity, air and water quality, as well as water balance. While the policy options could facilitate synergies with nature restoration objectives, such as peatland re-wetting, by providing price incentives, there could also be incentives for the intensification of agricultural practices in order to achieve emission reductions overall, that could have negative implications for biodiversity, particularly through increasing efficiencies for livestock production. Therefore, potential trade-offs between different environmental objectives such as increasing the risk of pollution swapping (decreasing methane emissions while increasing ammonia emissions), or decreasing areas of extensive livestock farming or increasing organic agriculture must also be factored. Risks of carbon leakage will be further discussed in the input paper for the 3rd workshop.

Finally, the choices made with regards to monitoring, reporting, and verification (MRV) of agricultural emissions and removals will have different implications in terms of the effectiveness of the policy. Each of the policy options will need to strike a balance between default MRV approaches to decrease

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administrative burdens and an on-farm MRV system which can create more direct incentives for reducing emissions or increasing removals.

1.2 Policy options to be assessed for this study

The research consortium for this project has begun the process of refining the policy options for consideration in the study which will assess the potential impacts of market-based policy options. The assessment of these options will help to make an informed decision to pursue feasible policy options, whilst discarding less feasible options. The initial selection of policy options is based on feedback from the worksheets which were submitted by participants from the first workshop. While the type of policy (carbon farming procurement, mandatory climate standard, emission trading system) and the point of obligation have been shortlisted, more specific details on policy design aspects of each of the five options, for the purposes of modelling, are to be further discussed and finalised based on feedback from the 2nd, 3rd and 4th workshops for the purposes of modelling.

The proposed set of options include:

1. Carbon Farming Procurement
2. Mandatory Climate Standard with a point of obligation for feed producers and/or food processors
3. Mandatory Climate Standard with a point of obligation for retailers and/or other actors further downstream (i.e. caterers)
4. Agri-Food ETS with a point of obligation for feed producers and/or food processors
5. Agri-Food ETS with a point of obligation on-farm

Table 1 below provides an overview of the potential scope of emissions for each of these five options. The scope of the emissions that should be covered under each of the five options for the assessment of impacts are to be further discussed in the workshops.

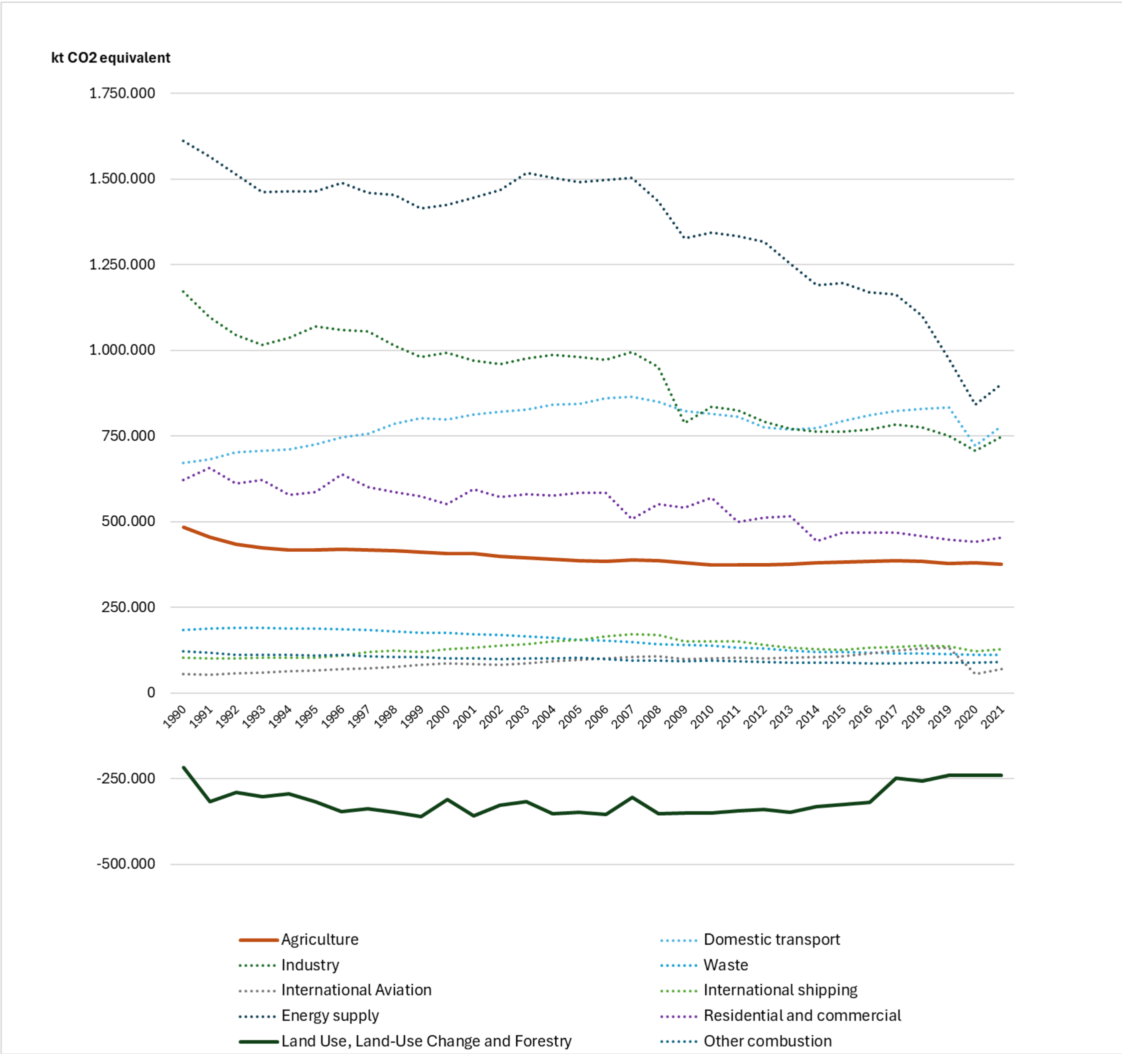
Table 1: Potential Emissions Scope for 5 Policy Options

GHG Source/ Activity	GHG			Potential emissions coverage (2022)	Included in Policy Option Scope				
	CH_4	N_2O	CO_2		Carbon Farming Procurement	Mandatory Climate Standard - Processors	Mandatory Climate Standard - Retailers	Agri-Food ETS - Processors	Agri-Food ETS – On-Farm
N_2O emissions from managed agricultural soils		✔		Up to 108.2 $MtCO_2e$	✔	✔		✔	✔
Urea application			✔	Up to 3.1 $MtCO_2e$	✔	✔		✔	✔
Other carbon-containing fertilisers			✔	Up to 0.7 $MtCO_2e$	✔	✔		✔	✔
Enteric Fermentation	✔			Up to 180.8 $MtCO_2e$	?	✔	✔	✔	✔
Manure Management	✔	✔		Up to 62.2 $MtCO_2e$	?	✔	✔	✔	✔
Emissions from croplands	✔	✔	✔	Up to 21,73 $MtCO_2e$	✔				✔
Emissions from grasslands			✔	Up to 19.46 $MtCO_2e$	✔				✔

2 The role of the agricultural sector in light of EU climate objectives

2.1 Agricultural and LULUCF emissions and removals trends and trajectory until 2030

Figure 1: EU-27 emission trends by aggregated sectors



Source: [EEA Dataviewer 2023]

For the past two decades, GHG emissions from the agricultural sector have remained largely stagnant. Following a decrease in emissions during the 1990s, minimal changes in the overall emissions volume have been observed since the early 2000s, with an overall reduction of only 2% between 2005 and 2021 (EEA, 2023). When accounting for LULUCF emissions from croplands and grasslands, agricultural activity currently accounts for approximately 13% of the total EU net GHG emissions (EEA Dataviewer, 2023). In 2022, approximately 49% of emissions from agriculture came from livestock enteric fermentation causing methane (CH4) emissions, while around 30% came from nitrous oxide emissions (N2O) in agricultural soils caused mainly by the use of synthetic fertilisers, and around 17% comes from manure management (both CH4 and N2O emissions) (EEA Dataviewer, 2023).

According to the EEA (2023), and based on Member State projections, *the emission reduction in 2030 would amount to 8% compared to 2005, in the scenario taking into account additional measures*", compared to the 12% needed to reach the climate target for 2030. The EUs 2023 Climate Progress Report projects that agricultural emissions will go down by 1% with existing measures, and by 5% (compared to 2005 levels) with additional measures by 2030, with the report stipulating that more effort will be needed to incentivize mitigation measures in the agricultural sector.

2.2 Contribution of agriculture to the 2040 climate target

The Commission's impact assessment accompanying the recommended 2040 climate target, illustrates the potential outcomes for agricultural GHG emissions beyond 2030 across a range of scenarios:

- Scenario 1 (S1): a net GHG reduction target up to 80% for 2040: The first policy scenario relies on the Fit-for-55 energy trends delivering the "linear" reduction path between 2030 and 2050. No specific mitigation of non-CO_2 emissions is foreseen under this scenario up until 2040, including in agriculture. By 2040, agricultural emissions are projected to reach 351 MtCO2 (app. 9% lower than 2015 levels).
- Scenario 2 (S2): a net GHG reduction target of 85-90% for 2040: Scenario 2 introduces a more ambitious approach in the land sector. This scenario targets GHG reductions by deploying technologies to reduce methane emissions, such as feed additives, farm-scale anaerobic digestion with biogas recovery, and selective breeding to enhance productivity and animal longevity. By 2040, agricultural emissions are projected to reach 302 MtCO2-eq (app. 22% reduction compared to 2015 levels)
- Scenario 3 (S3): a net GHG reduction target of 90-95% for 2040: Scenario 3 represents the highest level of ambition, assuming the full deployment of additional mitigation measures by 2040. These measures include nitrification inhibitors, precision agriculture technologies, and restoration of drained organic soils by 2040. By 2040, agricultural emissions are projected to reach 271 MtCO2-eq (app. 30% reduction compared to 2015 levels)
- LIFE scenario: The complementary scenario aims to achieve at least a 90% net GHG reduction by 2040, providing an alternative mitigation strategy to S3 that includes demand-side measures. LIFE expects a gradual consumer shift toward sustainable, healthy diets, in addition to the full deployment of available mitigation technologies. Under LIFE, agricultural emissions are projected to fall to 209 MtCO2-eq by 2040, representing a 46% decrease from 2015 levels.

The core S3 scenario and the LIFE variant illustrate the potential reductions in agricultural GHG emissions necessary to align with the proposed net -90% target by 2040. The two scenarios aim to achieve similar economy-wide net emission reductions, but through different means and sectoral contributions.

3 Drivers of climate mitigation outcomes along the agri-food value chain

3.1 Overall mitigation potential and cost-effectiveness of farm-level actions

The level of GHG emissions mitigation achieved by technological options[2], relative to their associated costs, can be assessed using marginal abatement costs (MACs). The "marginal abatement cost" refers to the expense of reducing an additional unit of emissions compared to a baseline level, with the sum of these marginal costs representing overall mitigation cost. A marginal abatement cost curve (MACC) visually ranks different GHG mitigation measures by their cost-effectiveness. Perez-Dominguez et al. (2021) calculate national and EU-wide MACCs for agriculture through various scenarios where GHG

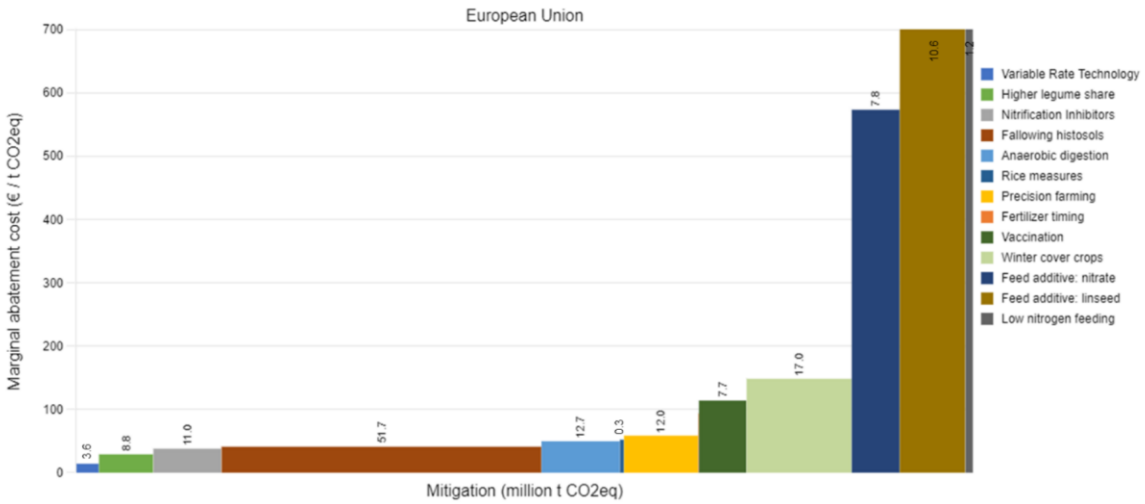
[2] Descriptions of technological mitigation actions that can be adopted at the farm-level are described in Annex I.

mitigation strategies are applied to the EU farming sector for 2030. The study outlines two approaches to constructing MACCs: the standalone measures approach, where each technological mitigation option is implemented in isolation, without considering interactions with other measures, and the combined measures approach, where each technological mitigation option is implemented cumulatively and interactions between the measures are taken into account.

Standalone measures approach

In the standalone measures approach, each bar in the MACC represents a distinct mitigation option. The width of the bar indicates the mitigation potential (in Mt CO_2eq), while the height represents the unit cost (EUR/t CO_2eq mitigated). These costs reflect the average unit cost if the mitigation option is implemented to its maximum possible extent. The bars are arranged from left to right, with the least expensive options on the left. A significant limitation of this approach is that it assumes each measure can be applied at its theoretical maximum, without considering interactions between measures. As a result, the mitigation potential of individual measures cannot be added together to calculate the total cumulative mitigation potential.

Figure 4: Mitigation potential by specific mitigation option



Notes: Maximum mitigation potential directly achieved by the specific technological mitigation option ('tech only'). The individual mitigation potentials cannot be added up to form a cumulative effect. Including CO_2 emissions: fallowing histosols, higher legume share on temporary grassland, winter cover crops. The y-axis shows marginal abatement costs in the context of a MACC looking at the entire figure, i.e. over all mitigation technologies, when moving from one technology to the next. However, for each technology the height of the bar represents the average costs per tonne CO_2eq abated. The costs for linseed and low nitrogen feeding go beyond 700 €/t CO_2eq.

Source: Perez-Dominguez et al., 2021

The study's results show the fallowing of histosols[3] emerging as the most effective measure for total emission reduction, offering more than 50 Mt CO_2eq of mitigation potential. From a marginal abatement cost perspective, variable rate technology and increasing the share of legumes on temporary grassland are the most cost-effective, having the lowest costs per tonne of CO_2eq abated. Other measures that show strong potential in terms of both abatement and cost-effectiveness include nitrification inhibitors, anaerobic digestion, and precision farming. However, it is important to note that the MACCs presented for each technology are averages, meaning some regions or farmers may experience lower or higher

[3] The fallowing of histosols refers to the practice of leaving histosol soils (soils rich in organic matter) uncultivated or resting for a period of time. Histosols are highly organic and can store large amounts of carbon. However, when these soils are drained or disturbed for agricultural use, they decompose and release significant amounts of carbon dioxide (CO_2) and other greenhouse gases into the atmosphere, contributing to climate change. By fallowing histosols—ceasing their cultivation and, ideally, rewetting them if they have been drained—the decomposition process slows, and the soil can start to retain carbon again. This practice can help preserve soil organic matter, reduce greenhouse gas emissions, and contribute to soil restoration and biodiversity conservation in the area

abatement costs per unit of CO_2eq. Consequently, measures with high mitigation potential but higher costs – such as vaccination against methanogenic bacteria[4], winter cover crops, and the use of feed additives like nitrate and linseed – should not be dismissed outright.

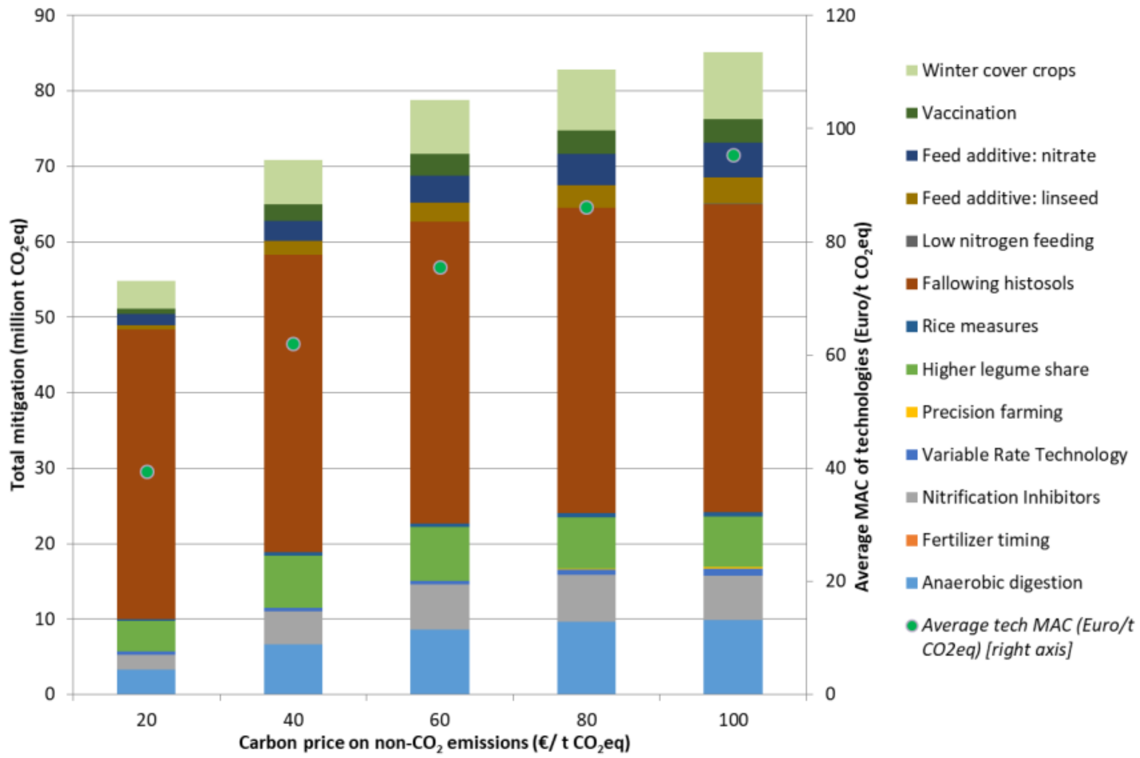
Combined measures approach

In the combined measures approach, all technological mitigation options are available simultaneously in every scenario and can be adopted cumulatively by farmers. In this approach, farmers choose technologies based on their relative costs. Unlike the standalone approach, which classifies mitigation technologies as either relatively cheap or expensive, the combined measures approach assesses their cost-effectiveness at various carbon price levels. A technology is considered cost-effective if it is adopted, as it would not be chosen if its unit cost exceeded the carbon price.

In this analysis, five scenarios are examined, each corresponding to a different carbon price (CP) on agricultural non-CO_2 emissions: CP 20, CP 40, CP 60, CP 80, and CP 100 Euros per tonne of CO_2eq. These carbon prices create a general incentive to reduce non-CO_2 GHG emissions, while the LULUCF-related emission reductions are treated as secondary effects resulting from the carbon price on agricultural emissions.

The figure below presents the technology-specific EU MACC illustrating the contribution of each technological option to total mitigation under the combined measures approach at the aggregated EU-28 level.

Figure 5: Contribution of each technology to total mitigation under a combined measures approach for EU27 (compared to baseline, 2030)



Note: All technological mitigation options are simultaneously available in all scenarios. The options 'fallowing histosols', 'winter cover crops' and 'higher legume share on temporary grassland' also cover CO_2 emissions. The carbon price only targets agricultural non-CO_2 (methane and nitrous oxide) emitting activities.

[4] Although such an option does not exist as of yet, and therefore costs are speculative at this point, it could be a feasible option in the future

Source: Perez-Dominguez et al., 2021

The highest mitigation is achieved by far through fallowing histosols at all carbon price levels, followed by anaerobic digestion, increasing the legume share on temporary grassland, winter cover crops, nitrification inhibitors, feed additives, and vaccination against methanogenic bacteria in the rumen. Winter cover crops, feed additives (linseed and nitrate), and vaccination are partially adopted even at relatively low carbon prices, meaning they are cost-effective in at least some regions, despite being classified as high mitigation and high-cost measures in the standalone approach.

In contrast, variable rate technology and precision farming see limited adoption under the combined measures approach, indicating they are less cost-effective, despite being categorized as high mitigation and relatively low cost in the standalone measures approach. This makes nitrification inhibitors the most cost-effective fertilizer-related option in the combined measures scenario.

The results highlight the importance of considering technologies in combination, rather than aggregating mitigation potentials from individual measures without accounting for their interactions. Focusing solely on standalone MACCs can lead to an overestimation of mitigation potential (Fellman et al. 2021). Cost-effectiveness is also region-specific, with some measures being more or less viable depending on local conditions. Additionally, the combined effect of certain strategies may not simply equal the sum of their individual impacts, as farm models have identified potential non-additive effects when mitigation methods are combined (del Prado et al., 2010). Further research is needed on the efficacy of these combined approaches (FAO, 2023). These conclusions also suggest that a flexible policy approach, allowing farmers to adopt the most cost-effective mitigation options suited to their specific circumstances, is important, especially given the varying outcomes in terms of cost-effectiveness under the two modelling approaches.[5]

It is also crucial to note that GHG abatement costs are a single-objective indicator. In the MACCs presented, costs are entirely allocated to GHG mitigation, ignoring any positive or negative impacts on other emissions, such as ammonia or nitrate leaching. Thus, a measure that ranks well for GHG mitigation may not be the most cost-effective or beneficial from a broader environmental perspective. Conversely, a measure with a less favourable ranking for GHG mitigation may still be worthwhile if it provides other unaccounted-for benefits. A brief discussion of the commonly observed co-benefits can be found in section 5.3.

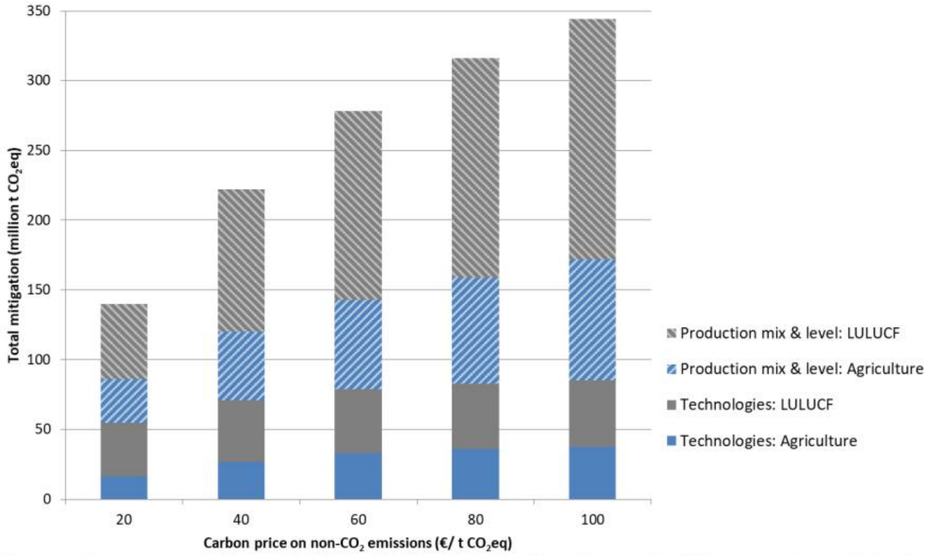
Mitigation beyond agricultural technology options

The MACCs in the combined measures approach, derived under different carbon price scenarios, show that total mitigation extends beyond just technological effects in each case. The figure below illustrates the mitigation achieved across the EU through technological options, as well as changes in production levels (e.g., reducing livestock numbers) and shifts in production mix (e.g., altering the composition or intensity of farming activities) at different carbon prices for the EU-28. It suggests that mitigation technologies contribute significantly to total emissions reduction at lower carbon prices, but their adoption becomes limited once carbon prices exceed 60 EUR/t CO2eq.

While the carbon price primarily targets non-CO_2 emissions from EU agriculture, around 66% of the total mitigation in all scenarios comes from CO_2 emissions and carbon sequestration in the LULUCF sector. The share of LULUCF mitigation, driven by changes in production mix and levels, increases from 41% to 50% as carbon prices rise. These LULUCF-related emissions reductions and removals are secondary effects, resulting from the carbon price on agricultural non-CO_2 emissions.

[5] This necessitates a smart design of the options with appropriate choices available to farmers, who can choose the lowest cost options but not necessarily the most cost-effective ones, wherein flexibility and complexity are interacting.

Figure 6: Total mitigation under the combined measures approach, EU28 (compared to the baseline, 2030)



Note: All technological mitigation options are simultaneously available in all scenarios. The 'tech only' mitigation effects linked to the breeding measures 'milk yields' and 'ruminant feed efficiency' cannot be reported in isolation and are included in the mitigation achieved by changes in the production mix and levels.

Source: Perez-Dominguez et al., 2021

In the analysis, carbon sequestration is treated symmetrically as negative emissions, meaning the cost of one unit of sequestered CO_2 is considered equal to the cost of one unit of avoided emissions. However, while emissions reductions from technology can be sustained year after year, yielding consistent annual mitigation benefits, carbon sequestration in soils is a finite process, as soils eventually reach saturation. To prevent the loss of sequestered carbon, farmers would need to continue applying the measure indefinitely or at least until the end of the planning period. This, however, is not reflected in the cost data, which results in a systematic bias in favour of measures that sequester carbon compared to those that reduce emissions in the analysis (Hellmann et al., 2021).

3.2 Co-benefits and trade-offs of on-farm mitigation actions: biodiversity, soil heath, air and water quality

Agricultural greenhouse gas (GHG) mitigation policies can produce both co-benefits and trade-offs. Some measures aimed at reducing agricultural GHG emissions can positively impact other environmental areas, while others may have unintended consequences, such as pollution swapping, where reducing one pollutant inadvertently increases another. Research on pollution swapping in agriculture is limited compared to industrial contexts, yet it affects climate, water, soil, and air quality (Verspecht et al., 2012). Additionally, some measures, like biodiversity protection and nutrient management, can positively impact both GHG emissions and broader environmental issues. Effective on-farm mitigation strategies should therefore consider such co-benefits, trade-offs, and interconnections to minimize environmental risks and maximize positive outcomes. Several agricultural practices offer both co-benefits and potential trade-offs for biodiversity. Practices such as peatland re-wetting, agroforestry, and managing soil organic carbon (SOC) show strong biodiversity co-benefits, helping improve soil health and supporting diverse plant and animal communities, but also pose certain risks as well (see Scheid et al., 2023).

Paludiculture, partial and full re-wetting of peatlands demonstrate strong biodiversity co-benefits, and very few, if any, environmental trade-offs. Soil health is restored upon re-wetting, with new vegetation in large areas of rewetted degraded peatlands storing large quantities of nutrients mobilised from degraded peat soils (Bonn et al., 2016). Re-wetted peatlands also provide support for specialised species, such as breeding birds and the recovery of aquatic macroinvertebrate fauna (Artz et al., 2018) and a diverse assemblage of aquatic organisms, resembling previously undisturbed peatland sites (Swindles et al., 2016). However, these restored peatlands might not fully match the biodiversity levels of pristine, undisturbed peatlands (Tanneberger et al., 2020; Renou-Wilson et al., 2019).

Agroforestry also offers substantial environmental benefits by mitigating soil erosion, enhancing nutrient cycling, and supporting biodiversity (Torralba et al., 2016). By incorporating trees into farmland, agroforestry reduces erosion from wind and water, improves soil fertility, and supports bird and invertebrate populations (Parcchini et al., 2008). Additionally, using nitrogen-fixing trees within agroforestry systems can reduce the need for synthetic nitrogen fertilizers while maintaining crop yields (Reise et al., 2022). This approach supports bird species typically associated with hedgerows and woodlands, enriching grassland ecosystems and promoting overall biodiversity. Agro-forestry can improve water filtration into the soil, reducing runoff and promoting groundwater recharge. This can help to stabilise local water cycles, making more water available for plants and reducing the frequency of drought stress (Quandt et al., 2023).

Measures to increase SOC, such as catch cropping, crop rotations, and reduced tilling, enhance soil structure and nutrient retention, further benefiting biodiversity. High SOC levels improve soil fertility and microbial diversity, supporting nutrient cycling and reducing the need for nitrogen-based fertilisers (Reise et al., 2022). Enhanced SOC also reduces soil erosion and nutrient leaching, which helps preserve soil and water quality. Soils with higher SOC can also retain more water enhancing water infiltration and reducing runoff – this helps to maintain soil moisture during dry periods, making water more available for crops and improving water use efficiency (Kerr & Oschner, 2019). Reduced tillage improves the soil's water holding capacity and reduces evaporation, allowing for more rainwater to infiltrate the soul and improving water retention (Brunel-Salidias et al., 2018).

Improved nutrient management, such as careful planning and timing of fertilizer application and including nitrogen-fixing legumes in rotations, is essential for reducing nitrous oxide emissions. Nutrient and manure management on farms, especially if reduced overall, can mitigate the detrimental impacts of synthetic fertilizers (Ozlu & Kumar, 2018; Pahalvi et al., 2021). While animal manure can enhance soil health by increasing organic matter and reducing soil density, improper use risks water contamination and biodiversity loss from nutrient runoff (Königer et al., 2021). High nitrogen and phosphorus levels from conventional farming can degrade nitrogen-sensitive habitats, such as bogs and heathlands, especially in protected areas (Kelleghan et al., 2021).

Various mitigation technologies exist, in agriculture which have strong potential for ammonia reductions, such as precision farming, optimising nitrogen application or using nitrification inhibitors, covering manure storage or applying manure using injection rather than broadcasting (Vandyck et al., 2021). According to the EEA (2023), the following measures can reduce both ammonia and methane emissions: feeding or genetic measures to increase production efficiency of livestock; reduction of livestock diseases, increasing fertility and longevity to increase production efficiency; acidification of slurry; and anaerobic digestion. With ambitious climate policies in the agriculture sector compatible with staying below 2C, ammonia emissions could potentially reach a level in 2050 approximately 30% below the 2010 level (JRC, 2017).

Livestock management practices, particularly grazing intensity, significantly affect biodiversity in grasslands. Heavy grazing can reduce plant diversity, while grazing exclusion can lead to the spread of less diverse shrublands. Research shows that light to moderate grazing, tailored to specific habitats, can help maintain or even increase plant diversity (Schietz & Rubenstein, 2016). However, site-specific studies are essential to ensure that livestock management is beneficial, as impacts vary widely depending on the environment and grazing practices.

Mitigation strategies to reduce greenhouse gas (GHG) emissions in agriculture can impact farmed animal welfare both positively and negatively. Key strategies include adjustments to animal feed, genetic selection, species shifts, and housing changes. For methane reduction, feed changes such as increasing concentrates over forage may reduce emissions but often lead to digestive issues like acidosis and bloat in cattle, sometimes causing severe health problems like liver abscesses or laminitis (Shields & Evans, 2016). Feed additives like fumarate and nitrates show potential but pose risks, including rumen pH disruption and nitrite toxicity, requiring careful management (Newbold et al., 2005). Genetic selection aimed at improving feed efficiency in livestock, especially dairy cows, has increased productivity but often strains animal health. High-yield cows, for example, face energy imbalances leading to metabolic disorders like laminitis, ketosis, and mastitis, tied to their intense production demands (Verkeemp et al., 2000). Shifting to non-ruminant species, like poultry, is more GHG-efficient than cattle farming but raises welfare concerns, including metabolic issues and leg disorders in poultry (FAO, 2013). Housing changes also affect welfare; slatted floors reduce emissions but may cause foot injuries, while outdoor access can reduce injuries and mobility issues (Shields & Evans, 2016). Some GHG mitigation measures, however, align well with animal welfare, such as extending animal lifespan, enhancing health, and reducing livestock numbers. These approaches contribute positively to both emissions reduction and animal well-being.

3.3 Mitigation strategies available to other agri-food value chain actors

The effectiveness of policy interventions aimed at facilitating changes in on-farm practices and reducing agricultural emissions hinges on the strategies of actors along the value chain. Depending on their role and position in the chain, these actors have leverage over both the supply and demand sides. Therefore, collective engagement from value chain actors is crucial for implementing an integrated systemic approach to achieving a sustainable agricultural transition.

The input paper from the first workshop prepared for this project discussed potential points of obligation for new climate policy interventions. As part of this discussion, it detailed the levers available to various types of actors along the value chain[6]. Given the relevance of these levers to policy effectiveness, examples of the relevant strategies are also included in the table below.

Table 2: Mitigation strategies for agri-food value chain actors

Type of actor	Mitigation strategies
Feed manufacturers	• Engagement with suppliers, creation of supplier incentive programmes (aimed at promoting sustainable cultivation practices upstream, such as e.g. optimized fertilizer application) • Collaboration with financial institutions to facilitate the provision of necessary finance or insurance to support suppliers in adopting more sustainable practices • Enhancing circularity in feed production through the recovery of nutrients from other industrial processes in the food and biofuel value chains • Innovation and preferential pricing strategies around low-emissive feeds and feed-additives (e.g. algae)
Synthetic fertiliser manufacturers	• Changing fertiliser formulation • Innovation and preferential pricing strategies around enhanced efficiency fertilisers (e.g. nitrification inhibitors, double inhibitors, controlled-release N fertilisers)
Food processors	• Engagement with suppliers, creation of supplier incentive programmes (aimed at promoting sustainable cultivation practices upstream, such as e.g. optimized fertilizer application, manure management) • Collaboration with financial institutions to facilitate the provision of necessary finance or insurance to support suppliers in adopting more sustainable practices • Product portfolio diversification, including e.g. improved offer of plant-based alternatives

[6] Sections 3.1.2 and 4.5. Available at: https://climate.ec.europa.eu/document/download/cdf7e657-ac93-4706-a1b9-3b1adba80dbd_en?filename=policy_crcf_agrifood_tw1_input_en.pdf

Type of actor	Mitigation strategies
	• Product reformulation, including e.g. reduction of meat or dairy content • Innovation in the area of plant-based meat and dairy alternatives or cultured meat and dairy • Marketing strategies aiming to steer consumer behaviour towards more sustainable products • Waste reduction and efficiency improvements
Retailers (& potentially other actors further downstream, i.e. caterers)	• Tailoring of internal procurement guidelines or supplier codes of conduct to include mandatory criteria relating to climate disclosure or performance • Product portfolio diversification, e.g. by increasing the availability, choice and affordability of sustainable options • Creating shopping experiences that facilitate sustainable consumer choices (e.g. through placement of products and store lay-out; opening exclusively plant-based store branches) • Informing customers about product sustainability, e.g. through responsible-choice labels, environmental labelling, disclosing climate-relevant information • Pricing strategies • Waste reduction

3.4 Changes in consumer behaviour

The parallel changes in the demand for agri-food products are a key factor in the expected effectiveness of policies, and substantial scientific evidence demonstrates that shifts in dietary choices can deliver significant climate mitigation benefits. The FAO defines sustainable diets as those which are healthy, have a low environmental impact, are affordable, and culturally acceptable. A variety of diets have been labelled as sustainable dietary patterns, including vegetarian, Mediterranean, vegan, as well as those following national dietary guidelines. Such diets may deliver both health and environmental benefits due to partial replacement of animal products with plant-based foods.

Europeans consume large quantities of GHG-intensive animal products, with the EU27 per capita consumption of animal protein amounting to more than twice the world average (European Commission, 2021). In 2020, each European consumed approximately 69.5 kilograms of meat and 236 kilograms of milk. These EU-wide average figures conceal significant national disparities: annual per capita meat consumption varies from 34 kilograms in Bulgaria to 62 kilograms in Luxembourg, while milk consumption ranges from 115 kilograms in Cyprus to 353 kilograms in Finland. Since 2011, there have been notable decreases in meat consumption per capita in Italy (-8 kg), Germany (-10 kg), and Belgium (-26 kg), while smaller changes occurred e.g. in France over the same period, where a shift from red meat to poultry has been observed (Pushkarev, 2021).

According to Birt et al. (2017), several trends are noticeable in shifting dietary patterns across the EU. Considering food supply, more meat is becoming available, and quantities of poultry are growing; in parallel, the availability of vegan proteins is increasing as well. Meat, fish, and dairy products are the main sources of protein, and protein intake is higher than what is recommended by the WHO, and twice as high as recommended by the World Cancer Research Fund (ibid). The Commission’s 2023-2035 Agricultural Outlook (2023) notes that consumer concerns about the impacts of their diets are likely to contribute to lower meat consumption, while the consumption of dairy products is due to stabilise, in line with changing habits (e.g. lower consumption of drinking milk) and expanding novel uses of dairy products (e.g. increasing use of dairy ingredients). The Outlook forecasts a decline in EU meat consumption from 67 kg in 2023 to 65,4 kg per capita by 2035, with this overall decline accompanied by shifts in the consumer basket. Beef is expected to continue its downward trend, with EU beef consumption projected to decrease by 0.9 kg per capita, while the ongoing replacement of pigmeat with poultry consumption is expected to persist.

Veganism is becoming less of a niche diet in western food culture, with approximately 7% of Europeans eating a fully or mostly plant-based diet (Perez-Cueto et al., 2022). Meanwhile, a flexitarian diet, characterized by reduced meat consumption and a preference for plant-based options (ibid), is increasingly becoming a norm, with 40% of Europeans identifying their diet as such (ibid). Europe is also expanding its market for meat replacements and other plant-based alternatives (Food Navigator, 2017; Faber et al., 2020). Approximately, 12% of households purchase plant-based alternatives and of these, almost two-thirds are repeat purchasers (Neuhofer & Lusk, 2022). With such trends, companies have moved towards launching more and more novel products, creating a need for innovative products based on market research, as well as developing new competencies in R&D capabilities (Saari et al., 2021). Strategies for hybrid products are also a potential driver for enabling a transition towards more plant-based foods (Banovic et al., 2022) – these are products combining meat and plant-based ingredients. Previous research has demonstrated that substituting 50% of beef with plant-based ingredients maintains consumer acceptance (Spencer & Guinard, 2018). While those consuming high protein diets are often not willing to reduce their meat consumption (Spencer et al 2018), they tend to be interested in new ways of eating healthier (Lang, 2020).

While the overall trend in meat consumption in the EU broadly conforms to general climate mitigation needs, more pronounced dietary would be needed to mitigate the risk of new supply-side policy actions being undermined by carbon leakage effects (Henderson and Verma, 2021; Zech and Schneider, 2019) and to meaningfully align with the EU's overall climate ambitions. A substantial body of scientific evidence underscores the need for extensive food system transformation, including reductions in meat and dairy consumption (FAO, 2017; IPCC, 2019; IPES Food, 2019; Willett et al., 2019; GCSA, 2020; SAPEA, 2020).

A review of a total of 210 scenarios within 63 studies modelling the impacts of sustainable dietary patterns[7] by Aleksandrowicz et al. (2016) found that reductions of over 70% in GHG emissions and land use, and 50% in water use, could be achieved by shifting typical Western diets to more environmentally sustainable dietary patterns. Medians of these impacts across all studies suggest possible reductions of between 20% and 30%. The largest impacts on GHG emissions came from switching to vegan diets (reducing emissions of a median of 53% and up to 69%) and vegetarian diets (reducing GHG emissions between 23-38%), and pescatarian (reducing GHG emissions 18-35%). Following healthy guidelines could reduce emissions between 20-30% (Hallstrom et al., 2015) and replacing ruminant meat with pork and poultry could reduce emissions between 18-33% (ibid). These results are largely based on national-level diets in high-income countries and are broadly consistent with findings from other recent studies covering the EU (e.g., Geibel & Freund, 2023), the UK (e.g., Green et al., 2015), and Europe and North America (e.g., Burke et al., 2023).

The LIFE scenario variant included in the Commission's modelling as part of the impact assessment accompanying the 2040 climate target communication also demonstrated a possible climate mitigation pathway including a combination of mitigation technologies with a gradual shift towards more sustainable and healthy diets as defined by the EAT-Lancet Commission by 25% by 2040, without reductions in calorific in-take. The assessment shows that such a scenario would enable a reduction in EU agricultural emissions by 46%[8] by 2040 compared to 2015 while strengthening the resilience of agricultural production (European Commission, 2024). Beyond the EU, the EAT-Lancet Commission estimates that a shift towards more plant-based diets could reduce global agricultural GHG emissions by up to 80% while reducing premature mortality by 19% (Geibel et al., 2023), and if combined with

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[7] The 14 dietary patterns include vegetarian, vegan, pescatarian, replacing ruminant with monogastric meat, balanced energy intake, following healthy guidelines, Mediterranean diet, New Nordic diet, and meat reduction, along with other sub-scenarios such as type of food supplemented by meat reduction and healthy guidelines with further optimization.

8 In this scenario, both demand declines and mitigation technologies are applied simultaneously. A marginal value of up to 250 EUR up to 30% can be attributed to mitigation technologies.

improved agricultural production practices and a reduction in food waste it could allow for 10 billion people to be fed within planetary boundaries (Springmann et al., 2018).

Discussion questions:

- Considering the potential of different mitigation options and the synergies / trade-off with environmental objectives as described in this section , which GHG emissions should the policy cover?
- What balance of incentives should the policy pursue between changing on-farm practices, changing the mitigation strategies of agri-food industries, or changing consumer behaviour?

4 Policy options and effectiveness

This section intends to facilitate discussions in the workshop on the practical aspects of each of the policy options that would influence their effectiveness in facilitating climate mitigation. There are potential “blind spots” in the discussions of policy design and the effectiveness of each of the policy options. One example of a potential blind spot is on the impacts of MRV choices on the effectiveness of the policy options, which is discussed in Section 4.2. Therefore, we highly encourage workshop participants to bring such blind spots to our attention in the workshops, as well as in the worksheets accompanying this input paper. In addition, ideas and thoughts on potential design solutions for such blind spots are also highly encouraged to be shared.

4.1 Potential effectiveness of “Carbon Farming Procurement”

Voluntary carbon markets enable companies, organisations and individuals to voluntarily trade verified emission reductions and carbon removals through the purchasing of carbon credits. Unlike mandatory carbon markets, VCMs currently operate outside of regulatory frameworks and allow for participants to take action on their own initiative. VCMs are intended to play a complementary role in addressing climate change by encouraging voluntary actions to reduce emissions and increase removals, helping to channel funds into projects that can make meaningful contributions to emission reductions and removals, especially in sectors where regulations are not necessarily already facilitating mitigation.

There are several motivating factors for voluntarily purchasing credits by investors. Many companies aim to demonstrate their commitment to sustainability and reducing their climate impacts. As mentioned in the input paper from the first workshop, the SBTi has reported a nearly 150% increase in the number of companies in the food, beverage, and agricultural sector setting targets aligned with its methodologies between 2022 and 2023. Participation in VCMs can assist companies in meeting internal climate and sustainability goals and demonstrate leadership in combating climate change. Environmental, Social, and Governance (ESG) factors are becoming critical criteria for investors. Companies participating in VCMs can attract ESG-focused investors and potentially access better financing options by demonstrating efforts to manage environmental risks. The impetus to participate may also come from supply chain pressures: many larger corporations are demanding that their suppliers reduce emissions. To maintain business relationships, entities may choose to participate in a VCM to align with expectations of their clients. Participation is also fuelled by enhancing the public image and brand value of a company among consumers, which is an increasingly important factor in consumers’decision-making process when making purchases. Companies perceived as being more proactive voluntarily may increase consumer loyalty and strengthen their reputation.

To build trust and to contribute towards effective climate mitigation impacts, VCMs need more oversight and transparency, and a focus on high-quality, impactful projects genuinely contributing to additional emission reductions and removals: through the CRCF, the EU aims to strengthen standardisation of methodological approaches and that such methodologies and better oversight ensure carbon farming projects are resulting in emission reductions and removals that are measurable and deliver unambiguous positive net benefits for climate mitigation. Under the CRCF, carbon farming projects will need to go beyond the "standard performance of comparable activities in similar circumstances" (European Commission 2022/0394 (COD)). The Commission intends to recognise certification schemes able to apply CRCF rules through Decisions, following a comprehensive assessment of governance, rules, and procedures.

Effectiveness of Voluntary Carbon markets – a literature review

Recently, the SBTi released a report (see Borjigin-Wang et al., 2024) summarising relevant evidence on carbon credits compiled in 2023 on the effectiveness of such certificates in corporate climate targets in relation to either emission reductions or emission avoidance. 406 pieces of evidence were collected for the report, and then assigned to hierarchical tiers[9] (i.e. those with low risk of bias or irrelevance), including evidence related to the extent to which carbon credits deliver on their intended mitigation outcomes. The empirical and observational evidence among the higher tier pieces demonstrates that carbon credits have "not been effective in delivering intended mitigation outcomes" – this evidence is based upon mostly peer-reviewed articles, including Badgley et al., 2022, West et al., 2020, West et al., 2023, Coffield et al., 2022, Probst et al., 2023, Haya et al., 2023 and Gill-Wiehl et al., 2023. Many of these sources highlighted methodological issues with crediting schemes that systematically incentivize over-crediting or overestimating emissions reductions or avoidance outcomes (see Guizar-Coutiño, 2022; Seyller, 2016; West et al., 2020; West et al., 2023; Withey, 2021). The reason behind over-crediting is due to the significant flexibility offered to project developers in performing estimates and applying safeguards (Haya et al 2023). Project developers benefit from selling more credits for doing less, whilst credit buyers seek inexpensive credits. Thus, higher levels of over-crediting are rooted in decisions based on motivations to generate more credits facilitating a race to the bottom in terms of credit quality (ibid). As a result, the report concludes that emissions reduction and removal credits are ineffective in delivering measurable mitigation outcomes under existing VCM standards and quantification methodologies.

Evidence suggests that there are risks of corporate buyers utilising credits for the purposes of offsetting, which can potentially hinder net-zero objectives and reduce climate finance. Non-offsetting uses, such as Beyond Value Chain Mitigation[10], may represent preferable uses of carbon credits to increase climate finance. However, evidence does also suggest that buyers of carbon credits are not solely utilizing carbon credits to meet their climate mitigation objectives. According to Trove (2023), companies utilizing material quantities of carbon credits, on average, decarbonise at twice the rate of companies not utilizing carbon credits (6% versus 3%), and those purchasing the most expensive credits, have an emission reduction of 7%. The purchase of carbon credits appears to be part of a larger climate mitigation strategy rather than a company's sole mitigation action (Trove 2023; Sylvera 2023). The credits such companies are buying represent a small proportion of their emission reductions (Ecosystem Marketplace 2023). Many firms engaging with carbon credits have set carbon prices within their organization to incentivize scope 1 and scope 2 emission reductions (Trove, 2023). VCM buyers are also 1.3 times more likely to have supplier engagement strategies and spent three times more on emissions reductions activities than the typical non-buyer (Ecosystem Marketplace, 2023).

Overall, the SBTi (2024) report determines that the treatment of carbon credits as interchangeable with emission reductions is inadvisable, and potentially damages global climate mitigation goals. The increasing growth of such evidence on the lack of effectiveness of VCMs has eroded stakeholder trust in such an instrument as a means of achieving climate mitigation objectives within organisations. Many organisations are becoming more reluctant to enter voluntary market transactions due to reputational risks from potential accusations of greenwashing and concerns about the quality, transparency, and integrity of carbon credits. Overall trade volumes in carbon credits in 2022 dropped

[9] A=i.e. peer reviewed journal article or government publication with a controlled research study or legal analysis; B = i.e. a case study or example, or white paper or report; C = i.e. commentary or news coverage.

[10] Beyond Value Chain Mitigation refers to "activities and investments that are not accounted for in a company's scope 1, 2, and 3 emissions and therefore do not count towards achieving value chain emission reductions. Efforts to deliver BVCM must not replace or delay corporate value chain decarbonization in line with a 1.5°C pathway – instead, BVCM is a mechanism by which companies go above and beyond value chain abatement" (SBTi 2024b, p.7).

by 51% (Ecosystem Marketplace 2023). However, credit prices rose from $4.04USD per tonne in 2021 to $7.37USD per tonne in 2022 (ibid). There are also predicted shortfalls in the supply of carbon credits in the future (ibid).

Newer credits generated with more robust methodologies is one of the explanations behind higher prices in 2022 (ibid). Increasing scrutiny of VCMs is facilitating improvements to standards using more robust methodologies, including the creation of integrity frameworks, such as the Integrity Council on the Voluntary Carbon Market (ICVCM) or the Carbon Credit Quality Initiative.

Design of this policy option

This particular policy option aims to achieve on-farm climate mitigation by facilitating both the uptake among farm operators of on-farm measures to generate CRCF units and the purchase of CRCF units. CRCF units could be purchased by the Commission/Member States through direct procurement. Alternatively, the Commission/Member States could act as an intermediary in the purchase of CRCF units through forward contracts; companies could then buy units from a pool of CRCF units instead of directly from farmers. For this policy option, one important question is where money for the purchasing of units would come from.

With procurement, feed-in-tariffs could be used to guarantee a fixed price for a CRCF unit over a time period to ensure income for farm operators of a carbon farming project. The purchase of units could occur either through government-backed contracts or through reverse auctioning, where operators submit bids to provide CRCF units at the lowest possible price per CO2 tonne. With forward contracts, the Commission would connect farm operators with buyers of certificates, or they could implement an auctioning approach, where buyers can submit competitive bids which start with a pre-defined threshold. The purchase of CRCF units by interested buyers could be further facilitated through the integration of CRCF methodologies into EU corporate sustainability requirements under the CSRD, ESRS, and Green Claims Directive.

To address potential imbalances in the supply of CRCF units (e.g. imbalanced supply of emission reductions vs carbon removals units, or of cheaper vs more expensive types of carbon farming activities), the Commission could facilitate the purchase of specific types of CRCF units, including through the creation of dedicated auction rounds for pre-determined categories of CRCF units (e.g. emission reductions vs removals, or dedicated funding for more expensive CRCF units).

Discussion on effectiveness

Under this policy option, climate mitigation in the agri-food sector is incentivised by providing stable demand for CRCF units, in which farm operators could be motivated to implement climate-friendly on-farm measures in order to generate additional income, specifically measures that can be certified under the CRCF regulatory framework. This motivation is underpinned by the reduction of revenue uncertainty for farm operators and through the reduction of unstable demand for CRCF units by mitigating market price risks that are currently a feature of voluntary carbon markets.

The Carbon Farming Procurement policy option could potentially overcome many of the shortfalls of VCMs outlined above, namely by supplying buyers with high-quality carbon units, and by overcoming the volatility in prices by providing stability in the demand for CRCF units as well as price stability. The policy option can shift voluntary markets towards better MRV and harmonisation. Because of the stability in demand for CRCF units and an effective minimum price for it, this would increase certainty for the farmers implementing CRCF activities and thus increase supply of CRCF units in general.

While the policy option can partially solve the issue of instability in demand for carbon credits, this will be highly dependent on how much funding is provided, thus what volume of units will be purchased at a certain price. This is dependent on how much money Member States or the Commission are willing to provide for this, whether there are rules influencing Member States' demand for certificates and if there are potential political risks of this changing over time. In addition, the policy is highly dependent on the willingness of farm operators to voluntarily participate in carbon projects. While the price stability does provide a monetary incentive, there is potential uncertainty in the supply of units due to the voluntary nature of the policy option – demand from procurement will not necessarily guarantee supply. The policy option is thus subject to a high degree of uncertainty in effectively reducing emissions and increasing removals as participation in the offering of CRCF units are voluntary, compared to the other types of policy options which have a mandated target for GHG emission reductions (Mandatory Climate Standard) or a "cap" on allowable emissions (ETS). Moreover, public procurement may crowd out direct private purchases. Lastly, there is also uncertainty as to whether such a policy option will facilitate price signals that are passed through the value chain to other supply chain actors, as well as on final consumer goods, thereby limiting impacts on changing supply chain and consumer behaviour.

Discussion Questions

- Under what conditions would this policy be effective in delivering the emission reductions and carbon removals needed for the agricultural sector to contribute to the EU-wide climate ambition?
- Should public bodies (e.g. at EU or national level) procure certificates?
- What considerations should be kept in mind in designing the procurement programme (e.g. dedicated purchase of units from specific categories of carbon farming activities)?

4.2 Potential effectiveness of Mandatory Climate Standard

This policy option mandates downstream actors to reduce their scope 3 farm-gate emissions year-on-year. The annual reduction requirement could be set in alignment with a climate mitigation trajectory needed to meet the EU's climate targets in 2040 and 2050.[11] Because the point of obligation would be further downstream, the policy option would incentivise the obligated party to incentivise emission reductions in the value chain or to implement other mitigation strategies as discussed in section 3.3 (for example, retailers may be incentivised to sell more low-emission products).

Effectiveness of Mandatory Climate Standards – a literature review

While previous EU standard setting legislation has not sought to encompass a whole value chain approach, an environmental mandatory standard for the agri-food sector has previously been under consideration as a potential policy option. The Commission's inception impact assessment[12] for the Sustainable Food System Law refers to the creation of general minimum binding sustainability requirements for food chain operators of food products. The approach implied that new EU rules applying to food system enterprises with the effect of raising standards and phasing out unsustainable practices or products in a methodical way. The assessment gives a very broad overview of the potential impacts of a policy package of actions in the food sector, in which the reduction of GHG emissions and the facilitation of carbon removals could be a result of, particularly through more efficient use of fertiliser and reducing and managing waste. Consideration of a mandatory standard in the agri-food sector was also recommended by the JRC in a 2022 report, stipulating that: "(w)hile voluntary measures and agreements… might be useful to initiate change in the short term, substantial change requires the formulation of ambitious and effective binding rules. Such rules would provide the necessary reliability and predictability for businesses by setting ambitious goals in combination with a practical timeframe" (JRC 2022, p. 19).

[11] To give a sense of magnitude, assuming that the mitigation trajectory for agricultural emissions is the one estimated in scenarios 2 and 3 of the 2040 Climate Target analysis (i.e. a 22-30% emission reduction in 2040 compared to 2015) this would be approximately 1-1.5% annually if the policy were to apply a linear trajectory between 2030 and 2050.

[12] An inception impact assessment provides views on the Commission's understanding of a problem and possible solutions and makes available any relevant information that they may have, including on possible impacts of the different options.

However, there is a lack of research on the potential climate effectiveness of mandatory standards in the agri-food sector. Indeed, much of the scientific literature focuses on the potential of carbon pricing as a means of climate mitigation in agriculture rather than standards. This dearth of scientific literature assessing the potential climate impacts of mandatory standards applies not only to the agri-food sector, but to all sectors. Stechemesser et al. (2024) evaluated 1500 climate policies across 41 countries implemented over the past 25 years, integrating a comprehensive climate policy database with a machine-learning-based extension to assess the emission reduction potential of different policy instruments. In identifying the most successful policy instrument types, the authors find that carbon-pricing is well-studied across many countries. In comparison, standards remain sparsely evaluated. Indeed, the assessment of combinations and interactions of policies which facilitate complementarities is poorly understood. Nevertheless, Stechemesser et al. (2024) collect enough evidence to determine that emission standards are the most frequently used policy in all sectors, with the exception of agri-food. In comparing effect sizes of GHG reductions, standards tend to have smaller effect sizes if they are a standalone measure.

The OECD (2022) recently developed the climate actions and policies measurement framework (CAPMF), which aims to measure the stringency of climate policies across countries, time, sectors, and instrument types – stringency is defined as the degree to which climate actions and policies incentivize or enable GHG emissions mitigation at home or abroad. The resulting database contains climate mitigation policies, comprising 128 policy variables, grouped into 56 instruments, covering 52 countries between the time-period 2000-2020. Results from the database indicate that the overall level of stringency was higher for emission trading systems (8.0) compared with mandatory standards (6.5), however the stringency of standards that have been implemented is higher compared with other policy types, including carbon taxes.

Stechemesser et al. (2024) find that mandatory standards may require complementary instruments to enable substantial emission reductions – in particular, the effect size of policy mixes combining standards with market mechanisms suggests the combination is the most effective at reducing emissions. Indeed, for sectors such as agri-food, which includes a significant share of consumers with behavioural factors such as myopia, such policy combinations with complementarities can be equally effective as carbon pricing (ibid). Such evidence suggests that combining a mandatory standard with the market mechanism allowing for the trading of CRCF units within a value chain may provide such complementarities. Indeed, other studies support such evidence of positive synergies in combining standards with market-based mechanisms as an effective combination for emission reductions (see Van den Bergh, 2021; Font Vivanco et al., 2016; Freire-Gonzalez, 2020; Van den Bergh, 2011).

Black et al. (2022) argue that the dearth of research on comparisons of effectiveness of standards and other types of policies in comparison with carbon pricing is related to the lack of methods measuring equivalence – Black et al. (2022) argue that metrics such as carbon price equivalence is generalizable in that it can be implemented with transparent and consistent multi-country mitigation models. The study also finds that alignment with national mitigation targets is not correlated with instrument types – national policies, whether carbon pricing or standards, differ significantly in terms of strength, sectoral composition, and adequacy to achieve mitigation objectives. Other research similarly finds no discernible difference in emission reductions for standards as a standalone policy compared with carbon pricing, or in combination with other policies. Dimanchev et al. (2023) finds that standards combined with market mechanisms reduces emissions with a similar cost-effectiveness of a standard as a standalone approach.

The Asian Development Bank (2023) argues that standards may be particularly useful for sectors with specific challenges in reducing emissions, particularly those related to information barriers, hard to abate emissions, and the pace of capital investment in infrastructure is not at the needed level. Standards can be tailored to the needs of a sector that may potentially prevent firms and consumers from responding to price signals created through carbon pricing mechanisms.

Impacts of MRV choices on the effectiveness of the policy option

The effectiveness of any policy option under consideration is heavily dependent on choices made about the underlying monitoring, reporting and verification (MRV). The unique nature and challenges of MRV in relation to biogenic emissions and removals present complex questions when designing an MRV system that serves as a cornerstone of these policy options.

MRV challenges in the context of agricultural and LULUCF emissions and removals

Both agricultural and LULUCF emissions and removals are difficult to monitor and verify for a variety of reasons, particularly when compared with the monitoring and verification of industrial emissions. CO2 emissions from fuel combustion can be accurately estimated based on the amount of fuel consumed and, while emissions of other gases are more complex, they are generally tied to industrial processes with reliable data. In contrast, AFOLU emissions sources and sinks and removals are diffuse and heterogeneous, as well as being less well understood compared to industrial emissions. They also depend heavily on localised contextual factors, such as soil conditions, weather patterns, long-term climate impacts, and natural disturbances.

For the accounting of AFOLU emissions, a dedicated volume of IPCC guidelines (2006) for national GHG inventories provide three calculation pathways (Tiers) characterized by different degrees of complexity. Tier 1 includes low-accuracy methodologies, which can be applied by using the default emission factors provided by the IPCC. Tier 2 methodologies require the use of national emission factors reflecting local pedo-climatic characteristics. Tier 2 methodology adopts a more site-specific and detailed assessment of factors influencing emissions. It considers a wide range of variables such as local climatic conditions, soil properties, livestock types, and management practices, resulting in more precise estimations. This level of detail allows policymakers, researchers, and farmers to make informed decisions about emission reduction strategies and the overall sustainability of agricultural practices. Tier 3 methodologies are based on model simulations or in situ measurements. These methods contain the highest level of detail, but require robust underlying scientific data, requiring that adequate amounts of this validated data are available to develop, apply and evaluate this approach.

Given the relative complexity of the physical processes underlying agricultural and LULUCF emissions and removals, GHG inventories at the Member State level rely much more on Tier 1 methods for these categories in comparison with other sectors, resulting in a higher degree of uncertainty. Member State GHG inventories vary significantly in terms of quality and precision, which complicates the tracking of national emission trends and, consequently, progress toward Nationally Determined Contributions. Estimating uncertainty in NGHGIs is itself fraught with challenges, as some countries do not report uncertainties at all, fail to report for certain categories, or provide insufficient information on how they calculate uncertainty.

Across the various categories of agricultural emissions, the 2023 EU GHG inventory report estimates the highest-level uncertainty for N2O from agricultural soils (75,7%) and N2O from manure management (68,4%), while the lowest uncertainty is associated with CH4 emissions from enteric fermentation (11,9%). In the context of the LULUCF emissions and removals data, the report shows significantly larger uncertainties. The most significant categories in terms of overall climate impact include CO2 emissions from cropland, associated with a level uncertainty of 188,4%, and CO2 emissions from grassland, with level uncertainty estimated at 110%. Although less significant in terms of overall volume, CH4 emissions from grasslands are associated with an even higher level of uncertainty, at 191,1%.

The CRCF Regulation plays an important role in facilitating improved monitoring, reporting and verification of selected types of agricultural and LULUCF emissions and removals by establishing quantification and certification methodologies. While the CRCF will serve as a key enabling tool, the project-focused approach and high-resolution MRV data which are characteristic of certified emission reductions and removals, do not automatically complement the available methods and current approaches to national and corporate inventory development. Partly due to the level of advancement in national GHG reporting described in the box above, the MRV applied to removals using carbon market methodologies do not necessarily 'nest' directly inside the accounts recorded in Member States' national GHG inventories (Zakkour & Tamme, 2024). While EU regulation requires gradual improvements in the MRV applied in national GHG inventories, it will take time and effort before the specific emissions and removals represented by CRCF certificates can be reflected (ibid.).

The challenges identified with regards to reflecting certified carbon removals and emission reductions in national GHG inventories apply, on a different scale, to corporate inventories, and are therefore relevant both for the policy option of Mandatory Climate Standard and for the policy option for a downstream ETS. The ESRS E1 Climate Change standard adopted under the CSRD requires the obligated actors to calculate or estimate scope 3 emissions using “suitable emissions factors” in accordance with the principles and provisions of the GHG Protocol Corporate Standard. It also requires companies to disclose information on GHG removals and storage from their own operations and value chain.

The CRCF certification process holds the potential to contribute to enhanced quality of corporate reporting, in particular by establishing harmonised rules for third-party auditing and by ensuring a good governance of certification schemes. The certificates of compliance will include information on gross emission data, which can provide important inputs into corporate inventories by reflecting the emissions of groups of suppliers. In addition, the CRCF units can be a way for companies to create incentives for farmers in their supply chain to adopt mitigation measures going beyond the standard practice.

An important question for discussion in this context is how to define the MRV requirements that are appropriate on two distinct levels:

- For the reporting of compliance (trajectory of total emissions and removals), requirements should build on the existing mandatory requirements under the CSRD
- For ensuring that the right incentives are provided to farmers to adopt good practices, requirements should build on the CRCF accounting methodologies and certification rules.

For instance, obligated parties could be allowed to report scope 3 emissions and removals using GHG data estimated in alignment with the general requirements of the GHG Protocol, with any uncertainties transparently disclosed. For an effective roll-out of the policy, companies should use simple and harmonised rules; while many existing programs and reporting practices are already established in the sector, the implementation of the CRCF framework with its harmonised rules for the certification process should help making the requirements of these programs more aligned and comparable. In parallel, the accounting requirements (in terms of additionality, baselines, permanence, etc) associated with CRCF units could be relevant for incentivizing farmers to go beyond standard practice.

However, the ‘nesting’ of accounted CRCF units in the companies’ yearly reports could raise some comparability issues that need to be considered in the design of the policy, keeping in mind the overall objective of simplicity and harmonization. This issue may have implications in terms of the effectiveness of the policy, because the choice made with respect to MRV requirements can impact the type of strategy that a company prioritises to comply with the standard: the more coarse the reporting framework, the less the companies reports will pick up on additional action undertaken by its suppliers, the less the incentives to invest in on-farm practices, and therefore the more weight will be given to other mitigation strategies (e.g. different product composition or marketing).

Discussion on effectiveness

As discussed above, the key advantage of this option is that it creates binding rather than voluntary requirements, which provides the opportunity to establish common targets and objectives for agri-food companies across the EU, delineating a clear, specific overarching objective. The unpredictable nature of the carbon crediting process often results in existing financial incentives in voluntary markets being insufficient to motivate farmers to adopt new sustainable practices for certification, particularly when carbon credit prices are low or uncertain (see Barbato & Strong, 2023).

Compared to the CRCF procurement option, a Mandatory Climate Standard would provide greater certainty for farmers by ensuring an increased demand for on-farm climate actions driven by compliance needs. Due to the mandatory nature of the policy option, the policy option will theoretically determine a price that will be enough of a financial incentive for farm operators to voluntarily sell credits. Under this option, downstream companies would need to buy credits to meet their obligated contribution towards emission reductions, thus increasing the demand for CRCF units, and ergo the price per units. While adopting changes in practices on-farm will result in costs for farmers, the voluntary nature of farmers' participation would ensure that the price of CRCF units should, at the very minimum, cover such costs. Another climate advantage of the policy option is that the standard can be progressively raised according to the needed climate contribution. The Commission can build in clauses related to the need to raise the standard over time in line with climate objectives. This could mean establishing a review every certain number of years. When standard increases, operators can be given an appropriate amount of time to reach the new standard.

On the buyers'side, the standard creates a level playing field for all companies producing or selling food in the EU, enabling them to achieve climate neutrality objectives while not putting them at a competitive disadvantage within the EU. Externally, the mandatory nature of the policy option allows for negotiating with third countries over risks of carbon leakage. This is an advantage compared to national level, as Matthews (2023) writes, "(w)ithout identifying a standard that is mandatory for EU producers to apply, there are no grounds to introduce import standards" (p.8). If standards are set at the EU level, then it becomes easier for standards to be upheld in international trade negotiations and the EU can pursue reciprocity in standards where required in order to pursue a level playing field for EU producers and operators (ibid).

Lastly, the mandatory nature of the policy means that mitigation can be further incentivised through correctional measures, for example, through the implementation of penalties for non-compliance. For example, under the EU CO_2 emission performance standard for cars and vans, if the average CO_2 emissions of a manufacturer's fleet exceed its specific emission target in a given year, the manufacturer must pay – for each of its new vehicles registered in that year – an excess emissions premium of €95 per g/km of target exceedance. As long as penalties exceed the cost of CRCF units which can be traded, there is a financial impetus for companies to meet their obligations under the standard.

Discussion Questions

- Under what conditions would this policy be effective in delivering the emission reductions and carbon removals needed for the agricultural sector to contribute to the EU-wide climate ambition?
- What would be the most efficient way to reconcile reporting and accounting methodologies to minimise the administrative burden of compliance and generate the right incentives for farmers?
- Could this option be combined with public procurement?

4.3 Potential effectiveness of Emission Trading Systems

The main difference between a mandatory climate standard and an emission trading system (ETS) is that, in an ETS, an EU-wide cap is established which places a limit on the amount of allowable emissions for all the obligated companies altogether (instead of establishing a mandatory reduction trajectory for each individual company). Units of emissions allowed ("allowances") are issued by an authority, and obligated parties must obtain and surrender a permit for every unit of GHG they emit. Allowances can be acquired through auctions, or purchased from other participants, or allocated for free. The cap on allowable emissions goes down over time, thereby decreasing the supply of allowances. This, in turn, impacts the prices of allowances, as the price of allowances reflects their scarcity, providing obligated parties a price-based cue of the value of reducing emissions.

Effectiveness of Emission Trading Systems – a literature review

The climate effectiveness of carbon pricing mechanisms such as carbon taxes and emission trading systems, is well studied in high income countries. As of 2022, 70 carbon pricing initiatives have been implemented globally, covering 47 national jurisdictions and representing almost a quarter of global GHG emissions (World Bank Carbon Pricing Dashboard, 2023). While results across a plethora of studies indicate mixed impacts, the overall results are largely positive. Most studies conclude that carbon pricing has a discernible effect on reducing GHG emissions across the energy, industry, transport, and buildings sectors (see Hoppe et al., 2023; Anderson 2019; Bayer & Aklin 2020; Anderson & Di Maria 2011; Saikawa 2018; Colmer et al., 2023; Schaeffer 2019; Best et al., 2020 Leroutier 2022; Abrell et al., 2022; Fageda & Teixido 2022).

Best et al. (2020) estimate a 2% reduction in the annual growth of emissions from fossil fuel combustion in countries with carbon pricing, compared with countries without carbon pricing. Hoppe et al. (2023) find that global carbon pricing schemes have led to average annual avoided emissions between 130-200 MtCO_2e/year. Dobbeling-Hildebrant (2024) assess the effectiveness of carbon pricing in reducing emissions using machine-learning assisted systematic review and meta-analysis. Based on 483 effect sizes extracted from 8- ex-post evaluations across 21 carbon pricing schemes, the initial years of a carbon price led to immediate reductions in 17 of the policies, with emission reductions ranging between -5% to -21%. Such large heterogeneity in effectiveness suggests differences in estimates are driven by the policy design and context that carbon pricing is implemented, while other variables such as differences in carbon prices, and sectoral coverage do not capture the heterogeneity identified in the study (ibid). Stechemesser et al. (2024) emphasise that while most types of policy instruments need complementing measures, carbon pricing is a notable exception in effectively causing large emission reductions alone: in effect size, it is the only policy instrument that achieves near equal or larger effect size as a standalone policy across all sectors, with 20% of all successful interventions being associated with pricing individually and 50% of all successful policy mixes include carbon pricing.

Hoppe et al. (2023) estimate the likely range of avoided emissions from the EU ETS to be between 3-9% of the emissions governed by its rules over the historic periods studied (usually between 2012-2016) compared to a reference scenario (Bayer & Aklin, 2020). Evidence on the EU ETS indicates that the effectiveness of carbon pricing is highly dependent on design aspects affecting price. The IPCC (2022) estimates that only a small number of carbon prices are aligned with estimates required to achieve limiting global warming to 1.5°C. Emission reductions varied for the EU ETS in response to design configurations, such as changes to the share of emission certificates auctioned, or the implementation of the market stability reserve (Colmer et al., 2023). Thus, the effectiveness of the EU ETS is dependent on the demand for certificates in the trading system, and the availability of surplus certificates (Hoppe et al., 2023).

The IPCC (2022) reviewed the effectiveness of emission trading systems. The report determines that all of the ETSs for which data are available have accumulated surplus allowances which reduces their effectiveness (Haites, 2018). These surplus allowances suggest that previously set caps were not sufficiently strict in relation to emissions trends. Many of these ETSs have taken steps to address the surplus by cancelling allowances and accelerating cap reductions. The EU introduced the Market Stability Reserve mechanism to withdraw excess allowances from the market during times of oversupply, while also allowing additional allowances to be released when supply is tight (Hepburn et al., 2016; Bruninx et al., 2020). Early results indicate that this mechanism has been somewhat effective in stabilizing prices during short-term market disruptions, such as the COVID pandemic (Gerlagh et al., 2020; Bocklet et al., 2019).

However, even with low prices Bayer & Aklin (2020) argue that the EU's ETS was successful in reducing emissions: the fact that obligated parties saw carbon markets as a credible policy option for reducing emissions over a long-term period, this perception of stability is enough to incentivise emission reductions, as mitigation actions can hinge on policy commitments to GHG reductions.

The previous exploratory study has a dedicated section providing an overview of scientific literature assessing the potential GHG impacts of carbon pricing in agriculture at different price levels (see Trinomics, 2023, Section 4.3, pages 136-146). Since the publication of the exploratory study, additional scientific studies assessing the potential GHG implications of carbon pricing for agriculture in the EU have been published, notably Stepanyan et al. (2023). Under scenarios in which carbon pricing is adopted only in Germany, EU agricultural emissions only decrease between -1% and -3%, but increase in the rest of the EU. For comparison, the study evaluates the integration of the agricultural sector into a carbon pricing scheme across the EU and estimate emissions to decrease between -9.9% and -23.2% with a carbon price of 100 €/tCO_2eq. The study does not incorporate the emissions and removals from the LULUCF sector in the analysis.

Impacts of MRV and other design features on the effectiveness of the policy option

As in the case of mandatory climate standards, the design of the underlying MRV system and the restrictions with regards to the trading of emission or removal units have the potential to significantly influence policy effectiveness of an agri-food emission trading system.

The original study (Trinomics, 2023) explored two possible complementary approaches to MRV, each with a view to mitigating the administrative burden placed on farmers. The first approach is the default method, which applies as a starting point to all regulated entities and relies on a minimum number of data points that are already universally collected and held by public authorities. While this approach alone may still be effective in facilitating changes in production levels and shifts in production mix leading to climate mitigation outcomes, it does not incentivise changes in practices or the adoption of new technologies, leaving some mitigation potential untapped. Under the second approach, farms would have the option to opt out of the default calculation by volunteering for a more detailed, farm-level calculation of net emissions supported by verification by a third-party assessor using certification methodologies approved by the Commission under the CRCF. Certified emissions calculations would reflect climate-friendly management techniques that the default calculation might overlook and would detail how the farm’s emissions differed from those implied by the default calculation. The effectiveness of a system based on voluntary certified MRV would depend, among other factors, on the price of ETS allowances, which serves as a threshold for the cost of mitigation and certification per unit of emissions, beyond which adopting and certifying emission reduction activities may no longer be economically attractive for farmers. Alternative approaches could involve a more universal, harmonized rollout of GHG calculations at the farm level, combining both voluntary and mandatory elements. This blended approach would balance effectiveness with other objectives, enabling the incentivization of mitigation actions. In a transitional phase, this process could, for example, require fewer data points than a full certification process. See also the relevant discussion under section 4.2.

Another crucial factor enhancing the effectiveness of an ETS relative to the other two types of policy options discussed in this paper is its ability to generate revenue. The revenue volumes depend, among others, on the degree of integration of public procurement as an integral part of the system (as described above), the degree of free allocation and allowance price levels. Revenue from the auctioning of allowances can be allocated toward various objectives, as determined by policymakers. One objective might be to support improved climate or mitigation outcomes by reinvesting in farms – particularly small and medium-sized operators – to facilitate technology transfer and reduce the financial risks of transitioning to climate-friendly practices. Alternatively, revenues could be directed toward social objectives, such as assisting vulnerable households with potential price increases, or allocated to a fund dedicated to research and innovation in the agricultural sector.

Discussion on effectiveness

As mentioned above, one of the main advantages of an ETS is, similar to the Mandatory Climate Standard, it provides predictability and stability – as the cap tightens over time, firms are incentivised to invest and plan for long-term objectives to reduce their emissions. According to several experts interviewed for the previous exploratory study (Trinomics, 2023), the price incentive allows for obligated parties to select the most cost-effective ways of reducing the largest amount of GHGs – in comparison, the CRCF procurement option is missing the predictability aspect of the Mandatory Climate Standard and the ETS, while the Mandatory Climate Standard does not necessarily have the formal pricing means through allowances and the pricing management options, such as a Market Stability Reserve, that an ETS offers.

One of the main disadvantages of an ETS is that it places considerable weight on“low-hanging fruit.” According to Hoppe et al. (2023), most of the emissions reductions attributed to carbon pricing schemes appear to be the result of low-cost operational measures that are relatively easy to implement and thus produce immediate emission reductions. The IPCC (2022) argues that the limitations of pricing policies are that they have limited impact on adoption of mitigation measures when decisions are not sensitive to prices and do not encourage adoption of higher cost mitigation measures. This could limit financial incentives to undertake more costly and long-term mitigation actions, such as peatland re-wetting. Indeed, the original exploratory study (Trinomics, 2023) emphasized the challenges for incentivising farmers to rewet their land or practice more sustainable land practices on peatlands, such as paludiculture. Thus, according to the IPCC (2022), carbon pricing is effective in facilitating incremental change towards reducing emissions by promoting the optimization of existing business models and facilitating the use of efficient technologies. However, for transitionary actions requiring more large-scale change which need high levels of financial investments, additional complementary measures may also be necessary (ibid).

For both the ETS and Mandatory Climate Standard, risks of production increasing outside the EU must be taken into consideration. Given the EU's integration into global agri-food and commodity markets, an increase in the stringency of agriculture-relevant climate policy may result in carbon leakage, undermining the effectiveness of the policy measures taken. As discussed in Section 3.4, consumer behaviour emerges as a critical variable that could mitigate the risk of carbon leakage. The various economic and market factors influencing carbon leakage, including exposure to international competition, will be explored in the third input paper produced as part of this study under the theme ‘Competitiveness.’

Discussion Questions

- Under what conditions would this policy be effective in delivering the emission reductions and carbon removals needed for the agricultural sector to contribute to the EU-wide climate ambition?
- What (dis)advantages are there for an ETS when compared to the Mandatory Climate Standard?
- Could this option be combined with public procurement?
- How can a potential bias towards “low-hanging fruit” be avoided?

5 Approach to assessing GHG impacts and other environmental impacts

5.1 Assessing potential “effectiveness”

The assessment of environmental impacts will focus mainly on emission reductions and carbon removals potentials in the EU. However, other indicators will be examined, including impacts on land use in the EU, biodiversity, air quality, soil erosion, water quality, as well as potential impacts in key concerned third countries, including emission reductions and removals in key third countries as well as potential land use impacts, biodiversity impacts, air quality impacts, and water quality impacts in key third countries.

For the environmental impacts we will make use of the MITERRA-Europe model, an environmental assessment model for agriculture in the EU. The model can be directly linked to the CAPRI model (which is used by the Commission), but the model also links to the AGMEMOD model, which is proposed to be used for the economic analysis in this project. MITERRA-Europe is a deterministic model designed to calculate emissions of greenhouse gases (CO_2, CH_4, and N_2O), nitrogen emissions (N_2O, NH_3, NOx, and NO_3), nutrient flows, and changes in soil organic carbon stocks on an annual basis, utilizing emission factors and leaching fractions. Developed to evaluate the impacts of agricultural policies and measures on nitrogen losses at the NUTS-2 level within the EU-28, this model draws from earlier frameworks like CAPRI (Common Agricultural Policy Regionalised Impact) and GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies). It has been enhanced with modules for nitrogen leaching, soil carbon, and greenhouse gas mitigation strategies.

The input data includes activity metrics such as livestock numbers and crop areas and yields sourced from CAPRI, Eurostat, and FAOSTAT, along with spatial environmental data like soil and climate information. Emission factors for GHGs (IPCC and NIR) and for NH_3, as well as excretion factors and manure management system data (GAINS), are also integrated. Soil carbon calculations follow the established rules of the RothC model. The model is capable of simulating carbon sequestration, GHG and NH_3 emission reductions, and NO_3 leaching. Additionally, it employs a life cycle assessment (LCA) approach to evaluate all GHG and nitrogen emissions up to the farm-gate. The effectiveness of mitigation strategies and long-term scenarios can also be analysed, using activity data from other economic models like CAPRI or AGMEMOD.

AGMEMOD stands for "AGricultural MEmber states MODelling." Since its inception in 2001, it has been developed by the AGMEMOD Partnership, which includes a consortium of national university institutes and research agencies from EU countries and prospective accession countries (Chantreuil et al., 2011). This dynamic, partial equilibrium system operates across multiple countries and markets within a GAMS environment (Van Leeuwen et al., 2008). AGMEMOD offers detailed insights into the primary agricultural sectors of each EU Member State, with most equations estimated econometrically at the individual country level. In instances where estimation was not practical or meaningful, parameters have been calibrated instead. The country models capture the behavioural responses of economic agents to fluctuations in prices, policy instruments, and other external variables affecting the agricultural market. For each commodity in each country, key factors such as agricultural production, supply, demand, trade, stocks, and domestic prices are derived from econometrically estimated equations. Input costs are considered in relation to supply, and relevant environmental restrictions are also incorporated where applicable.

AGMEMOD's projections combine econometric results with insights provided by market experts, ensuring that the modelling outcomes are validated through standard econometric methods and consultations with specialists knowledgeable about the agricultural market in the relevant EU Member States.

AGMEMOD will be utilised in conjunction with MITERRA-Europe. This modelling system has previously been tested and developed in the context of the H2020 project 'SUPREMA'.[13] More specifically, AGMEMOD is able to assess the impact on land use and the level of agricultural activities, i.e. changes in crop and livestock production, in response to various factors including shocks on yields, changes in the CAP/environmental body of legislation, etc. Subsequently, MITERRA-Europe translates these changes in agricultural production and land use into environmental indicators. In doing so, MITERRA relies on a detailed and spatially disaggregated representation of agricultural land use, farming practices, and the related emissions.

[13] See, also: https://www.suprema-project.eu/images/Deliverable_D32.pdf.

5.2 Limitations of models and needed inputs from stakeholders

Environmental impacts can be determined through activity data, such as animal numbers and crop areas, and emission factors which can be affected by different mitigation actions. Changes in activity data can be derived from sector-economic modelling, when possible. However, there are issues of information gaps that will require stakeholder inputs in order to elicit insights based on the stakeholders' expertise into potential changes that may occur on-farm. There are relevant information gaps for estimating relevant environmental impacts by the environmental model (Miterra), expected production effects and land use effects per farm; and how many farms will adopt the policy option by farm type.

In principle, the agri-food sector model (AGMEMOD) can project production and land use changes that result from a specific ETS policy option on farm business and provide such as prior information to the environmental model (Miterra). However, as AGMEMOD is driven through assumptions on e.g. macroeconomy, technologies and CAP policy, and potential ETS instruments are not captured, it required expert knowledge (from stakeholders) about where and how to implement certain aspects of the policy options in the tool. It also requires some insight on how these instruments may influence ("shock") specific farm business. This usually goes via return and cost structure of farm types, which means that an agri-food model needs external input about the size of the"shock", e.g. the carbon tax price in dairy farming compared to current production costs (without a carbon tax), or how much transaction costs of the adopted ETS will increase current production costs (thus without costs for ETS).

Annex I: Mitigation actions at the farm-level

Livestock emissions

As outlined in previous chapters, direct livestock emissions of methane (CH_4) and nitrous oxide (N_2O) from enteric fermentation and manure management account for approximately 65% of all emissions from the agricultural sector. Due to methane's short atmospheric lifespan, mitigating these emissions is considered a highly effective strategy for curbing global warming in the short term and limiting temperature increases to 1.5°C (Beauchemin et al., 2020; European Commission, 2021; Global Methane Initiative, 2021). Consequently, reducing livestock emissions is crucial for mitigating agriculture's contribution to climate change.

Methane emissions from enteric fermentation can be mitigated through various strategies, broadly categorized by the FAO (2023) as: i.) animal breeding and management (e.g. improved feed efficiency, animal health and reproduction); ii.) feed management, diet formulation and precision feeding; iii.) forages (e.g. increased forage digestibility, perennial legumes); and iv.) rumen manipulation (e.g. chemical inhibitors, seaweeds). Most interventions within these categories, as reviewed by the FAO, offer a modest expected CH_4 decrease range of 15% or less. The only interventions deemed to have an expected CH_4 reduction of 25% or more are rumen manipulation measures (3-nitrooxypropanol (3-NOP), chemical inhibitors of methane production, bromoform containing seaweeds) applied in the context of confined ruminant systems.

Strategies can either decrease absolute emissions (grams of CH_4 per animal per day), emissions yield (grams of CH_4 per kilogram of dry matter intake), or emissions intensity (grams of CH_4 per kilogram of meat or milk produced). Strategies that enhance animal performance and production efficiency tend to reduce CH_4 intensity. This not only improves GHG efficiency but can also increase farmers' profitability (Gerber et al., 2013). However, solely increasing animal productivity is unlikely to sufficiently reduce total GHG emissions from ruminant production globally (Ungerfeld et al., 2022).

Moreover, efforts to reduce CH_4 emissions can sometimes lead to increased emissions of other greenhouse gases (Cardoso et al., 2016) or raise animal welfare concerns (Llonch et al., 2017). For instance, while high-fat diets for dairy cattle can decrease enteric CH_4 emissions, they may also increase the CH_4 production potential of manure during storage (Petersen et al., 2013)."

Strategies for mitigating emissions from manure include: the employment of anaerobic digestion systems to maximize CH_4 production for collection and use as fuel (Clemens et al., 2006; Montes et al., 2013), frequent manure removal from animal housing or storage (Andersen et al., 2015), manure cooling (Ni et al., 2008), manure acidification (Petersen, Andersen and Eriksen, 2012), the addition of amendments that inhibit CH_4 production (Andersen et al., 2018), the separation of solids, the use of biofilters and scrubbers, manure management systems that promote aerobic conditions (Montes et al., 2013), as well as land application and land management strategies (after FAO, 2023). Anaerobic digestion coupled with biogas collection and utilization represents a highly effective strategy for mitigating methane emissions from manure, provided that fugitive emissions are minimised (ibid.).

N_2O emissions from agricultural soils

Agricultural soils, primarily due to synthetic and organic nitrogen fertilizer use, are the second-largest source of agricultural emissions, primarily of nitrous oxide (N_2O). Optimizing nitrogen (N) management to balance yield targets with minimizing environmental losses remains a significant challenge (Han et al., 2017). Soil N_2O emissions arise from microbial nitrification and denitrification processes, influenced by various soil properties such as moisture content, texture, pH, organic matter source, and the carbon-to-nitrogen ratio of amendments. This complex interplay leads to considerable variability in N_2O emissions and the mechanisms governing them.

In literature, approaches to nitrogen management tend to be broadly grouped under two main categories. The first one is referred to as ‘‘the 4Rs’’ concept; targeting management strategies that optimize application rate, chemical composition, timing and placement of fertilizers. Beyond the focus on crop uptake, other processes governing N cycling and agroecosystem-scale N saturation are not addressed by these practices (idem.). The second N management approach, known as 'ecologically based nutrient management' (ENM) (Drinkwater and Snapp, 2007), aims to reduce N saturation by optimizing N inputs and increasing reliance on internal soil N cycling. Strategies compatible with ENM include crop diversification, reduced bare fallow periods (with cover crops or perennials), and greater utilization of legume N sources. Several practices which do not fall under these two main approaches, such as substituting inorganic fertilizers with manure, can also affect N_2O emissions and other nitrogen losses, dependent on the timing and rate

A meta-analysis of comparisons of practices conducted by Han et al. (2017) concluded that N fertilizer rates had the most significant impact on N_2O emissions. Across various management practices, the quantity of applied N, rather than its source (fertilizer, legume biomass, or animal manure), was the primary driver of N_2O fluxes. Another conclusion of the study was that substantial N_2O mitigation was possible with minimal to no yield losses by implementing well-designed N management strategies. The study emphasized that yield losses are not equivalent to economic losses, and by aligning crop N demands with economic returns, farmers can avoid significant N_2O emissions and achieve environmental benefits without compromising yields (McSwiney and Robertson, 2005; Robertson and Vitousek, 2009; Hoben et al., 2011; Linquist et al., 2012).

Peatland rewetting

Peatland re-wetting represents a significant lever for rapidly reducing emissions from organic soils through rewetting of peatlands and wetlands, or by preventing high emissions per hectare over a short timescale. Raising water levels in these areas reduces emissions from organic soil materials, offering two key approaches to mitigation: taking land out of production entirely or adopting paludiculture, which allows for the productive use of wet and rewetted peatlands while preserving the peat soil. In the long term, peatland and wetland restoration also contributes to carbon removal (IPCC, 2022).

Given the growing global competition for land and the importance of maintaining rural livelihoods and biodiversity hotspots, simply halting land use is often not viable. Therefore, a fundamental shift to "wet" land use is necessary. Tanneberger et al. (2020) emphasise the need to explore a variety of wetland land-use options for European peatlands. Land-use options for rewetted peatlands in Europe can be broadly categorized into:

- High-intensity paludiculture: This involves cultivating selected wetland crops under intensive management to produce high quantities or high-quality biomass (e.g., cattail, sphagnum moss, or sundew).
- Low-intensity paludiculture: Involves the regular harvesting of spontaneously established vegetation, such as sedges or grasses, for biomass use (e.g., permanent grassland paludiculture under mowing or grazing).
- Wet wilderness: This option focuses on ecosystem services and biodiversity conservation, with no biomass harvesting or other on-site management ("rewilding").

Although value chains for paludiculture biomass are still underdeveloped, the demand for such biomass is growing as various sectors seek sustainable materials to meet climate targets (Agora, 2024). Emerging markets offer great potential for using paludiculture biomass in industries such as packaging, construction (as insulation material), and horticulture (as a peat substitute). Solar photovoltaic installations on rewetted peatlands also present an attractive option for income generation.

Management of soil organic carbon in croplands and grasslands

Agricultural practices that enhance carbon sequestration in both soil and above-ground biomass are accessible to nearly all farmers, whether in arable, livestock, mixed, or extensive systems. These practices include sustainable soil management techniques such as using cover crops, reducing tillage, retaining crop residues, and improving water management on both cropland and grassland (IPCC, 2022; Kay et al., 2019; Sykes et al., 2020). Agroforestry, which integrates woody vegetation into land used for grazing or crop production, is another effective strategy. While converting cropland back into grassland can also sequester carbon, these benefits unfold over a longer time horizon.

While SOC sequestration has potential for climate mitigation, its overall impact is modest and highly context specific. One key limitation is the concept of sink saturation, where the soil's ability to store carbon reaches a maximum over time (Six et al., 2002; Smith, 2012). This saturation occurs due to finite mineral surface availability and environmental constraints on carbon stabilization and decomposition, which define a new equilibrium for SOC storage capacity (Stewart et al., 2007).

The concept of sink saturation highlights that soil organic carbon (SOC) sequestration has a finite capacity, and the rate of sequestration slows as the soil approaches its maximum or effective storage limit (Poulton et al., 2018; Stewart et al., 2007). This means that SOC sequestration is not only time-limited but that the rate of carbon capture declines sharply as SOC levels rise (Baveye et al., 2018). Despite this, many studies, with a few exceptions (e.g., Sommer & Bossio, 2014), often assume a constant sequestration rate over the period needed to reach a new equilibrium (Bossio et al., 2020; Fuss et al., 2018). Some assessments focus on annual sequestration rates at specific points in time and compare them to other emission reduction strategies. For instance, the IPCC Working Group 3 (2022) ranks SOC sequestration as the fourth most effective mitigation option by 2030, following solar and wind energy.

Table 3: Mitigation actions across the agri-food value chain

Value chain actor	Potential mitigation actions
Cattle/Dairy/Pig Farm	Anaerobic digestion at farm scale, low nitrogen feed, feed additives, improved feed efficiency, genetic selection, shifting species towards non-ruminant animals, forages, rumen manipulation measures, frequent manure removal from housing/storage, manure cooling, manure acidification, manure management systems, manure application strategies, low emission housing, manure storage with basin in concrete
Arable Farm	Better timing of fertilization, nitrification inhibitors, precision farming, variable rate technology, increasing legume share on temporary grassland, rice measures, fallowing histosols (organic soils/peatland re-wetting), paludiculture, cover crops, reduced tillage, retaining crop residues, substitution of mineral fertilisers with organic fertilisers
Arable/mixed/ extensive livestock farm	Agro-forestry
Feed manufacturers	Engagement with suppliers (i.e. sourcing of certified feedstuffs), creation of supplier incentive programmes, facilitate provision of finance to support suppliers, enhance circularity in feed production, preferential pricing strategies for low emissive feeds/feed additives
Synthetic fertiliser manufacturers	Changing fertiliser formulation, innovation and preferential pricing strategies around enhanced efficiency fertilisers
Food processors	Engagement with suppliers, creation of supplier incentive programmes, facilitate provision of necessary finance to support suppliers, product portfolio diversification (i.e. improved offer of PBAs), product reformulation, innovation in plant-based meat and dairy alternatives, marketing strategies to steer consumer behaviour, waste reduction
Retailers	Tailoring internal procurement guidelines or supplier codes of conduct to include mandatory criteria for climate disclosure or performance, product portfolio diversification, shopping experiences to facilitate consumer choice, information and communication measures for consumers (i.e. product labelling), pricing strategies, waste reduction
Other	