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Fertilising Climate Policy: The Dual Impact of CBAM on EU Agricultural Emissions and Regional Disparities

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ABSTRACT

The Carbon Border Adjustment Mechanism (CBAM), scheduled to become fully operational in 2026, is designed to complement the EU Emissions Trading System (ETS) by replacing free emission allowances and preventing carbon leakage to non-EU regions. CBAM initially covers energy-intensive sectors, including mineral nitrogen (N) fertiliser production. Although mineral N fertiliser production is already included in the EU ETS, it is currently exempt from carbon charges owing to full compensation through free allowances. The phase-out of these allowances and the introduction of CBAM are expected to increase the prices of both imported and domestically produced fertilisers, indirectly affecting the EU agricultural sector. This study quantitatively assesses the impacts of the expected fertiliser price changes on the EU agricultural sector and related environmental outcomes using the Modular Applied GeNeral Equilibrium Tool (MAGNET) and the Common Agricultural Policy Regionalised Impact (CAPRI) model. The results indicate that the combined effect of phasing out free allowances and implementing CBAM will double mineral N fertiliser prices. Higher prices are projected to reduce demand, leading to a 21.4% decline in domestic production and a 37% reduction in imports. Overall mineral N fertiliser use in the EU is expected to decrease by 22%, partially replaced by manure. Consequently, EU agricultural factor income is projected to fall by 7.7%, primarily affecting high-input regions. Meanwhile, non-EU agricultural income is projected to rise slightly by 0.05%, driven by higher exports. EU agricultural greenhouse gas emissions are expected to decrease by 22 megatons of CO_2-equivalent, with no significant increase globally.

1 | Introduction

Currently, the agricultural and land use, land use change, and forestry (LULUCF) sectors are the only sectors not included in the EU Emissions Trading System (ETS) (European Parliament 2023a). However, mineral fertiliser production is part of the ETS and is subject to current developments and the EU's increasingly stringent climate policies. In 2005, the EU established the world's first ETS for the industrial and energy sectors. Since then, the ETS has undergone substantial development and is now in its fourth phase. It covers emissions from electricity and heat generation, industrial manufacturing, intra-European aviation and maritime transport, accounting for approximately 40% of total EU greenhouse gas (GHG) emissions. In the current phase, roughly 66% of emissions covered by the ETS receive free allowances to prevent carbon leakage through emissions embedded in imports. The share of free allowances varies widely across sectors, from 8% for sulphite pulp production to 171% for adipic acid (European Commission 2021). While the EU has significantly reduced

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domestic GHG emissions, emissions embedded in imported goods have increased, partially offsetting efforts to reduce the global emission footprint (European Parliament 2023b). Unilateral climate policies may therefore shift production abroad, potentially increasing global emissions if production moves to regions with more carbon-intensive practices (Böhringer et al. 2022; Fournier Gabela et al. 2024).

These unilateral policies could also create economic disadvantages for adopting countries, negatively affecting the competitiveness of local producers (Zhong and Pei 2024). To address these concerns, the EU introduced the Carbon Border Adjustment Mechanism (CBAM), covering imports of cement, iron and steel, aluminium, mineral fertilisers, electricity, and hydrogen. CBAM is implemented in phases, aligned with the gradual phase-out of free allowances, and entered its full operational phase on 1 January 2026. Revenue from CBAM is collected by national authorities and allocated to the EU budget as part of the EU's own resources. Lin and Zhao (2023) identified four priority sectors in which CBAM would have a low economic impact but high potential for emission reduction: plastics, mineral fertilisers, aluminium, and copper. Notably, aluminium and mineral fertilisers are already included in the current CBAM.

Although agriculture and LULUCF are not currently subject to carbon pricing, their integration into the ETS and CBAM is increasingly debated and studied (Spiegel et al. 2024; Stepanyan et al. 2023). The agricultural sector is indirectly affected by CBAM through its use of synthetic fertilisers, which are integrated into the EU ETS. Specifically, carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions from mineral fertiliser production are covered by the ETS, whereas other agricultural emissions, such as N_2O from fertiliser application, remain excluded.

CBAM is implemented as a carbon levy on imports, potentially combined with export rebates and other adjustments. Zhao et al. (2020) proposed three indicators to assess CBAM's effectiveness: its ability to promote fair competition, mitigate carbon leakage, and enhance global welfare. They further classified CBAM's potential effects as direct or indirect. Direct effects arise from market impacts owing to changes in the relative prices of domestic and imported goods. CBAM aims to restore, rather than enhance, domestic competitiveness lost through unilateral carbon policies, primarily by increasing the relative cost of imports.[1] This is expected to reduce carbon leakage by reestablishing competitive parity. However, exporting countries may redirect trade to less-regulated markets and expand production of carbon-intensive goods, potentially increasing global emissions overall (Fang et al. 2020; Jakob et al. 2013). Indirect effects relate to CBAM's capacity to incentivise third countries to adopt stricter climate policies, for example, by joining a climate club or implementing more efficient, low-emission technologies, thereby contributing to global emission reductions. Most of the EU's major trading partners have signalled their willingness to align their emission trading policies more closely with those of the EU (Shum 2024).

Unlike the EU ETS, which operates under a cap-and-trade system with a defined emissions target, CBAM does not set specific emissions limits, allowing trade to proceed without direct quantitative restrictions. CBAM is likely to indirectly affect agriculture, as it covers fertiliser imports and can influence their prices.

According to FAOSTAT (2024), the EU remained the world's fifth-largest producer of mineral nitrogen (N) fertilisers in 2022, following China, India, the United States, and Russia. As shown in Figure 1a, China, India, and Russia substantially increased mineral N fertiliser production between 1992 and 2022, whereas production in the EU and the United States declined.

Historically, the EU was a significant net exporter of mineral N fertilisers until 1998. Since the early 2000s, EU imports have increased substantially, and by 2022, the region had become a net importer (see Figure 1b). As CBAM will impose carbon pricing on imported mineral fertilisers based on their embedded emissions, and free allowances under the EU ETS are gradually being phased out—which currently cover all emissions from nitric acid production and 80% of ammonia production emissions, reflecting the share of total ammonia output used in mineral fertiliser production (European Commission 2023)—fertiliser prices in the EU are likely to rise. Higher prices may reduce demand, leading to lower mineral fertiliser imports.

Against this background, this study assesses the impact of CBAM in combination with the EU ETS, focusing on the phase-out of free allowances and its effects on the agricultural sector

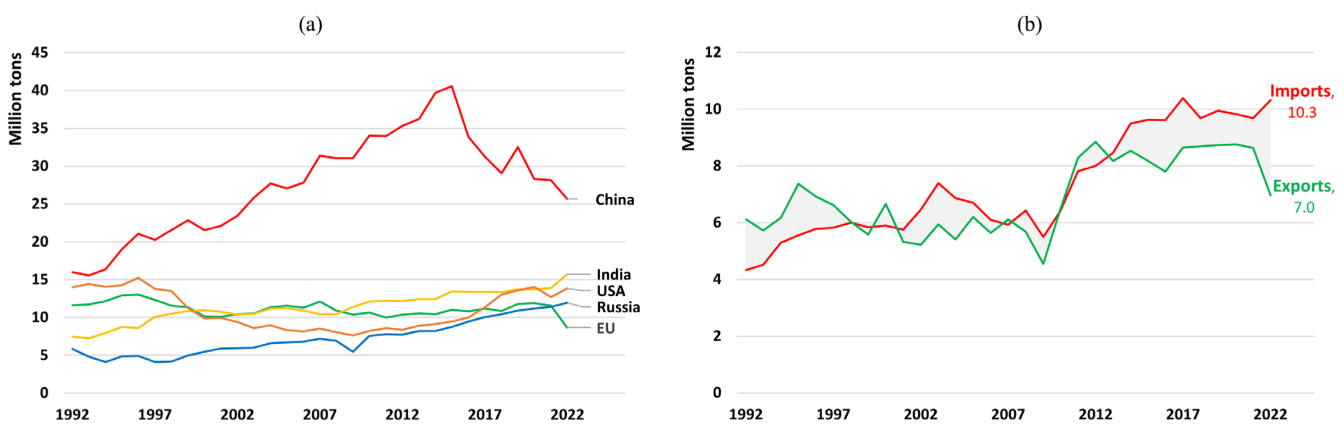

FIGURE 1 | (a) Trends in mineral N fertiliser production among the five leading producers. (b) EU mineral N fertiliser trade trends, 1992–2022. *Source:* FAOSTAT (2024). [Colour figure can be viewed at wileyonlinelibrary.com]

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through mineral N fertiliser[2] markets. We examine the potential increase in mineral fertiliser prices, the regional impacts on farm income, and EU and global GHG emissions. Under CBAM, the fertiliser sector includes N-based fertilisers, while mixed fertilisers containing phosphorus and potassium are assumed to have zero emissions from production (European Commission 2023). To our knowledge, no study has yet examined the effects of CBAM on mineral fertiliser production and prices. Nor has prior research assessed how these effects may influence the use of mineral N fertiliser in agriculture, substitution with organic alternatives, and the resulting impacts on agricultural output and environmental outcomes. This study provides the first comprehensive analysis of the broader consequences of CBAM implementation. We employ two well-established simulation models: the Modular Applied General Equilibrium Tool (MAGNET), a global computable general equilibrium (CGE) model, and the Common Agricultural Policy Regionalised Impact (CAPRI) model, a global partial equilibrium (PE) model with a detailed representation of the EU agricultural sector.

The remainder of this paper is organised as follows. Section 2 provides an overview of the two simulation models and explains the approach for linking them. Section 3 describes the scenarios simulated for each model. Section 4 presents the results of the study, and Sections 5 and 6 provide discussion and concluding remarks, respectively.

2 | Methods

Estimating the impact of CBAM on mineral fertiliser production requires a modelling framework capable of calculating how the EU ETS and CBAM affect prices and of accounting for mineral fertiliser use in agriculture. The framework should consider factors such as substitution with organic fertilisers and how these changes influence overall agricultural production decisions. No single model captures all these aspects; therefore, this study combines the CGE model MAGNET with the PE model CAPRI. In the literature, two common approaches for linking different models are discussed: soft and hard linkages (Delzeit et al. 2020). Hard linkage is a more complex method that aims to create responsive interactions between the structural and behavioural elements of the models (Pelikan et al. 2015; Philippidis et al. 2017). It requires greater expertise to implement, and the robustness of the linked models can be uncertain. Soft linkage is more flexible, in which models exchange factor prices and are harmonised through a baseline process (Haß et al. 2024). This information is calculated iteratively until both models converge on selected key variables.

2.1 | MAGNET

The MAGNET is a CGE model widely used to examine economic, environmental, and trade policy interactions. It builds on the core framework of the Global Trade Analysis Project (GTAP) while incorporating specialised features that address specific policy issues, including GHG emissions, resource management, and the economic impacts of trade and energy policies. GTAP data provide a detailed representation of domestic economies, bilateral trade, international transport costs, and trade protection measures across countries and regions. This study uses the most recent GTAP database (version 11), with 2017 as the reference year. This release includes 65 economic sectors across 141 countries and 19 regions, covering 99.1% of global GDP and 96.4% of the world's population, making it highly suitable for comprehensive economy-wide analysis (Aguiar et al. 2022).

In MAGNET, the GTAP database is further disaggregated into 155 sectors, which are streamlined to 78 sectors to align with research priorities. A key feature relevant to this analysis is the explicit representation of mineral fertiliser production as a distinct sector, allowing estimation of changes in mineral fertiliser prices. EU fertiliser purchaser prices in the model are determined through an Armington constant elasticity of substitution (CES) aggregation of domestic and imported supplies. Consequently, prices reflect a weighted average of CIF prices—including tariffs, transport margins, and CBAM rates—rather than being tied to a single import parity condition. The reference scenario projects data from 2017 to 2030.

In our analysis, MAGNET represents the economy through extensive systems of equations calibrated to the base year 2017. These equations enforce equilibrium conditions, including market clearing for goods and factors, zero profits under perfect competition, and household behaviour optimised within the income and price constraints of that period (Dixon and Rimmer 2025). By integrating environmental and economic aspects through additional accounting and behavioural equations, MAGNET enables detailed analysis of the EU ETS, bioeconomic developments, and climate policy measures. This functionality allows the model to consistently assess policy interactions at regional, national, and global levels. The EU ETS in MAGNET is based on the GTAP-E framework (Burniaux and Truong 2002; McDougall and Golub 2007), which remains foundational for GTAP applications (Peters 2016). The model includes accounting equations for GHG emissions, aggregating emissions by type, emitting sector, or agent (e.g., households or government) for each region. Swapping parameters ensure that emission gases, emitters, and regions are assigned to specific trading schemes, enabling the modeller to impose detailed emission reductions or simulate carbon tax changes. This flexibility allows the analysis to reflect the design of a specific ETS.

In MAGNET, the EU ETS covers electricity, petroleum and coal products; gas manufacturing and distribution; mineral fertilisers; energy-intensive industries (iron and steel, cement, pulp and paper, chemicals, aluminium); as well as aviation and transportation. The model integrates environmental tax equations with the standard tax framework, and endogenous slack equations using 'closure swaps' ensure that targeted emission reductions generate internal environmental tax rates. These tax rates are applied to the relevant gases, combustion activities, sectors/agents, and regions specified by the modeller. The ETS accounts for carbon constraints and permitted trading among industries and regions, calculating endogenous changes in emissions for each sector and area within the trading scheme. The analysis assumes perfect market conditions for permit trading and uniform emission factors across industries. While these assumptions may not capture all real-world complexities, the model provides a reasonable basis for assessing the ETS and its economic impacts.

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For this study, the EU ETS is excluded from the baseline to accurately reflect current conditions, as free allowances currently cover all emissions in the fertiliser sector.[3] As CBAM is implemented, these free allowances are gradually phased out, requiring producers to begin paying carbon prices for their emissions.

2.2 | CAPRI

We use the CAPRI model, a comparative static PE model, to analyse the agricultural sector. CAPRI was developed to assess policy and market impacts from global to regional levels. It integrates a detailed supply module, focused on Europe, with a global market module.

The supply module consists of independent nonlinear programming models representing 280 NUTS 2 regions across the EU-27, Norway, the Western Balkans, and Turkey, covering roughly 50 crop and livestock activities. These models use the Positive Mathematical Programming approach, providing flexibility to capture key interactions between production and environmental factors (Gocht et al. 2017). Each model maximises regional agricultural income under constraints such as land availability, nutrient balances, and policy requirements.

The market module is a spatial, deterministic, comparative static PE model representing approximately 60 primary and secondary agricultural products across 80 countries and country groups worldwide. International trade follows a two-stage Armington framework, differentiating goods by origin based on consumer preferences derived from historical trade data. In the first stage, total demand is determined by balancing domestic and average import prices. This framework enables modelling of bilateral trade flows and captures the effects of trade policies, including bilateral and multilateral agreements (Gocht and Witzke 2025). Market equilibrium in CAPRI is achieved through iterative exchanges between the supply and market modules, reconciling prices, supply levels, and feed demand until convergence. CAPRI endogenously accounts for CO_2 and non-CO_2 emissions and removals within the agricultural sector. Emissions are defined based on production processes, inputs, and outputs, allowing the model to capture detailed interactions among EU agricultural activities and their environmental impacts.

The model also includes a detailed nutrient flow component for each region and activity, explicitly representing feeding and fertilising practices to balance nutrient needs and availability while calculating yields for each agricultural activity. Nutrient surplus and balance are calculated at the NUTS2 level for each crop group and for three nutrients: nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O). Crop nutrient requirements are met through three sources: purchased mineral fertilisers, animal manure, and crop residues. Manure production is calculated per animal per year, depending on animal type, rearing period, and live weight at the beginning and end of the period. N emissions from livestock activities are linked to crude protein intake. For crops, per-hectare nutrient requirements are calculated based on yield, and alternative technologies are available for each crop, allowing producers to choose between higher-input, higher-yield and lower-input, lower-yield practices (Gocht and Witzke 2025).

This information is used to quantify GHG emissions according to IPCC (2006) guidelines. Most emission sources are modelled using the Tier 2 approach, while Tier 1 is applied when data are unavailable (Pérez Domínguez et al. 2020). In non-EU regions, emissions are calculated on a product basis (Jansson and Säll 2018), with total emissions determined by multiplying region-specific emission factors by production volumes for scenario analysis.

MAGNET and CAPRI are linked through mineral fertiliser prices, which are calculated in MAGNET based on simulated EU ETS and CBAM policies. These price changes are transferred to CAPRI, which accounts for fertiliser use in agriculture and potential substitution with organic alternatives. This global-to-local linkage enables assessment of the sectoral and regional impacts of CBAM on agriculture through changes in fertiliser markets.

3 | Scenario Definition

3.1 | Reference Scenario

CAPRI and MAGNET use a reference scenario based on trend-based assumptions for exogenous variables and agricultural policies up to 2030. In CAPRI, these assumptions are derived from the European Commission's Agricultural Outlook 2022–2032 (European Commission 2022), whereas in MAGNET, SSP2 assumptions are used as exogenous variables. The reference scenario projects how the agricultural sector and demand might evolve over time under current policies, including all changes already planned in existing legislation, but excluding the effects of the EU ETS and CBAM. It serves as a baseline for the scenario analysis. The scenario accounts for trends in country-level population growth, inflation, GDP growth, and technological progress, such as yield improvements and increasing efficiency in feed use (Rieger et al. 2023). Additional details on the main assumptions for the reference scenarios in CAPRI and MAGNET are provided in Table 1.

To ensure that the reference scenario accurately reflects current conditions in the fertiliser sector, this study excludes the EU ETS from the baseline analysis. At present, all emissions within the fertiliser sector are fully covered by free allowances, so fertiliser producers do not incur carbon pricing costs under the existing framework. With the introduction of CBAM, these free allowances are gradually phased out. Only after this transition will fertiliser producers face costs associated with carbon pricing. This approach allows the effects of CBAM implementation to be captured more precisely, as it shifts the sector from a regime of free allowances to one in which carbon pricing becomes a direct financial consideration for producers.

3.2 | EU ETS and CBAM Scenario

Our impact scenario uses the MAGNET model to simulate the effects of the EU ETS and CBAM in 2030, assuming that climate targets for that year are achieved—that is, a 55% reduction in net GHG emissions relative to 1990 levels. The resulting changes in

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TABLE 1 | Comparison of model assumptions in CAPRI and MAGNET.

Model	CAPRI	MAGNET
Model type	Partial Equilibrium (PE)	Computable General Equilibrium Model (CGE)
Regional coverage	All NUTS2 regions in Europe, 80 world regions aggregated to about 40 trade regions	141 regions and 19 regions, including all 27 EU member states
Coverage of activities and products	Supply Model: About 50 crop and animal activities and inputs for each NUTS2 region Market Model: About 65 primary and processed agricultural products	155 sectors (of which 29 are agricultural sectors)
Database	EUROSTAT, FADN and other statistics	GTAP 11 and other databases
Base year	2017	2017
Projection year	2030	2030
Policy	Brexit, CAP after 2023; Voluntary Coupled Support; Eco-Schemes; Free trade agreements	Biofuels, CAP direct payments; Free trade agreements
Supply Side	Supply Model: Non-linear Positive Mathematical Programming models for all European NUTS2 regions Market Model: Behavioural functions with flexible functional forms for non-EU regions	Constant elasticity of substitution functions with flexible nesting structure, which links industries in value added chains from primary goods, over intermediate processing stages, to the final assembly of goods and services for consumption
Demand Side	Generalised Leontief expenditure function with price- and income-independent minimum consumption levels	Constant difference of elasticities expenditure function allowing budget shares of different goods and services to adjust with income changes
Trade	Bilateral trade flows are modelled using the Armington assumptions	Bilateral trade flows are modelled using the Armington assumptions
Fertilisers	Nutrient balances are calculated for each crop group and nutrient (N, P_2O_5, K_2O), with NPK needs met through mineral fertilisers, animal manure, and crop residues	Fertiliser is treated as an intermediate input in production. N, P_2O_5, K_2O are explicitly considered (Bartelings et al. 2016)
Endogenous variables	Demand and supply quantities including biofuels, prices, yields, feed input coefficients, mix of organic and inorganic fertiliser per crop	Prices and quantities of national and international product and factor markets; income and welfare effects, gross domestic product
Limitations	Only captures the agricultural sector. Only food related household expenditures are captured	Groups agri-food products into broad categories
Main benefits for this study	Highly detailed and regionally differentiated representation of demand and supply of agricultural products in the EU and a link to international markets. Detailed depiction of environmental indicators such as nutrient balances and GHG emissions	Captures all economic sectors of the economy. Some agri-food supply chains are included (e.g., meat, dairy, oils and biofuels)

Source: Own depiction based on Rieger et al. (2023).

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mineral fertiliser prices are then passed to the CAPRI model as an exogenous shock.

In MAGNET, the EU ETS and CBAM are implemented to evaluate the effects of climate policies on global trade, emissions, and industrial competitiveness. The EU ETS is represented as a cap-and-trade system in which a carbon price applies to emissions from regulated sectors, including cement, iron and steel, aluminium, fertilisers, and electricity. Emission permits are limited and tradable among firms, indirectly introducing sector-specific carbon costs that affect production, consumption, and trade flows. The model captures the economic impact of an ETS using these cost structures (Woltjer et al. 2014). This setup enables the analysis of both micro- and macroeconomic consequences of carbon pricing within the EU.

CBAM is modelled in MAGNET as a carbon levy on imports from countries lacking an equivalent carbon-pricing framework. It targets sectors already covered by the EU ETS and gradually replaces free allowances for domestic producers to maintain compliance with WTO rules. The import levy is determined by the carbon content of imported goods and the prevailing EU ETS carbon price, ensuring parity in carbon costs between domestic and foreign producers. Emission intensity is estimated using inverse Leontief coefficients for each relevant sector. This framework allows assessment of CBAM's role in limiting carbon leakage and supporting the global competitiveness of EU industries under stricter climate regulations, while highlighting key policy trade-offs.

The CAPRI reference scenario assumes a status quo based on information available in mid-2023, including only agricultural, environmental, and trade policies that have already been ratified. It is calibrated to the European Commission's outlook for agricultural markets, income, and the environment (European Commission 2022), which relies on the OECD/FAO (2022) agricultural market outlook and provides medium-term projections up to 2030 within a consistent framework. This framework incorporates external assumptions on macroeconomic developments, such as GDP growth, exchange rates, world oil prices, and population growth. A detailed description of the CAPRI calibration process is provided by Himics et al. (2014).

In CAPRI, we simulate the price changes of mineral fertiliser derived from MAGNET, applying the global-to-local linkage between the two models. This linkage allows a detailed assessment of changes in mineral fertiliser use, substitution with organic fertilisers at the regional (NUTS2) level, shifts in agricultural production, price variations in final and intermediate products, impacts on agricultural trade, environmental effects, agricultural income, and overall agricultural welfare.

Although the EU ETS and CBAM also affect sectors such as electricity and fuels, their primary impact on agriculture operates through fertiliser production costs, as energy costs are embedded in fertiliser prices and electricity/fuel constitute a small share of total agricultural costs. Focusing on this dominant channel captures the main policy effect, whereas including smaller secondary input price changes would increase complexity without materially affecting the results.

4 | Results

We begin by estimating carbon prices using a cap-and-trade system that closely reflects the current structure of the EU ETS. The model endogenously determines the price required to meet the EU's fixed emission reduction targets, as explained in Section 3. For 2030, the resulting carbon price is €120 per ton of CO_2 equivalent, consistent with external estimates such as Guivarch and Rogelj (2017). This price forms the basis for calculating the CBAM rate for that period. The results are presented relative to a baseline without the EU ETS, which accounts for the free allowances currently covering all mineral fertiliser production in the EU. Appendix I reports the results for the ETS-only scenario to clarify CBAM's decomposition effect.

As shown in Figure A1, under the EU ETS without CBAM, mineral fertiliser imports increase substantially, indicating a loss of competitiveness for EU producers. Since mineral fertiliser production is currently fully covered by free allowances, the ETS-only scenario can also be interpreted as the phase-out of these allowances. In addition to the existing EU ETS, where imports into the EU rose by 187%, the introduction of CBAM on mineral fertilisers increases import costs heterogeneously across origins, reflecting differences in emission intensities and reducing the EU's import dependence. For example, the effective import levy on fertilisers from the Middle East and North Africa—currently the EU's largest external supplier—doubles, substantially raising the EU market price of mineral fertilisers.

Taken together, the EU ETS and CBAM result in a 99% increase in mineral fertiliser prices within the EU in 2030 compared to the reference scenario. Simulation results indicate that by 2030, the combined ETS and CBAM scenario reduces EU fertiliser production by 21.4%, whereas the ETS-only scenario leads to a 79% reduction. In the ETS-only scenario, the absence of border measures on carbon-intensive imports allows higher mineral fertiliser imports, producing a stronger negative impact on domestic production than in the ETS and CBAM scenario. Imports from non-EU regions decrease by 37% (Figure 2a). As mineral fertiliser prices nearly double, EU demand declines, while domestic producers face elevated carbon costs that increase production expenses and erode their competitiveness in international markets.

The EU's reduced imports of mineral fertilisers do not lead to significant increases in fertiliser use in other regions. As shown in Figure 2b, global demand for mineral fertilisers rises slightly, but this increase is minor compared to the decline in EU demand. Consequently, substantial emissions leakage does not occur in the sector.

Figure 3 shows that the largest emissions reduction occurs in the EU electricity sector, amounting to 564 megatons of CO_2-equivalent ($MtCO_2eq$). Although emissions in this sector rise slightly in non-EU[4] regions, the net global reduction remains 485 $MtCO_2eq$. The transportation, fossil fuel, and manufacturing sectors follow the electricity sector in total reductions. Emissions from mineral fertiliser production decrease by approximately 6 $MtCO_2eq$ in the EU, while increasing by 4 $MtCO_2eq$ in non-EU regions, resulting in a net reduction of 2

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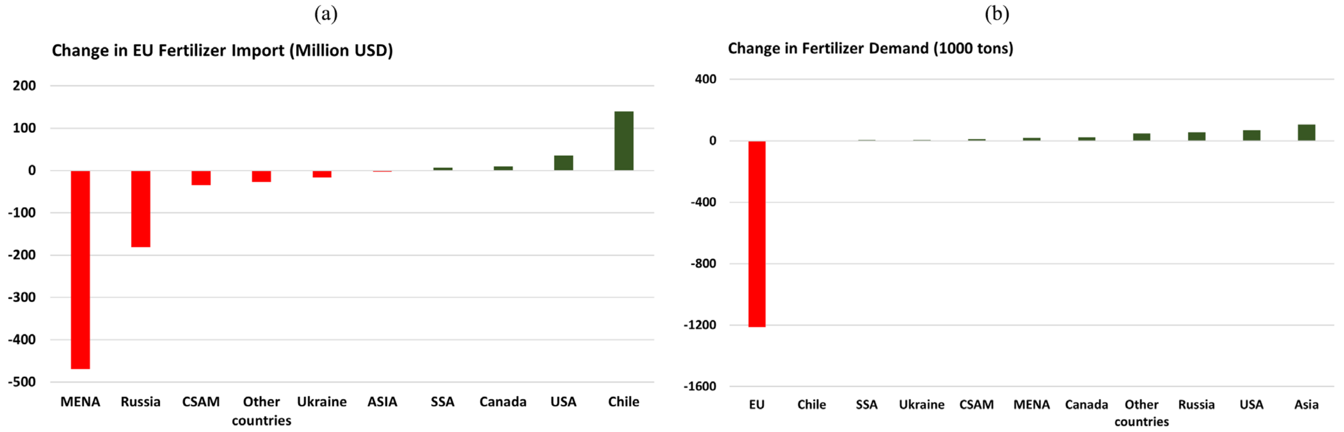

FIGURE 2 | (a) Net change in EU fertiliser imports and (b) net change in global fertiliser demand in 2030 compared to the reference scenario. *Source:* Own calculations using the MAGNET model. CSAM, Central and South America; MENA, Middle East and North Africa; SSA, Sub-Saharan Africa; Other countries: aggregate of regions not individually represented. [Colour figure can be viewed at wileyonlinelibrary.com]

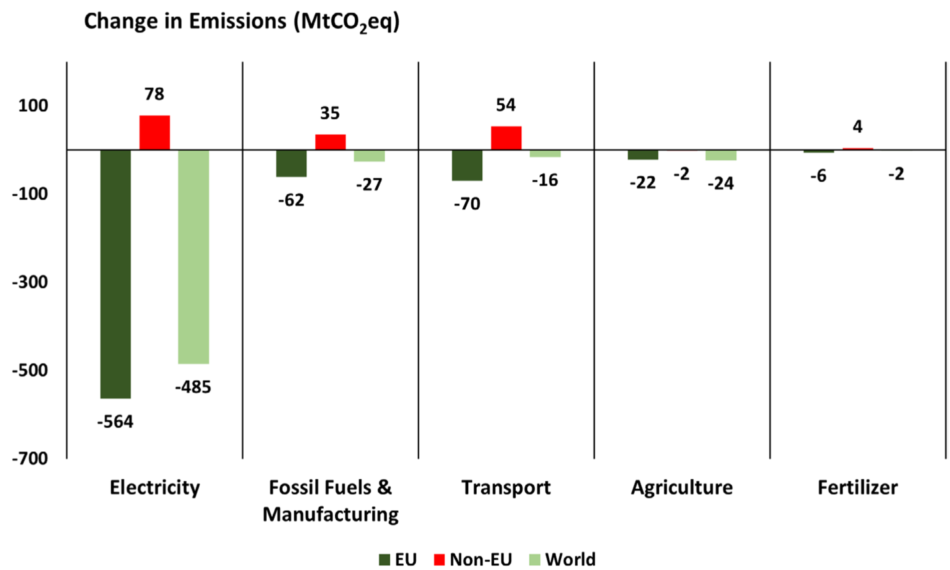

FIGURE 3 | Absolute change in emissions in 2030 for economic sectors compared to the reference scenario. *Source:* Own calculations using the MAGNET and CAPRI models. [Colour figure can be viewed at wileyonlinelibrary.com]

$MtCO_2eq$. Emission reductions in the agricultural sector, which is not directly covered by either the EU ETS or CBAM, are discussed later in this section.

Total emissions across all sectors in the EU decline significantly, by approximately 760 $MtCO_2eq$. Although total emissions in non-EU regions increase by about 190 $MtCO_2eq$, the net global emission reduction remains substantial (Figure 4).

The increase in mineral fertiliser prices leads to a 5.4% reduction in overall EU agricultural GHG emissions, equivalent to 22.1 $MtCO_2eq$. A substantial portion of this reduction comes from decreased N_2O emissions (Figure 5a), primarily due to lower mineral fertiliser application (Figure 5b), as well as reduced leaching, runoff, and volatilisation. Specifically, the total N surplus in the EU is projected to decline by 15% by 2030. Gaseous N losses from mineral fertiliser use are expected to decrease by 21%, while N runoff from mineral fertilisers is projected to fall by 27%, reducing the soil-level N surplus by 20%. Some of the mitigated emissions are linked to the adoption of technological mitigation measures prompted by rising fertiliser prices. Because the EU ETS and CBAM policies indirectly influence agriculture through fertiliser costs, technologies that enhance N efficiency—such as precision farming techniques and nitrification inhibitors—are expected to see wider adoption. Further improvements in manure storage and application technologies are also projected.

In the EU, total mineral fertiliser use is expected to decline by approximately 22%, corresponding to a reduction of 13 kg per hectare in utilised agricultural area (UAA). This decrease in mineral fertiliser use also reduces the application of phosphorus (P) and potassium (K) by 13% and 19%, respectively, owing to interdependence in fertiliser management. Manure use changes only minimally at the aggregate level. Figure 6 presents a regional (NUTS2) breakdown of EU mineral fertiliser use per hectare of UAA.

Several factors affect the magnitude of the reduction in mineral fertiliser use. Regions with high initial levels of mineral fertiliser

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application tend to reduce usage the most. Regions with a high share of N-intensive crops—such as sugar beets, maize, wheat, and rapeseed—combined with substantial animal production, that is, mixed farming systems, can reduce mineral fertiliser application by substituting it with manure. For example, the Italian region of Emilia-Romagna substantially reduces mineral fertiliser use for cereals, oilseeds, fodder, and vegetables while significantly increasing manure application as a substitute. In contrast, regions without access to organic alternatives struggle to offset mineral N use.

Farm structure also influences the reduction in mineral fertiliser use. Regions dominated by smallholder farms with limited financial resilience and bargaining power are forced to sharply reduce usage. Another factor is the baseline fertiliser price: regions with higher initial fertiliser costs, for example, due to logistical or transportation expenses, experience a larger reduction when prices double.

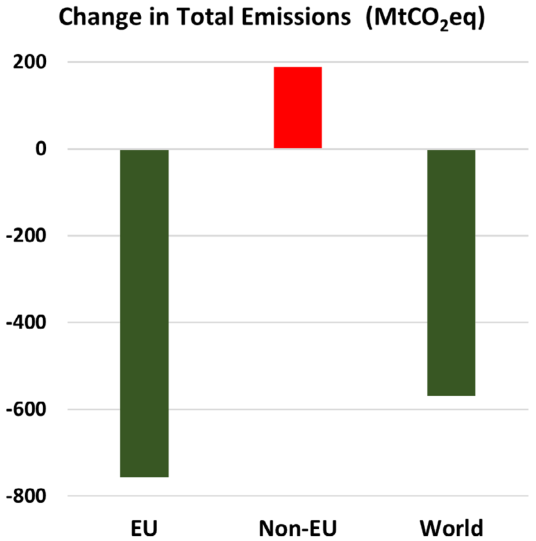

FIGURE 4 | Absolute changes in total GHG emissions across all sectors in 2030 compared to the reference scenario. Source: Own calculations using the MAGNET model. [Colour figure can be viewed at wileyonlinelibrary.com]

Notably, the increase in mineral fertiliser prices within the EU does not result in higher agricultural emissions globally. As shown in Figure 7a, EU agricultural GHG emissions decrease by 22 $MtCO_2eq$, while non-EU agricultural emissions decline by 2 $MtCO_2eq$, yielding a net global reduction of 24 $MtCO_2eq$. The reduction in non-EU agricultural emissions is primarily driven by lower emissions from meat production, particularly beef.

This reduction is driven by higher global feed prices, as shown in Figure 9, resulting from the reduced EU supply. Some shifts in crop production outside the EU do not cause significant emission leakage because the relative emission intensities of cereal and oilseed production inside and outside the EU are similar, meaning the location of production has little effect on global agricultural emissions (Table 3). In contrast, EU meat production is roughly four times more efficient than production in the rest of the world; relocating meat production would therefore result in substantial emission leakage.

Higher mineral fertiliser prices also reduce the EU's UAA by 0.8 million hectares, mainly owing to a 4.3% decrease in cereal production and a 3% decrease in oilseed production (Figure 7b). Production of other arable crops falls by 10%, primarily owing to reduced sugar beet cultivation, which has high N requirements. Total fodder[5] production declines by 5% because of grassland extensification and lower fodder maize production. Conversely, set-aside areas and fallow land increase by roughly 15%, while the proportion of legumes rises by 6.5% owing to their N-fixing properties. Meat production is only marginally affected, as producers can offset reduced fodder availability by importing tradable feed.

As shown in Figure 8a, EU crop producer prices are more strongly affected by 2030 than in the reference scenario. The largest increase is for cereals, approximately 7%, followed by oilseeds at 5% and other arable crops (pulses, potatoes, yams, manioc, cassava, and other roots) at 1%. Global producer price changes are more modest, with cereals rising about 1.5% and oilseeds about 1% (Figure 8b). The strong response of cereal prices to changes in mineral fertiliser prices reflects their high dependence on N inputs (Dakpo et al. 2023). Consumer price changes are smaller in both the EU and globally, with the largest increases in oilseed

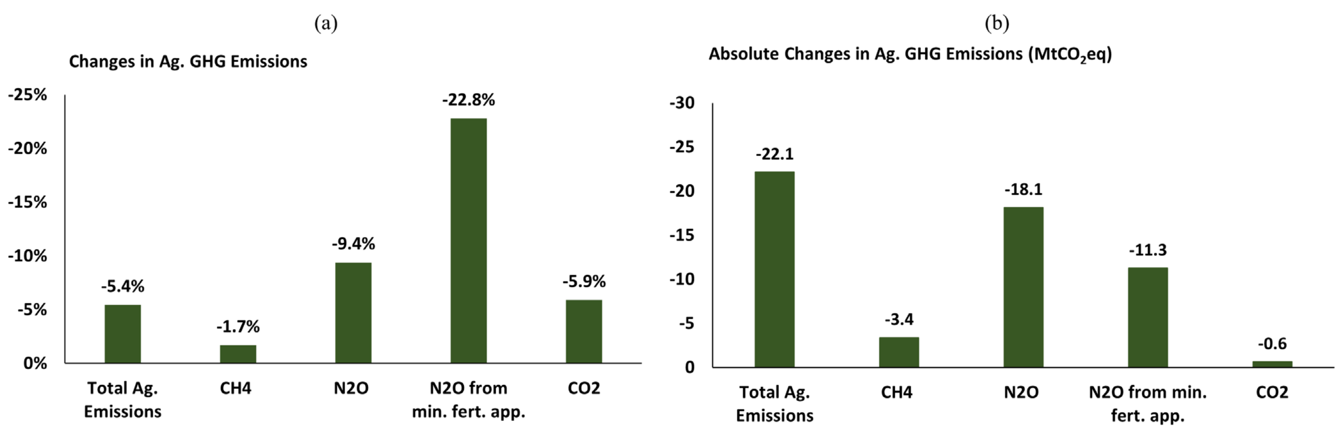

FIGURE 5 | Relative (a) and absolute (b) changes in EU agricultural GHG emissions in 2030 compared to the reference scenario. *Source:* Own calculations using the CAPRI model. [Colour figure can be viewed at wileyonlinelibrary.com]

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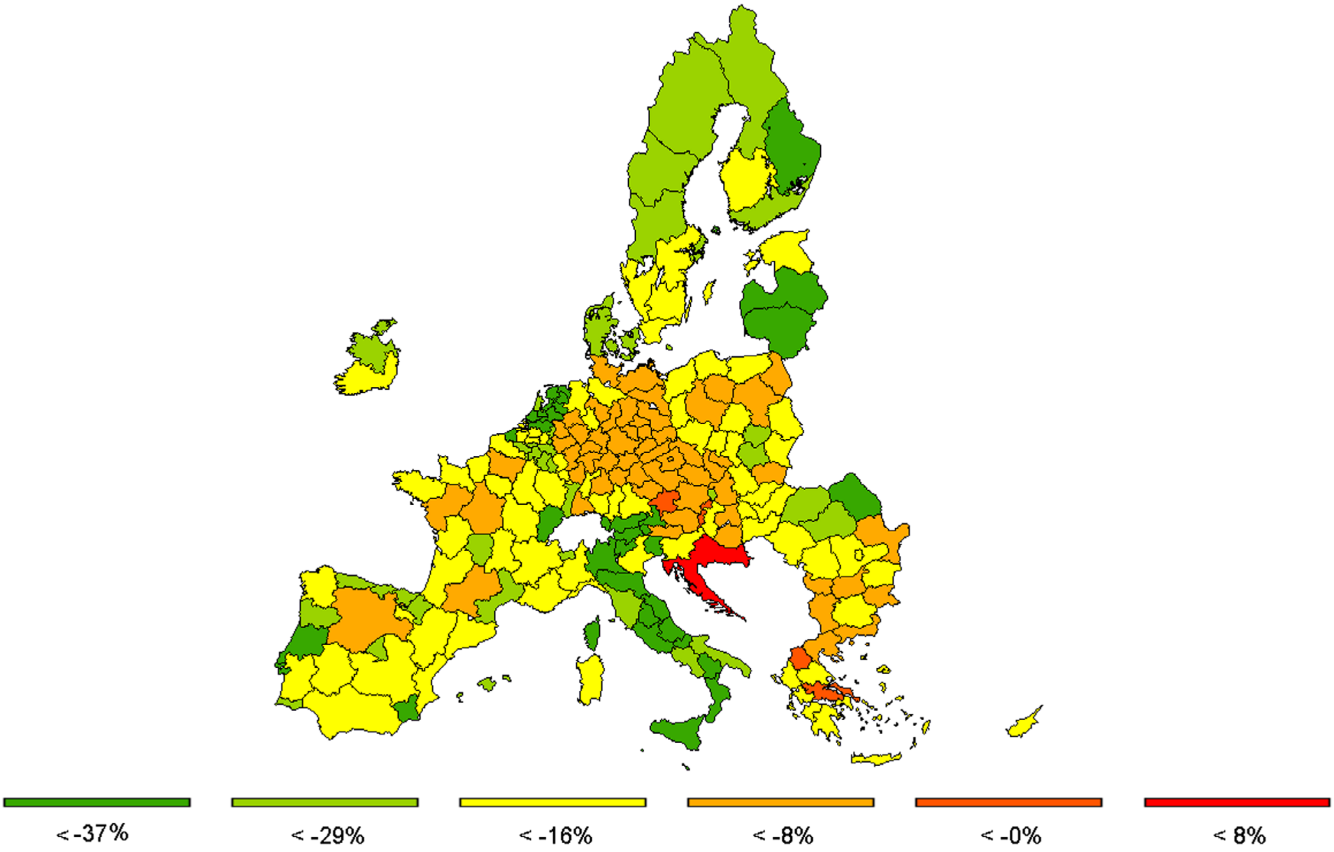

FIGURE 6 | Relative changes in mineral fertiliser use per hectare of UAA at the NUTS2 level in 2030 compared to the reference scenario. *Source:* Own calculations using the CAPRI model. [Colour figure can be viewed at wileyonlinelibrary.com]

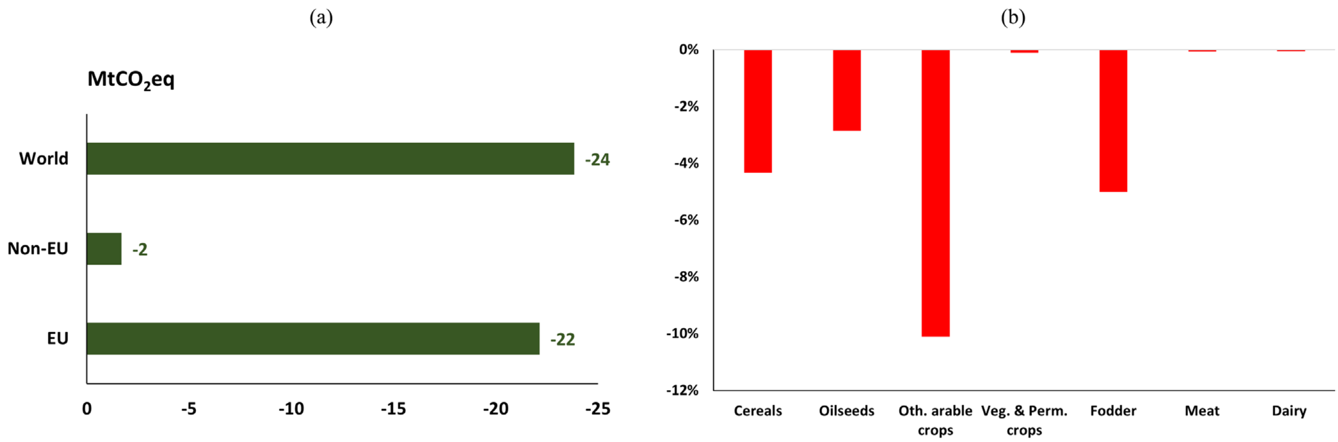

FIGURE 7 | (a) Absolute change in global agricultural emissions compared to the reference scenario (leakage) and (b) relative changes in EU agricultural production in 2030 compared to the reference scenario. Source: Own calculations using the CAPRI model. [Colour figure can be viewed at wileyonlinelibrary.com]

prices at 1.5% and 0.3%, respectively. Notably, producer and consumer price changes for animal products are similar in magnitude within the EU and worldwide.

Price increases for animal products are modest because producers can offset higher feed costs by importing tradable feed, which in turn causes only a slight rise in global feed prices. In the EU, non-tradable fodder prices increase by roughly 16%, prompting ruminant producers to optimise the feed mix by substituting fodder—primarily grass and fodder maize—with tradable items such as cereals and energy- and protein-rich feedstuffs (Table 2). Producers of monogastric animals adjust by replacing cereals in the feed mix with energy- and protein-rich components.

As shown in Table 3, the EU reduces its cereal and oilseed exports while increasing imports, resulting in a weaker net trade position for these commodities. The impact of trade on meat commodities is minimal owing to higher feed imports.

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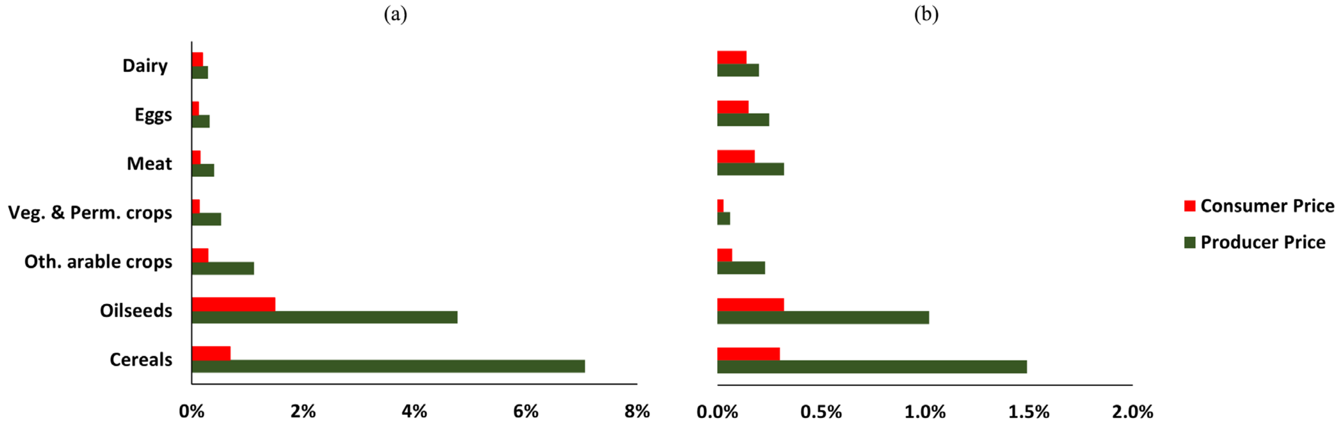

FIGURE 8 | Relative changes in producer and consumer prices of marketable food products in 2030 compared to the reference scenario: (a) EU and (b) global. *Source:* Own calculations using the CAPRI model. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 | Relative changes in the EU feed mix in 2030 compared to the reference scenario.

		Ruminants					Monogastric	
		For dairy production	**Other cows**	**Male adult cattle high weight**	**Male adult cattle low weight**	**Sheep and goat**	**Pig fattening**	**Poultry fattening**
Tradable	Feed other	0.02%	0.51%	0.72%	0.68%	0.73%	—	—
	Feed rich protein	3.15%	8.06%	7.18%	13.13%	2.60%	0.16%	0.13%
	Feed cereals	10.13%	7.62%	5.63%	7.08%	6.98%	−0.15%	−0.21%
	Feed rich energy	5.08%	7.80%	4.87%	8.17%	3.16%	2.67%	2.47%
Non-Tradable	Grass	−8.55%	−9.23%	−10.18%	−9.38%	−5.77%	—	—
	Fodder maize	−5.14%	−11.07%	−10.34%	−9.24%	−5.57%	—	—
	Fodder root crops	4.65%	4.29%	2.73%	2.54%	4.71%	—	—
	Oth. fodder on arable land	1.59%	−0.68%	0.13%	−0.03%	6.55%	—	—

Source: Own calculations using the CAPRI model.

Total agricultural factor income in the EU decreases by 7.7%, with heterogeneous effects across regions. Table 4 provides a detailed decomposition of agricultural income for three regions with relatively high income losses (Ile-de-France, Limousin in France, and Östra Mellansverige in Sweden) and three regions with relatively low income losses (Peloponnisos in Greece, Murcia in Spain, and Liguria in Italy). Income declines most sharply in regions where input costs account for a larger share of output value. In the reference scenario, the regions with the steepest income reductions already allocate 59%–86% of output value to input costs. Under the EU ETS and CBAM, input costs rise further to 72%–95% of output, leaving minimal room for profit. Regions with lower input-to-output ratios experience substantially smaller income losses. In animal-producing areas, non-tradable fodder becomes more expensive owing to grassland extensification and reduced fodder maize production. Consequently, producers increasingly substitute fodder with tradable feed at significantly higher prices, as shown in Figure 9. EU consumer welfare declines by 0.1%, equivalent to 2.5 billion euros, or 5.6 euros per capita.

Agricultural factor income in non-EU countries rises slightly, by 0.05%, owing to higher prices and increased EU demand. However, the higher prices negatively affect consumer welfare in non-EU countries, resulting in a 0.01% decline, equivalent to 8.3 billion euros.

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TABLE 3 | Changes in world import and export shares for the EU and non-EU countries in 2030 compared to the reference scenario, along with corresponding emission intensities per tonne of commodity.

		World export share	World import share	Emission intensity [kg CO_2eq/t]
Cereals	EU	−12.47%	6.27%	109
	non-EU	2.17%	−0.72%	137
Oilseeds	EU	−3.87%	1.58%	238
	non-EU	0.36%	−0.14%	185
Meat	EU	−0.08%	0.11%	3302
	non-EU	0.04%	−0.01%	12,335
Beef	EU	−0.32%	0.45%	14,128
	non-EU	0.04%	−0.02%	33,895
Feed cereals	EU	−12.65%	6.36%	109
	non-EU	1.95%	−0.68%	137
Feed rich protein	EU	−1.56%	1.47%	—
	non-EU	0.09%	−0.51%	—
Feed rich energy	EU	−3.55%	5.03%	—
	non-EU	0.14%	−0.25%	—
Feed other	EU	−1.46%	1.03%	1065
	non-EU	0.25%	−0.12%	2329

Note: Emission intensities for protein are not reported, as these are primarily by-products of non-primary agricultural activities such as brewing and milling.
Source: Own calculations using the CAPRI model.

Figure 10 shows relative income changes across all NUTS2 regions in the EU, following a pattern similar to that observed in the regions discussed above.

5 | Discussion

The modelling results suggest that integrating the EU ETS and CBAM, together with the phase-out of free allowances, implies a carbon price of €120 per ton of CO_2 equivalent in 2030. This estimate aligns with previous findings, such as those of Guivarch and Rogelj (2017). Because the results are reported relative to a reference scenario without a carbon price in the EU ETS, they reflect the role currently played by free allowances covering mineral fertiliser production in the EU. A comparison of scenarios highlights the importance of policy design. An ETS-only scenario, which can be interpreted as a unilateral phase-out of free allowances, is associated with substantial competitiveness losses for EU mineral fertiliser producers, reflected in a strong increase in imports and a pronounced contraction of domestic production. By contrast, the introduction of CBAM raises import costs heterogeneously across origins according to emission intensities, thereby mitigating competitiveness distortions by creating a more level playing field between EU producers and foreign suppliers.

Simultaneously, the EU ETS increases the production costs of mineral fertilisers within the EU, and the application of equivalent border adjustments raises import prices. An important implication of this combined policy is the marked increase in mineral fertiliser prices within the EU, which induces a contraction in fertiliser demand. This decline in EU demand, together with the reduced export competitiveness of EU producers in international markets, contributes to a moderate reduction in domestic mineral fertiliser production relative to the reference scenario. Although lower EU demand slightly reduces mineral fertiliser prices elsewhere, the associated demand increases in non-EU regions remain insufficient to offset the reductions within the EU, indicating limited carbon leakage under the simulated scenario.

From a global perspective, emission increases in non-EU regions remain substantially smaller than the reductions within the EU, including those in the agricultural sector. Overall, the net effect on global emissions remains negative, suggesting that the combination of the EU ETS and CBAM achieves its intended objective of limiting leakage. The decline in global beef production further reflects the transmission of higher fertiliser prices to feed costs, illustrating the sensitivity of livestock systems to input price changes.

An important implication of higher fertiliser prices is the adjustment of agricultural production practices. These responses are reflected in the reduced use of mineral fertilisers and associated inputs; adjustments in crop choice, including increased cultivation of legumes and reduced production of N-intensive crops; extensification of grassland; and the adoption of technologies that improve N use efficiency, such as precision farming, nitrification inhibitors, advanced manure management, and optimised fertiliser timing. Consistent with this, the model does not project significant grassland expansion or associated biodiversity side effects within the simulated period.

The increase in fertiliser prices also implies a reduction in mineral fertiliser application rates and agricultural GHG emissions within the EU. Comparing this effect with existing policy targets, such as the European Green Deal objective of reducing nutrient losses by 50% by 2030, suggests that price-based mechanisms operating through fertiliser markets may contribute to emission reductions but are unlikely, on their own, to fully achieve broader nutrient management goals. Regional differences in impact reflect heterogeneous production structures and input cost shares, highlighting that distributional consequences may vary substantially across Member States.

From a trade and policy perspective, the combined implementation of CBAM and EU ETS may generate competitive pressures in export markets for segments of the fertiliser industry and for downstream sectors not covered by CBAM. These distributional effects may influence stakeholder positions regarding the allocation of CBAM revenue or the design of accompanying policy measures. In this context, interaction with the Common Agricultural Policy (CAP) becomes relevant. Targeted support mechanisms or incentives for adopting efficiency-enhancing technologies could potentially mitigate income losses while reinforcing mitigation incentives. For example, Himics et al. (2020) suggested reallocating current

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TABLE 4 | Regional input, output, and income indicators (million euros) with ratios (%) and relative changes, comparing the reference scenario with the EU ETS and CBAM scenario for 2030.

Category	Metric	Peloponnisos (Greece)	Murcia (Spain)	Liguria (Italy)	Ile-de-France (France)	Limousin (France)	Oestra Mellansverige (Sweden)
Income and output	Agricultural income	2488/2411 −1.9% ▼	3432/3369 −1.8% ▼	1149/1126 −2.0% ▼	762/586 −23.1% ▼	569/409 −28.2% ▼	436/336 −23.1% ▼
	Premiums	268/267 −0.1% ▼	122/122 0.0%	26/26 0.0%	140/139 −0.4% ▼	319/318 −0.3% ▼	219/218 −0.5% ▼
	EAA Output	2942/2948 0.2% ▲	4533/4544 0.2% ▲	1303/1303 0.0% ▲	1532/1575 2.8% ▲	1815/1822 0.4% ▲	1303/1304 0.1% ▲
	– Crops	2694/2700 0.2% ▲	3451/3452 0.0% ▲	1263/1263 0.0% ▲	1287/1333 3.5% ▲	429/436 1.7% ▲	430/428 −0.4% ▲
	– Animals	248/248 0.0%	1082/1090 0.7% ▲	40/40 0.0%	245/242 −1.3% ▼	1386/1385 −0.1% ▼	873/876 0.3% ▲
Input costs	Total EAA Input	722/774 7.3% ▲	1224/1297 6.0% ▲	180/203 12.6% ▲	910/1128 24.0% ▲	1565/1731 10.6% ▲	1085/1186 9.3% ▲
	– Crop-specific	201/243 21% ▲	229/268 16.6% ▲	73/89 23.2% ▲	554/726 31.2% ▲	404/526 30.1% ▲	314/407 29.6% ▲
	– Animal-specific	134/140 4.7% ▲	580/606 4.5% ▲	16/17 6.3% ▲	78/81 3.9% ▲	928/955 2.9% ▲	361/369 2.2% ▲
	– Other	387/391 1.0% ▲	414/423 2.2% ▲	92/97 5.3% ▲	278/321 15.3% ▲	232/250 7.5% ▲	410/410 0.0%
Key ratios	Premiums/Income	11%/11%	4%/4%	2%/2%	18%/24% ▲	56%/78% ▲	50%/65% ▲
	Crop Output Share	92%/92%	76%/76%	97%/97%	84%/85% ▲	24%/24%	33%/33%
	Animal Output Share	8%/8%	24%/24%	3%/3%	16%/15% ▼	76%/76%	67%/67%
	Input Costs/Output	25%/26% ▲	27%/29% ▲	14%/16% ▲	59%/72% ▲	86%/95% ▲	83%/91% ▲
	– Crop Input Share	28%/31% ▲	19%/21% ▲	40%/44% ▲	61%/64% ▲	26%/30% ▲	29%/34% ▲
	– Animal Input Share	19%/18% ▼	47%/47%	9%/8% ▼	9%/7% ▼	59%/55% ▼	33%/31% ▼
	– Other Input Share	54%/51% ▼	34%/33% ▼	51%/48% ▼	31%/28% ▼	15%/14% ▼	38%/35% ▼

Source: Own calculations using the CAPRI model.

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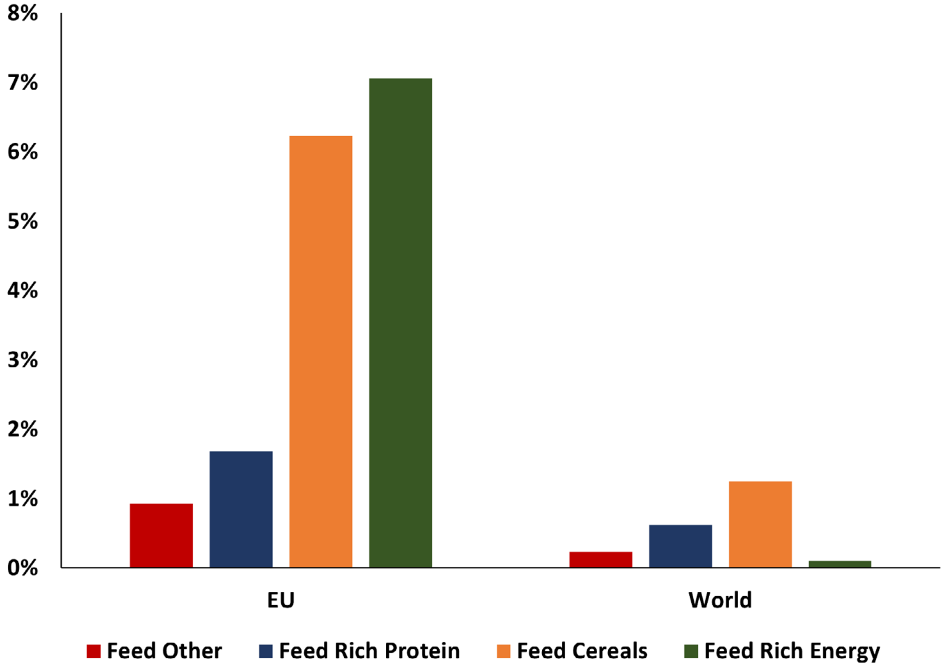

FIGURE 9 | Relative changes in producer prices of marketable feed in 2030 compared to the reference scenario: EU and global. *Source:* Own calculations using the CAPRI model. [Colour figure can be viewed at wileyonlinelibrary.com]

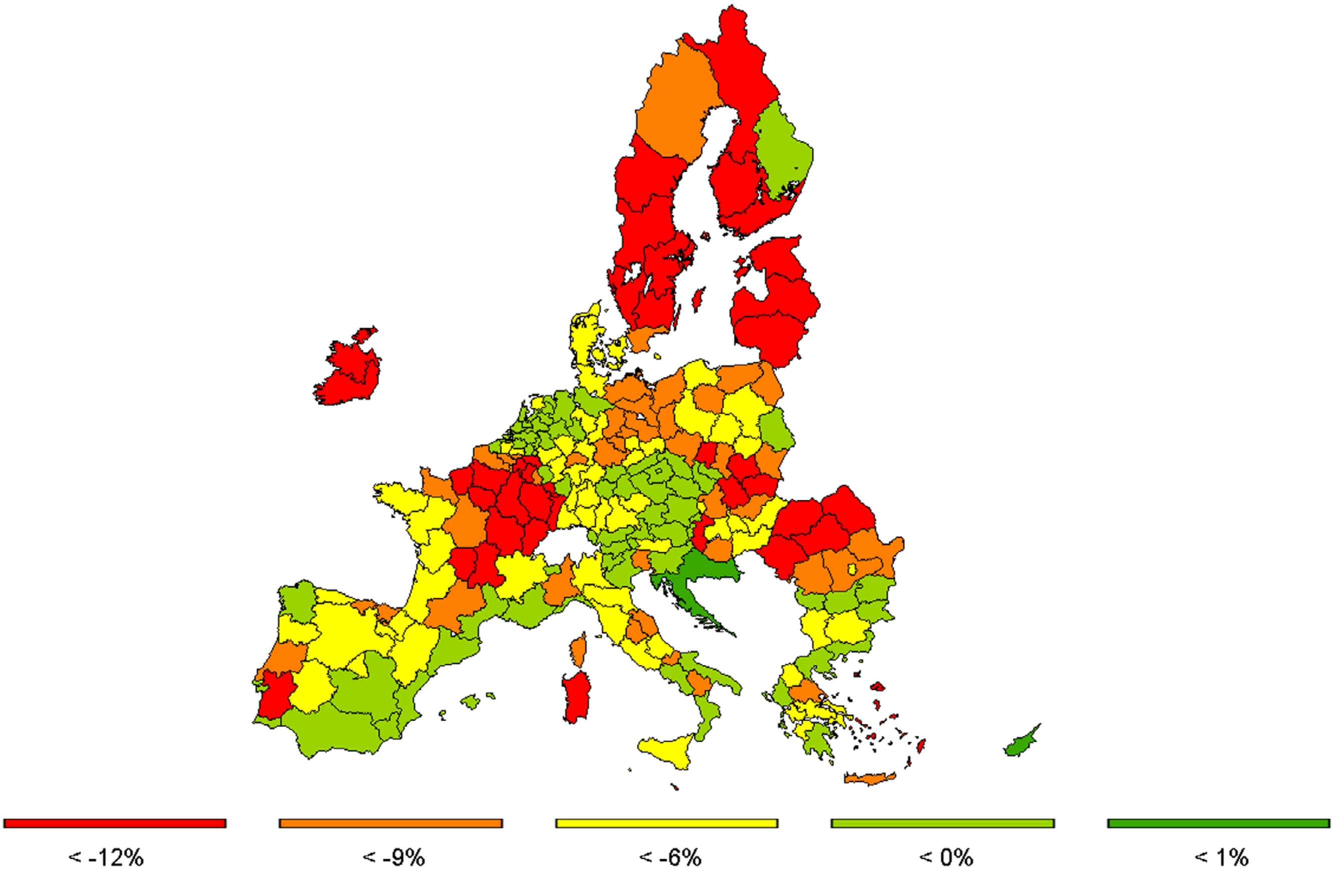

FIGURE 10 | Relative changes in agricultural income at the NUTS2 level in 2030 compared to the reference scenario. *Source:* Own calculations using the CAPRI model. [Colour figure can be viewed at wileyonlinelibrary.com]

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basic CAP payments to farmers to reduce GHG emissions. Recent policy discussions at the EU level, including the European Commission's Vision for Agriculture and Food (European Commission 2025), emphasise targeted support for farmers in need, strategic autonomy and resilience, and the uptake of innovative technologies.

These results suggest that higher fertiliser prices increase the relative attractiveness of N-efficient technologies, indicating that complementary CAP instruments can accelerate such transitions. The European Commission also acknowledges the risks of the agricultural sector's dependence on imported inputs, such as fertilisers and feed, and identifies reducing these dependencies as a critical objective, partly addressed through mechanisms such as CBAM. Havlík et al. (2025) highlighted five priority actions for the EU agricultural sector to boost competitiveness, ensure food security, and reduce environmental impacts. The key to achieving these objectives is integrated nutrient management. Reducing reliance on fertilisers through precision farming, green fertilisers, improved manure recycling, and domestic cultivation of protein crops can lessen dependence on imports, a major vulnerability. In light of these results, higher fertiliser prices may reinforce incentives for such adjustments, suggesting that carbon pricing instruments and strategic autonomy objectives may be partially aligned.

These findings also inform ongoing debates on extending carbon pricing and CBAM to primary agricultural emissions. Although the inclusion of the agricultural sector in these mechanisms has been increasingly debated and investigated recently (Spiegel et al. 2024), implementing CBAM in agriculture faces challenges owing to concerns about carbon leakage and feasibility (Fournier Gabela et al. 2024). Recent research has directly examined the potential of carbon pricing and border adjustment mechanisms in agriculture to reduce GHGs. A global carbon tax in agriculture of €120 per ton of CO2eq could reduce global agricultural emissions by 19%, whereas a unilateral EU tax combined with a CBAM for the agricultural sector would yield only a 0.15% reduction in global agricultural emissions, indicating that a unilateral carbon tax in the EU causes significant emission leakage (Jansson et al. 2024). Hence, integrating the agricultural sector into CBAM poses challenges, as agriculture currently lacks a carbon pricing system. Moreover, Matthews (2022) identified additional practical obstacles to implementing CBAM in the agricultural sector, including the difficulty of determining the actual embedded emissions in imported agri-food products owing to highly complex supply chains. In contrast, Fournier Gabela et al. (2024) proposed design features for CBAM that support its administrative, technical, and legal feasibility. However, integrating the agricultural sector into CBAM remains challenging, as no carbon pricing or aligned monitoring system currently exists for agriculture.

This study has some limitations that should be acknowledged when interpreting the findings. Although the modelling framework incorporates a range of behavioural responses by producers, it does not capture potential structural shifts towards organic production systems, as suggested by Sørensen et al. (2025), beyond those reflected in reference scenario trends. Another limitation concerns future development pathways for hydrogen-based (green) fertiliser technologies. If green fertilisers become cost-competitive more rapidly than assumed, the impact of carbon pricing on fertiliser production and prices may be less significant. Consequently, projections of fertiliser prices and the associated behavioural responses remain sensitive to assumptions regarding technological change and energy system transformation. A strategy for green fertiliser production, including its potential implications for N_2O emissions, is required to guide the transformation of the agricultural sector. For example, Becker (2025) suggested that introducing a quota for green N in fertiliser production would drive demand for green hydrogen, reduce agricultural emissions, and establish a lead market for hydrogen derivatives while supporting industrial transformation in Germany and Europe.

Additionally, the analysis considers the effects of the EU ETS and CBAM on agriculture primarily through the fertiliser market channel. Although electricity and transport costs also influence agricultural production, electricity cost shares are relatively small and largely embedded in fertiliser production, whereas transport effects cannot be fully represented in the modelling framework. Finally, the uncertainty surrounding the future trajectory of EU ETS carbon prices constitutes an additional source of variation. Although the simulated price path is consistent with observed dynamics and policy parameters, deviations in economic growth, technological uptake, and international trade responses can alter the effective carbon prices and associated market adjustments. These uncertainties should be considered when interpreting the magnitude—but not the direction—of the simulated effects.

6 | Conclusion

This study combines CGE and PE modelling approaches to assess how the integration of the EU ETS and CBAM, together with the phase-out of free allowances, affects fertiliser markets and agriculture. The results suggest that the EU farming sector is indirectly exposed to carbon pricing through fertiliser production channels. Higher mineral fertiliser prices reduce fertiliser demand and induce behavioural adjustments in crop choice, input intensity, and technology adoption. While the policy combination generates competitiveness pressures in some segments, global emissions decline overall, and carbon leakage remains limited under the simulated scenario.

By explicitly linking fertiliser market adjustments to agricultural production responses, this study provides new evidence on how existing mitigation instruments under the EU ETS and CBAM are transmitted to agricultural markets. Although current policy frameworks do not directly price non-CO_2 agricultural emissions, such as N_2O from fertiliser application or CH_4 from livestock production, the results indicate that price-based mechanisms in upstream sectors can induce indirect emission reductions in agriculture.

Simultaneously, distributional impacts across regions and farm types warrant careful consideration. Income effects may shape political feasibility and influence debates on the allocation of

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CBAM revenue and CAP reform. Future research should investigate how alternative development pathways for green fertilisers and different revenue recycling mechanisms interact with agricultural market outcomes and welfare effects.

Author Contributions

D.S. conceptualised the study, performed the simulations with the CAPRI model, analysed the results, and wrote the original manuscript draft. O.Z. performed the simulations with the MAGNET model and contributed to analysing the results and to writing the manuscript. C.H. contributed to the conceptual design of the study, led the discussion section, and contributed to writing and revising the manuscript. J.P. contributed to the conceptual design of the study and contributed to analysing the results and to writing the manuscript. J.R. contributed to the conceptual design of the study and to writing the manuscript. B.O. conceived the original idea of the study and contributed to writing the manuscript. A.G. contributed to analysing the results, to writing the manuscript, and supervised the project. All authors discussed the results and commented on the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Endnotes

[1] Such a practice is inconsistent with WTO principles of non-discrimination and national treatment (Fournier Gabela et al. 2024).

[2] Referred to as mineral fertiliser in this paper.

[3] Free allowances are not captured by the model.

[4] All regions outside the EU.

[5] Fodder, which is not tradable, includes grass, fodder maize, fodder root crops, and other fodder grown on arable land.

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Appendix I

Below we present the change in imports of the scenario in which only the impact of the EU Emissions Trading System (ETS) is modelled, without considering the EU Carbon Border Adjustment Mechanism (CBAM), in 2030 relative to the reference scenario. These results help to better interpret the findings of the combined EU ETS and CBAM scenario presented in the paper. Under the ETS-only scenario, assuming the complete phase-out of free allowances and the absence of a CBAM, imports of mineral nitrogen (N) fertiliser to the EU increase by 187% in 2030 compared to the reference scenario, mainly from the MENA region and Russia. Fertiliser production within the EU decreases by 79%.

The impact of the EU ETS on the price of mineral N fertiliser is minimal (less than 1% price increase) compared to the combined effect of the EU ETS and CBAM, with a 99% price increase, given that local production is easily substituted by cheap imports. Consequently, the reduction in agricultural GHG emissions is smaller.

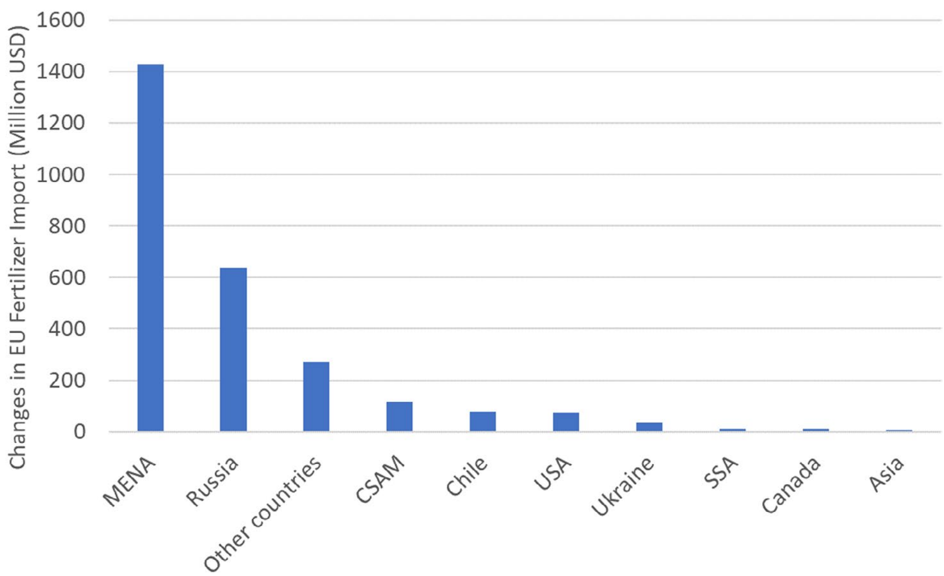

FIGURE A1 | Net change in EU fertiliser imports under the ETS-only scenario in 2030 compared to the reference scenario. *Source:* Own calculations using the MAGNET model. CSAM, Central and South America; MENA, Middle East and North Africa; SSA: Sub-Saharan Africa; Other countries: an aggregate group of regions other than the ones represented. [Colour figure can be viewed at wileyonlinelibrary.com]

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