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Unintended Consequences of EU-Climate Policies: Carbon Leakage in Global Forest and Agricultural Markets

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Abstract

In July 2025, the European Commission (EC) proposed an EU climate target to reduce net greenhouse gas emissions by at least 90% by 2040 relative to 1990, complementing the goal of reaching climate neutrality by 2050. The proposal assumes explicit sector-specific greenhouse gas (GHG) mitigation pathways for EU agriculture and the LULUCF sector until 2050. Unilateral EU climate mitigation may however generate international spillover effects through changes in global production, trade, and emissions. One major concern is carbon leakage, whereby production and GHG emissions are displaced to non-EU regions in response to domestic climate policies. We expand on the EC's impact assessment underlying the 2040 climate target proposal, by providing an integrated and more granular evaluation of the impacts of the proposed mitigation pathways on global forest and agricultural markets. For this purpose, we link the global forest sector model TiMBA with the agriculture-specialized computable general equilibrium model MAGNET. A joint baseline is constructed under SSP2 assumptions, and two unilateral climate policy scenarios for forestry and agriculture are implemented, equivalent to the sector-specific targets of Scenario 3 of the EC's impact assessment: By 2050, the forestry sector provides 75% of the headline LULUCF mitigation target, i.e., a target of -250 Mt CO_2-eq. carbon removals; while agricultural CH_4 emissions are reduced by 31.5% and agricultural N_2O emissions by 44.5% relative to 2015. Our analysis evaluates changes in production, trade patterns, and emissions at the country and sectoral level and quantifies potential leakage effects.

Keywords

Carbon leakage, climate policy, non-CO_2 greenhouse gas emissions, forest carbon sequestration, carbon environmental modelling

1 Introduction

The European Commission (EC), as an intermediate step towards the goal of reaching climate neutrality in 2050, proposed an EU climate target for 2040 that would reduce net greenhouse gas (GHG) emissions by at least 90% relative to 1990. The target proposal assumes novel GHG reduction pathways on the sectoral contribution of agriculture and in the Land Use, Land-Use Change and Forestry (LULUCF) sector, laid out in a complementary impact assessment (European Commission 2024). Scenario S3 of this impact assessment, chosen for the headline proposal, assumes a reduction of agricultural methane emissions by 26% and 31.5% and of agricultural nitrous oxide emissions by 39% and 44.5% until 2040 and 2050, respectively, relative to 2015 levels. The impact assessment also provides mitigation requirements for the LULUCF sector, expanding on the existing 2030 targets of the EU-LULUCF regulation (European Union 2023). Ambitious unilateral climate policies such as the prescribed mitigation pathways, while not yet legally binding or linked to specific implementing policies, raise concerns about international spillovers that undermine their effectiveness, notably carbon leakage.

Carbon leakage describes the relocation of production and GHG emissions to regions with laxer environmental regulation as a response to a tightening of domestic climate policies (Grubb *et al* 2022). Carbon leakage mainly transmits through a ‘competitiveness’-channel, where carbon pricing raises domestic prices and induces households to substitute towards relatively cheaper foreign products (Hoel 1996). Assuming higher emission intensity in foreign production, domestic emission savings would be counteracted by foreign emission expansion. In the ‘competitiveness’ perspective, the magnitude of carbon leakage thus depends on the implicit carbon price differential between domestic and foreign legislations, the differential of GHG efficiency in domestic vis-à-vis foreign production, as well as on substitutability both for final commodity demand as well as for production intermediates. Other transmission channels of carbon leakage, although often neglected in modelling, operate via world energy market prices, capital markets, and strategic free-riding in global climate policy (Fournier Gabela *et al* 2024).

Sector-specific studies on carbon leakage in agriculture, mostly model-based and using stylized carbon prices, consistently find that unilateral carbon pricing of agricultural non-CO_2 emissions in the EU or OECD, or providing farmers with GHG reduction subsidies, induces non-negligible carbon leakage to the rest of the world (Himics *et al* 2018, Himics *et al* 2020, Arvanitopoulos *et al* 2021, Pérez-Domínguez *et al* 2025). Leakage rates typically increase with rising domestic carbon prices (Himics *et al* 2018, Frank *et al* 2021, Henderson and Verma 2021, Stepanyan *et al* 2023), but can be counteracted by the domestic adoption of GHG mitigation technologies (Himics *et al* 2018; Pérez-Domínguez *et al* 2025; Stepanyan *et al* 2023), the adoption of symmetric carbon pricing regimes internationally (Fellmann *et al* 2018, Frank *et al* 2021, Henderson and Verma 2021, Jansson *et al* 2024), as well as the implementation of agricultural border adjustment mechanisms (Fournier Gabela *et al* 2024, Jansson *et al* 2024).

Studies on production and carbon leakage in the forest sector investigate, for example, adverse effects of unilateral forest conservation efforts (Murray 2008). Future simulations in global partial equilibrium models such as GFPM, GLOBIOM, and EFI-GTM, have consistently established leakage risks due to forestry-related policies (Jonsson *et al* 2012): Increasing forest protection, eliminating illegal logging, introducing enhanced carbon sequestration targets or forest conservation strategies such as REDD, all reduce domestic production while inducing production and carbon leakage through higher harvesting in other regions (Sohngen *et al* 1999, Li *et al* 2008, Jonsson *et al* 2012, Kallio *et al* 2018, Di Fulvio *et al* 2025, Kallio and Rannestad 2025). While consistently finding leakage effects in the forestry sector, none of these studies place their results within a broader macroeconomic context, as they rely exclusively on partial equilibrium modelling frameworks.

A recent hybrid study of Pérez-Domínguez *et al* (2025) studied GHG mitigation measures in the AFOLU sector, including both agriculture and forestry-oriented policies, to contribute to the EU’s climate targets in 2030 and 2050. Informed by CAPRI calculations and considering technological mitigation options, they find a combined scenario with lower EU forest harvest, agricultural non-CO_2 carbon pricing, and histosol protection, to be the most cost-effective measure, yet also offset by carbon leakage of 4% of gross mitigation. The study has a similar scope to ours but does not strictly cater to exogenous mitigation pathways and rather assesses variable outcomes of fixed mitigation designs.

We contribute to these existing studies on carbon leakage in agriculture and forestry by establishing an integrated, soft-coupled modelling framework of an agriculture-specialized computable generable equilibrium model (MAGNET) and a partial equilibrium model for the forestry sector (TiMBA). This allows us embed granular sectoral and cross-sectoral policy responses within the broader economic development and capture global interactions. We use this setup to study the global production, trade, and emission effects of the concrete sector-specific EU climate targets for agriculture and forestry proposed in European Commission (2024). We therefore also expand on the EC’s impact assessment by delivering a more nuanced evaluation of the global policy effects of the implied mitigation pathways on agriculture and forestry. The remainder of this paper proceeds as follows: Section 2 introduces to the models used, as well as to scenario construction and model coupling procedures. In the results-related Section 3, we evaluate changes in production and trade patterns, as well as emissions on the country and sectoral level and show potential leakage effects. The paper concludes in Section 4 with a discussion of mitigation design options and how model frameworks like the established TiMBA–MAGNET link can be used for subsequent scenario analysis.

2 Methods

2.1 Models and data

To allow for an integrated, *ex-ante* economic evaluation of the novel mitigation GHG mitigation pathways for forestry and agriculture, we link the two models TiMBA (Timber market Model for policy-Based Analysis) and MAGNET (Modular Applied GeNeral Equilibrium Tool).

TiMBA is an open-source, global, partial economic equilibrium model to simulate production, consumption, trade and prices for 16 wood-based product groups in 180 countries, capturing global developments and interdependencies (TI-FSM *et al* 2025). The model determines the market equilibrium by ensuring market clearance, balancing raw material needs with the manufacturing and demand of wood products while imposing constraints on trade, following principles similar to those of Samuelson (1952). TiMBA recursively calculates the market equilibrium for each country and product endogenously over a given period by maximizing social surplus in the global forest sector. Scenario simulations are driven by both exogenous and endogenous parameters and assumptions about future market dynamics and policy directives. The model's output includes detailed information on production, consumption, trade volumes, cost and prices, as well as forest area and stock developments. Main model inputs include forest product statistics and forest resource data provided by the Food and Agriculture Organization (FAOSTAT 2025, FRA 2025). The carbon module extends these functionalities to quantify and price carbon stocks and fluxes based on TiMBA's forest sector projections (Honkomp 2026).

MAGNET is a global, multi-sector, multi-region, recursive dynamic computable general equilibrium (CGE) model (Woltjer and Kuiper 2014), built around the economic architecture of the Global Trade Analysis Project (GTAP) model (Hertel 1997, Corong *et al* 2017). MAGNET allows for global ex-ante policy evaluations, by capturing interactions across agriculture, land use, industry, services and representing international trade responses across 141 regions. Key model properties include a nested constant elasticity of substitution (CES) production function, private household demand with a constant differences of elasticities (CDE) utility specification, and international trade represented by Armington elasticities (Armington 1969). MAGNET is specialized and has been used to inform policy analyses in fields such as agricultural economics, bioeconomy and climate mitigation (Henderson *et al* 2019, Frank *et al* 2021, Henderson and Verma 2021, Fujimori *et al* 2022); for which it features expansion modules to standard GTAP, for example on endogenous land supply, greenhouse gas accounting, and biofuels (Philippidis *et al* 2018). MAGNET draws on the GTAP 11 database (Aguiar *et al* 2022), and further disaggregates bioeconomic sectors, in total featuring 141 countries, 113 sectors as well as 127 commodities and byproducts. The underlying GTAP 11 database is founded on social accounting matrices and satellite data sources. As for greenhouse gas emission data, GTAP 11 bases CO_2 combustion-based emissions on the GTAP-E volume using the Tier 1 IPCC method (IPCC 2006, 2019); for non-CO_2 emissions, data is sourced from FAOSTAT (FAO 2026) and EDGAR v.7.0 (Branco *et al* 2022) (Chepeliev 2024). To enable technological mitigation of greenhouse gas emissions in agriculture, MAGNET utilizes US EPA (2013) and Ragnauth *et al* (2015) data on marginal abatement cost curves (MACCs), calibrated for MAGNET by Henderson *et al* (2019). These MACCs are based on a bottom-up (farm-level) engineering cost approach, through which break-even prices for mitigation technologies were determined based on the present value of their respective costs and benefits. For emissions due to enteric fermentation and manure management in the livestock-subsector, improved feed conversion, antibiotics, bovine somatotropin, propionate precursors, antimethanogenic feed additives and intensive grazes were considered as mitigation technologies. For soils-related N_2O emission, no till, reduced fertilization, split nitrogen fertilization, nitrification inhibitors and residue incorporation were assessed. For rice production and associated CH_4 and N_2O emissions, a range of management regimes were evaluated, varying in flooding, tillage and fertilizer-use patterns. Aggregate MACCs in 2030 for livestock, cropland and rice were mapped to corresponding MAGNET sectors as described in Henderson *et al* (2019). We re-calibrate these MACCs through linear regressions (0 – 200 USD/t CO2-eq.) to eliminate no-regret mitigation at negative shadow prices and impose no technological mitigation at a zero shadow price. This allows us to address concerns of lack of information or behavioral constraints to adaption, yet leads to a systematic underrepresentation of technology effects at low but an overrepresentation of technology effects at high carbon prices.

2.2 Scenario construction and model-linkage

The two models are coupled iteratively through the exchange of key parameters. For the reference scenario until 2050, we draw on demographic and macroeconomic projections of the Shared Socioeconomic Pathways 2 (SSP2), the "middle of the road" scenario (IPCC 2021). Specifically, we employ population projections from the IIASA-WiC POP dataset, GDP (in bn. constant 2017 USD, PPP) projections from the OECD ENV-Growth dataset, both sourced from IIASA's SSP Scenario Explorer (IIASA 2025); and labour-force projections by occupation that are natively included in MAGNET. Based on these SSP2 assumptions, joint results are constructed via a soft-linkage exchange of key parameters: TiMBA provides projections for forest production that are used to overwrite endogenous forest production in MAGNET through sectoral productivity shocks on both factor and intermediate inputs. MAGNET provides data on land allocation across eight land-use categories. We applied an end-point linkage approach, whereby the trajectories of these key variables in both models are required to converge at the end of the simulation horizon, i.e., 2050. Inter-period variability over the period from 2020 to 2050 is not explicitly considered within this framework. Convergence in the iterative coupling procedure is assessed using predefined termination criteria, and model outputs are exchanged until these termination criteria are met (Delzeit *et al* 2020): the percentage point difference in forest production or forestland growth rates (2050-2020) between successive iterations (i.e., current versus previous run) must remain below 1 pp. at the global level and below 5 pps. at the regional level for more than 95% of the global aggregate. Consequently, deviations in small regions that exceed the 5 pps. threshold do not prevent convergence, provided the overall threshold (95% of the global total) is satisfied. Population projections are held constant throughout the coupling procedure.

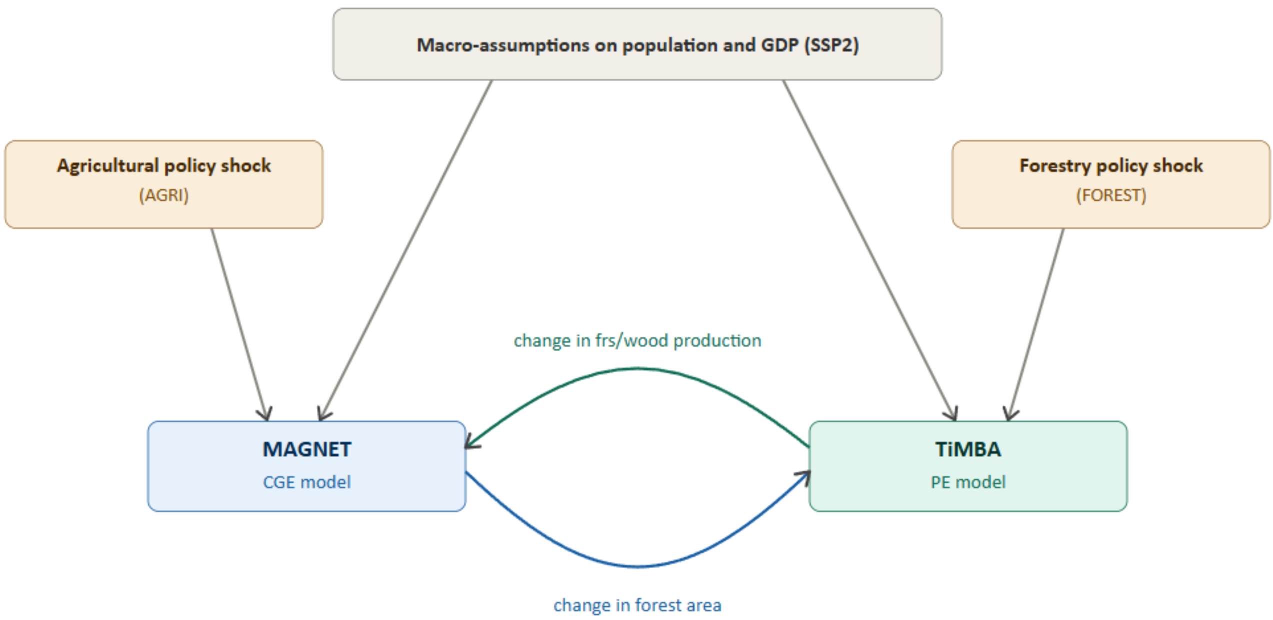

Figure 1: *Framework of MAGNET-TiMBA model linkage.*

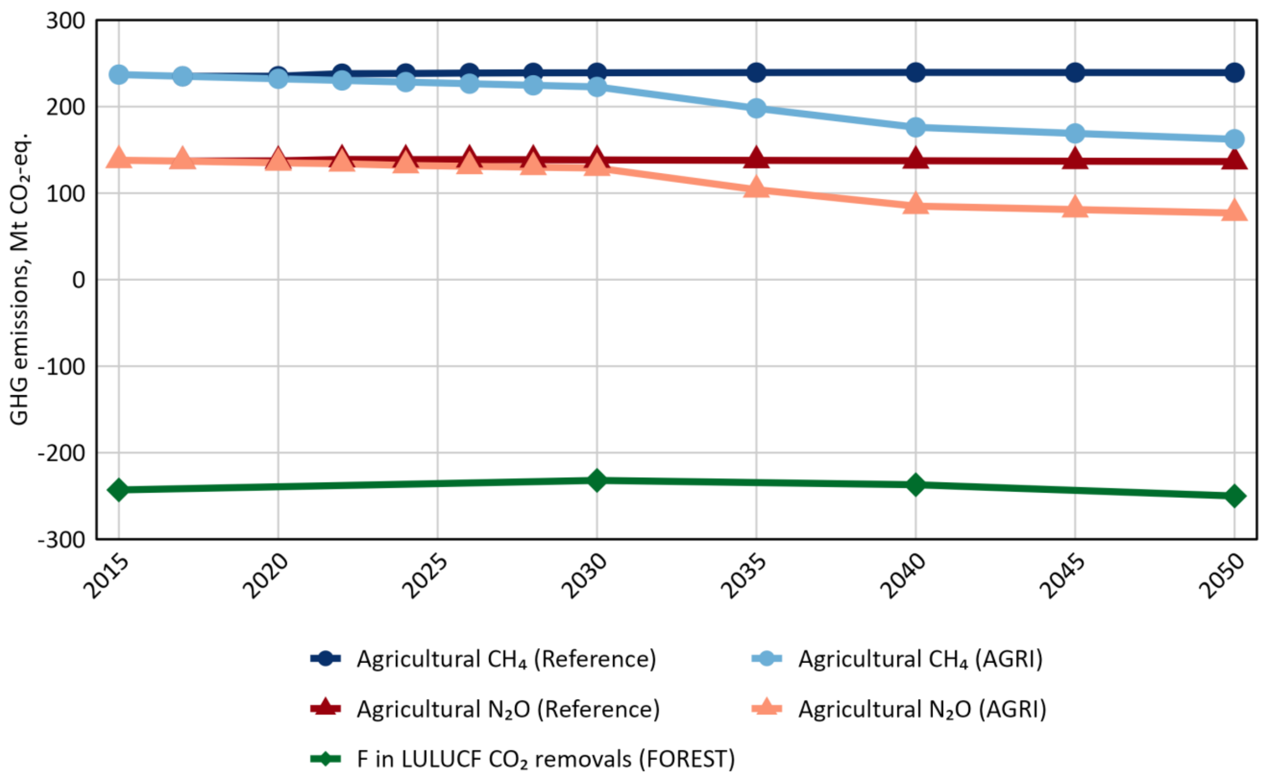

Figure 2: *GHG mitigation pathways. Own calculations using MAGNET (agricultural CH_4 & N_2O reference); European Commission 2024 (agricultural CH_4 & N_2O mitigation scenario AGRI). MAGNET reference emissions are scaled to match European Commission 2024 levels. Agricultural CH_4 and N_2O emissions are converted to CO_2-eq. using 100-year global warming potentials from IPCC AR5 (IPCC 2013). 'F in LULUCF' removals based on European Commission 2024 and assuming 75% contribution of the forestry subsector to overall LULUCF removals.*

Two policy scenarios are implemented relative to the coupled reference. In the 'FOREST' scenario, forestry provides 75% (Pilli et al. 2020) of the desired LULUCF emission reductions under the EU-LULUCF-regulation until 2030, and thereafter under the novel EC mitigation assumptions (S3) until 2050. This corresponds to forestry-specific net removal targets of -232 Mt CO_2 in 2030, -238 Mt CO_2 in 2040, and -250 CO_2 in 2050 (European Union 2023, European Commission 2024). The targets are implemented by introducing an implicit carbon price on forest biomass. The carbon price is calibrated iteratively so that each Member State achieves its required national emission reduction target. The approach rewards mitigation through additional carbon storage in forest biomass.

In MAGNET, for the 'AGRI' scenario, agricultural non-CO_2 GHG emissions follow mitigation pathways aligned to the same S3 scenario. These mitigation pathways prescribe a reduction in agricultural CH_4 emissions by 26% and 31.5%, and N_2O by 38% and 44.5% compared to 2015 levels by 2040 and 2050, respectively (European Commission 2024). We impose these targets to MAGNET's GHG accounting module and let two burden-sharing shadow prices on CH_4 and N_2O emissions, respectively, adjust endogenously. Without the adoption of mitigation technologies, reductions in combustion-emissions are realized via lower demand for intermediate fuel inputs. For non-combustion emissions, such as enteric fermentation in livestock farming, reductions transmit via lower sectoral output. In both cases, reductions in emission intensity due to technological mitigation set in as a linear function of the endogenous shadow prices. To capture the additional costs of technology adoption, MAGNET applies a Hicks-neutral total factor productivity shock to the top of the nested CES production function, requiring affected sectors to use additional factor inputs to produce the same level of output as before the shock. As a third policy scenario, we combine the separate 'FOREST' and 'AGRI' policies into a 'FOREST+AGRI (F+A)' scenario: The 'FOREST' policy is imposed in TiMBA, the 'AGRI' policy is imposed in MAGNET.

3 Results

3.1 Model convergence & implicit carbon prices

Model convergence is assessed using the termination criteria described in Section 2.2. For the reference scenario, we consider the linkage complete after five iterations. The global termination criterion is satisfied after two iterations. The regional termination criterion is satisfied by all but one region. 'ROW_WTO', consisting of small economies not included in other regional aggregations, could not be stabilized with our approach. Still, since 95% of the global aggregate in forest production and forestland development are considered converged, this deviation is accepted. The 'AGRI' scenario linkage is considered stabilized after six additional iterations after the reference coupling. Again, 'ROW_WTO' constitutes an outlier that exceeds our termination criteria.

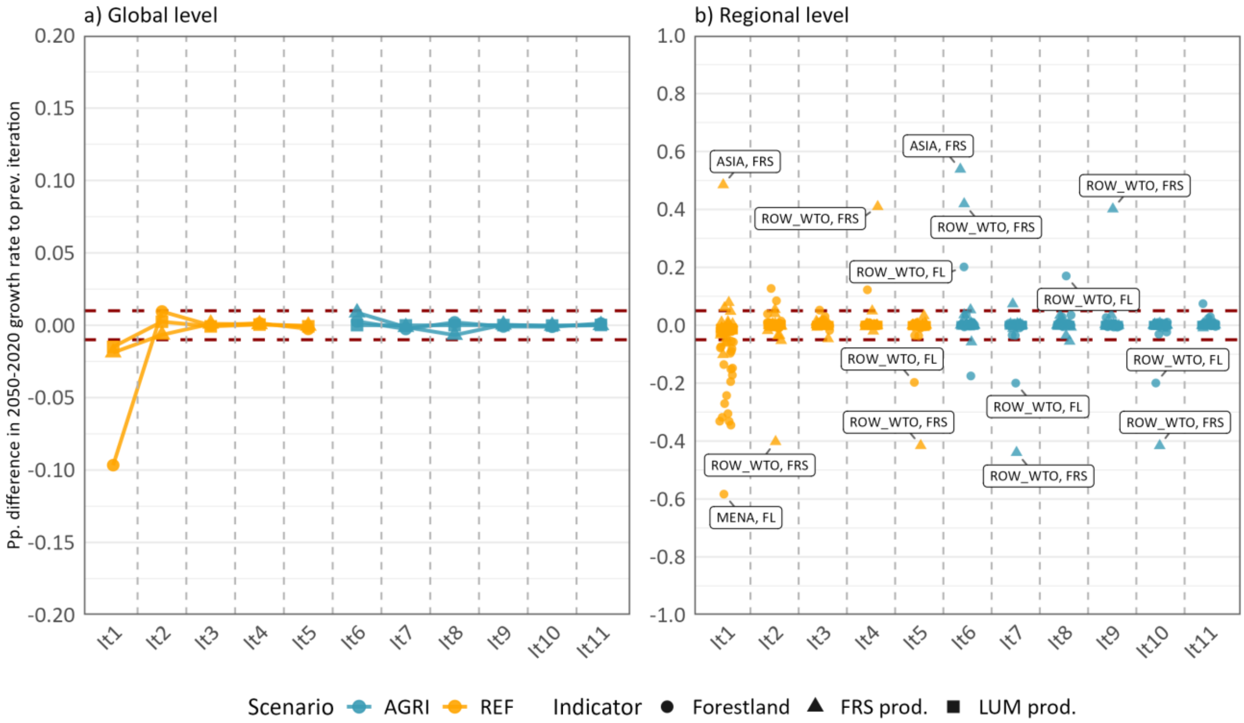

Figure 3: *(a) TiMBA-MAGNET model convergence over iterations at the global level. (b) TiMBA-MAGNET model convergence at the regional level. Authors' own calculations using TiMBA and MAGNET.*

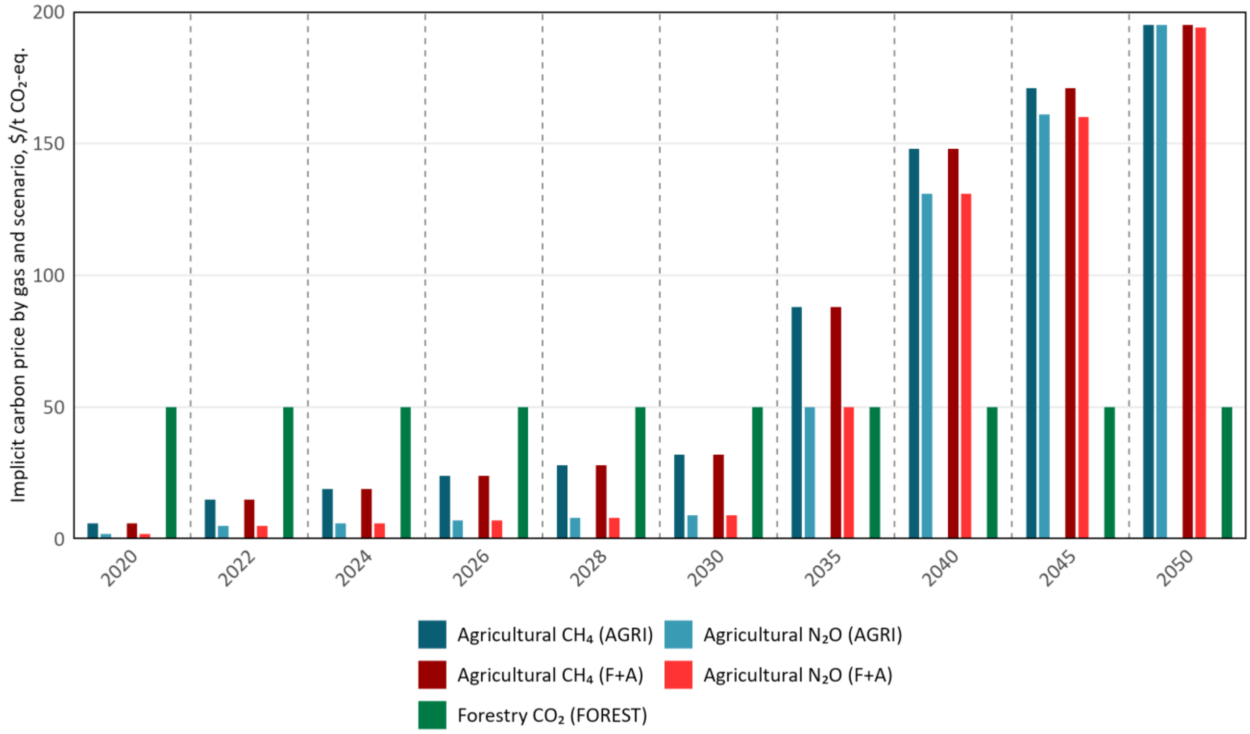

Figure 4: *Implicit carbon prices by gas and scenario over time. Based on authors' calculations using TiMBA and MAGNET.* **PRICES FOR TiMBA PLACEHOLDER ONLY**

All policies considered transmit through implicit carbon prices. In the 'AGRI' scenario, the endogenous shadow prices on agricultural CH_4 and N_2O emissions rise to 195 USD/t CO_2-eq. in 2050, respectively. In the combined 'FORESTRY+AGRI' scenario, the shadow prices in MAGNET on CH_4 and N_2O emissions are almost identical to the 'AGRI' scenario, indicating little impact of changed forestry production on agricultural production and GHG emissions.

3.2 Changes in production at the country and sectoral level.

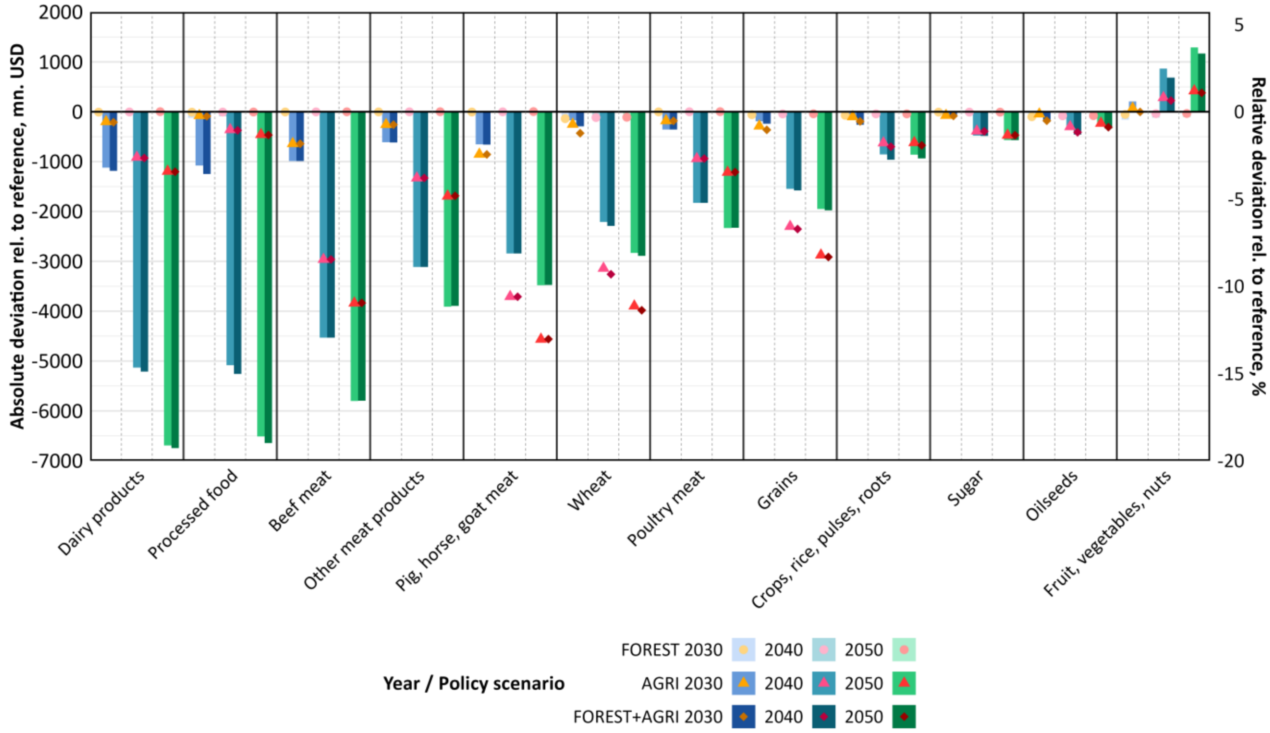

Figure 5: *Changes in EU production value by sector, scenario, and time. Based on authors' calculations using TiMBA and MAGNET. Absolute deviations to the reference scenario in mn. USD on the left y-axis, relative deviations in percent on the right y-axis.*

The increasing shadow prices on agricultural CH_4 and N_2O emissions induce reductions in EU agricultural production. The reductions are, in absolute terms, most pronounced in the dairy, downstream food processing, and meat sectors. In relative terms, sheep and goat meat as well as wheat and grains are affected most strongly. Due to the burden-sharing allocation of emission reductions within agricultural sectors and thus changing relative prices; the fruits, vegetables and nuts sector is able to expand its production. Policy effects are only relevant for the 'AGRI' and 'FOREST+AGRI' scenarios, for which they are almost identical. For the 'FOREST' scenario, agricultural production in the EU is virtually unchanged. All effects increase over time responding to increasing shadow prices.

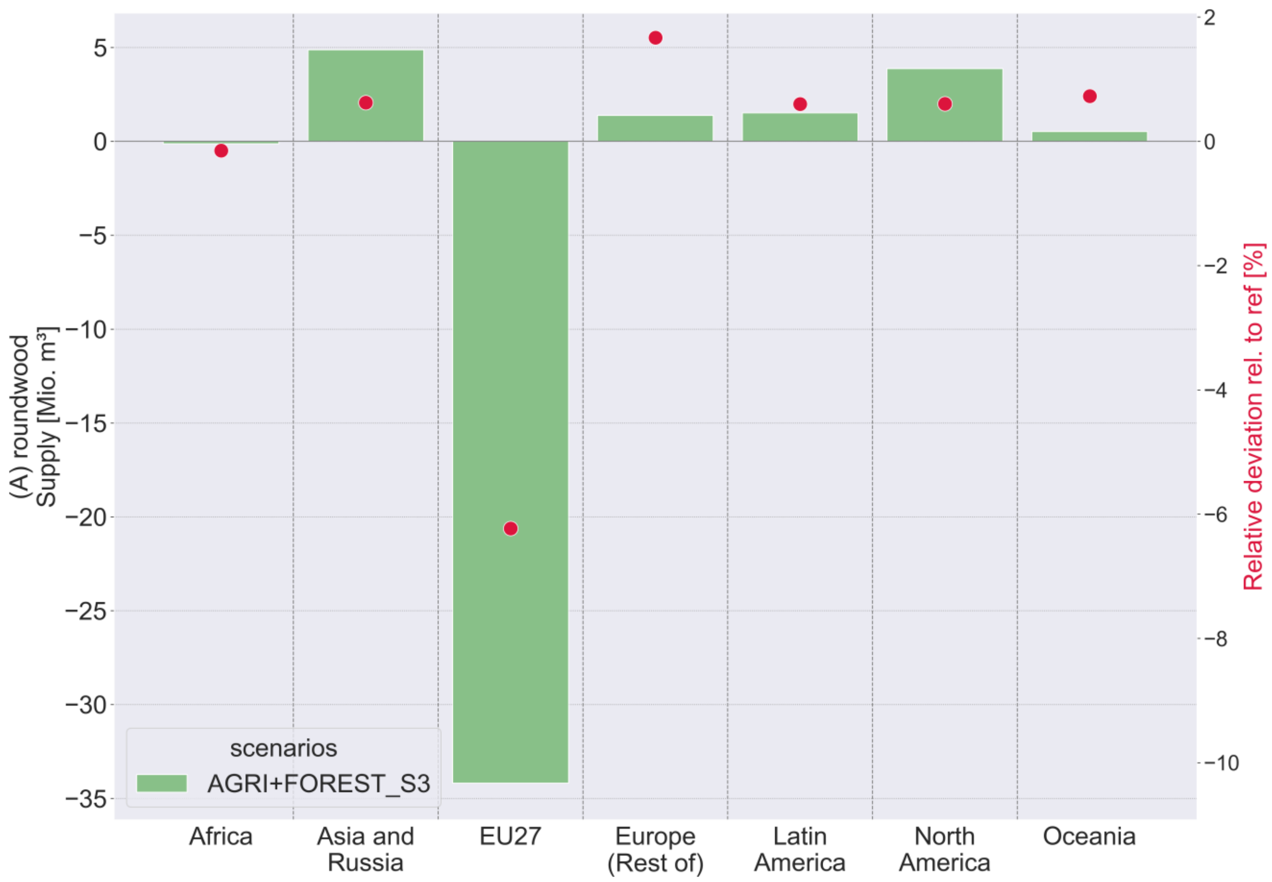

Figure 6: *Changes in production values for roundwood from TiMBA for 'FOREST+AGRI' scenario relative to reference.*

3.3 Changes in trade patterns.

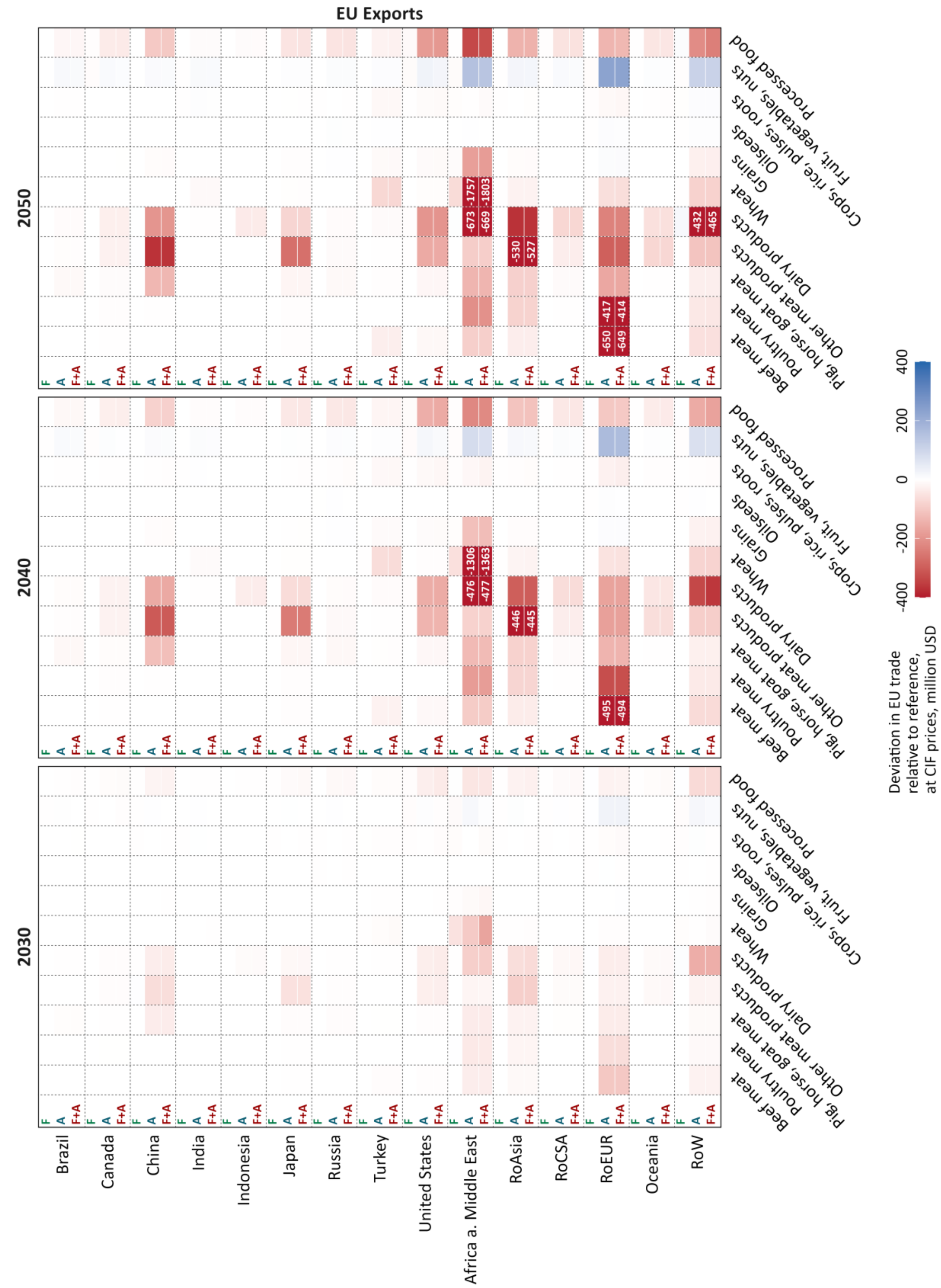

Figure 7: *Changes in EU agricultural exports by sector, scenario, and time. Own calculations using TiMBA and MAGNET. Cell values correspond to absolute deviations between reference and F (FOREST), A (AGRI), F+A*

(FOREST+AGRI) scenario calculations. The colour scale is capped at -400 to +400 mn. USD, which accommodates observations up to the 99th percentile. Outlier values beyond this scale are colored with the highest intensity and reported explicitly. Country aggregations are, in ISO 3166-1 alpha-3 coding: Africa a. Middle East (GTAP database countries in Africa and Middle East excl. IRN, IRQ, LBN, PSE, SYR); RoEUR (CHE, GBR, NOR, UKR); RoCSA (GTAP database countries in Central and South America excl. BRA, HTI); Oceania (NZL, AUS); RoAsia (AFG, BGD, BRN, HKG, KHM, KOR, LAO, LKA, MYS, NPL, PAK, PHL, SGP, THA, TWN, VNM); RoW (ALB, ARM, AZE, BLR, GEO, HTI, IRN, IRQ, KAZ, KGZ, LBN, MNG, PSE, SRB, SYR, TJK, UZB).

EU agricultural trade is affected by the 'AGRI' and 'FOREST+AGRI' scenarios, but remains largely unchanged relative to the reference in the 'FOREST' scenario. EU meat, dairy, and wheat exports decline the strongest, mostly to Africa and the Middle East, RoAsia, RoEUR, and China. The single most affected export flow are wheat exports to Africa and the Middle East, adding to potential global food security implications of unilateral agricultural GHG pricing found in previous studies (Fujimori *et al* 2022, Jansson *et al* 2024). While we observe higher imports from other regions to Africa and the Middle East, as well as higher domestic production of wheat and substitutes, we find a mild increase in food price and decrease in food consumption indicators compared to reference calculations. On the import side, the 'AGRI' and 'FOREST+AGRI' scenario result particularly in higher meat imports into the EU compared to the coupled reference. Beef meat is more strongly sourced from Brazil and RoCSA; sheep and goat meat from China and Oceania. All emerging patterns intensify over time, in line with the rising unilateral carbon prices.

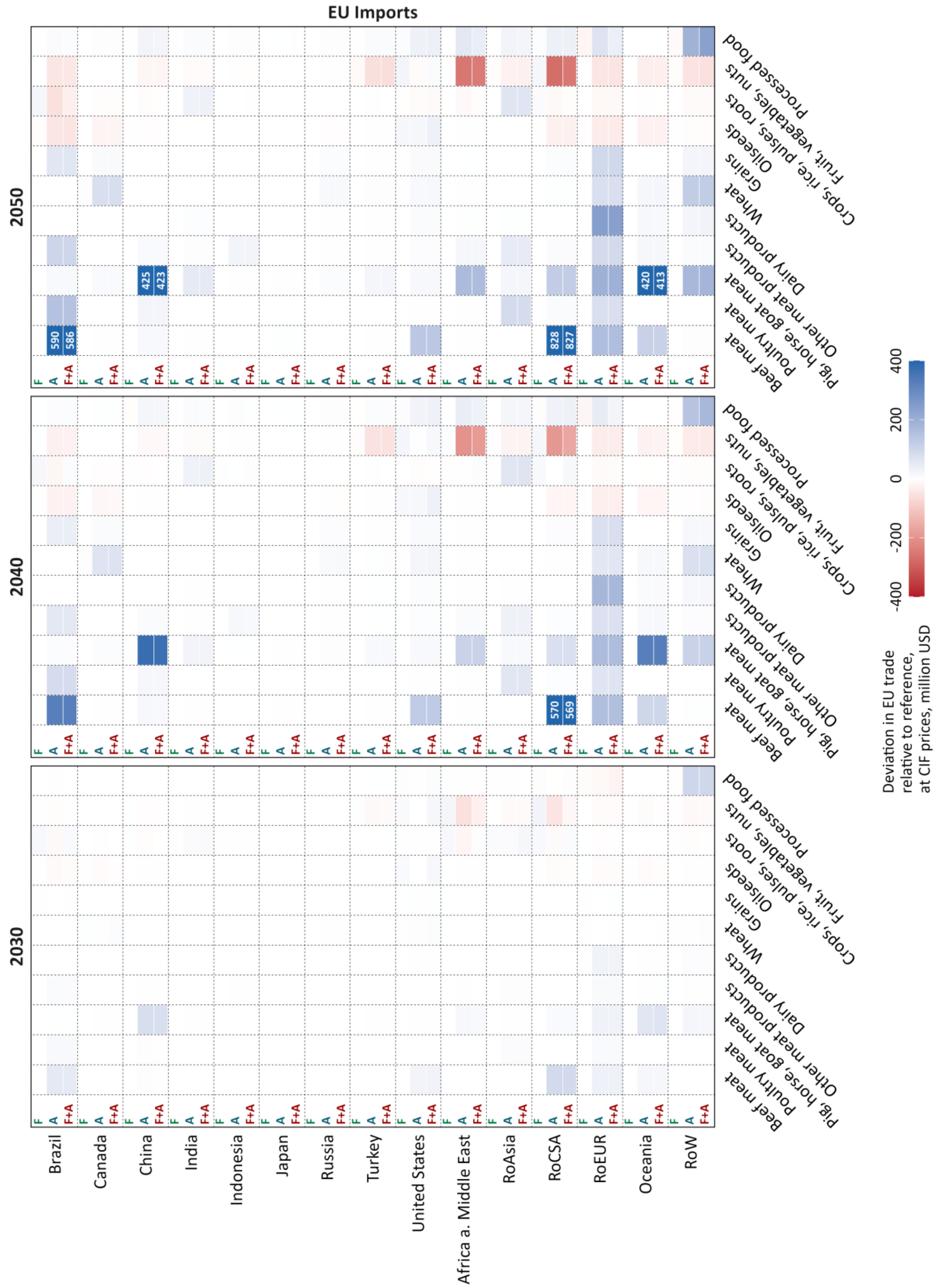

Figure 8: *Changes in EU agricultural imports by sector, scenario, and time. Own calculations using MAGNET. Cell values correspond to absolute deviations between reference and F (FOREST), A (AGRI), F+A (FOREST+AGRI) scenario calculations. Outlier highlighting and country aggregations as described in Figure 4.*

3.4 Changes in emissions at the country and sectoral level.

The 'AGRI' and 'FOREST+AGRI' scenarios realize the intended emission reductions in the EU. Domestic emission savings are however offset by x% carbon leakage. Emission increases are concentrated in major agricultural exporters such as India and Brazil, but also in Africa and the Middle East, due to the high emission intensity of increased local production. Our calculations indicate substantial emission increases in 'ROW_WTO'. Since this region showed strong variability within our model coupling procedure, and could not be contained within our model convergence criteria, we refrain from further interpretation of these results. The 'FOREST' scenario only minorly impacts agricultural GHG emissions, in line with the low EU production and trade effects observed. Some emission reductions are estimated for Africa and the Middle East in the 'FOREST' specification, inducing also a sizable difference between the 'AGRI' and 'FOREST+AGRI' emission effects for that region.

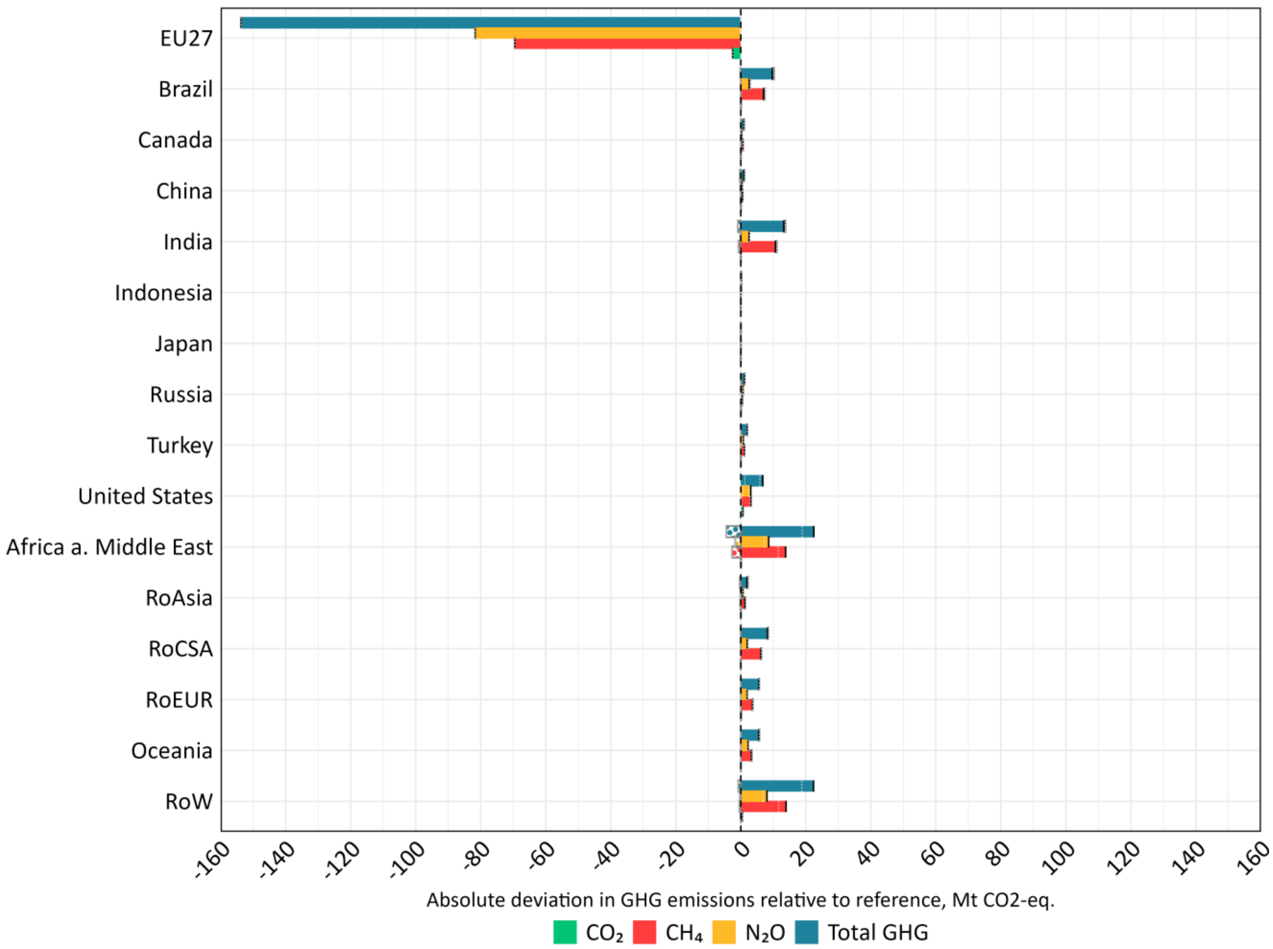

Figure 9: *Change in agricultural GHG emissions in 2050 in 'FOREST+AGRI' scenario rel. to reference by country and gas. Based on authors' calculations using MAGNET. White dashed lines or, in case of opposite treatment effects, dashed bars, indicate effect of 'AGRI' policy rel. to reference. White dotted lines or, in case of opposite treatment effect, dotted bars, indicate effect of 'FOREST' policy rel. to reference.*

Figure 10: *Change in forestry carbon stocks in 2050 in 'FOREST+AGRI' scenario rel. to reference by region.*

4 Discussion and conclusion

Discussion of results:

Our results largely align with previous research on carbon leakage in agriculture and forestry. The shadow prices on agricultural non-CO2 emissions in the 'AGRI' and 'FOREST+AGRI' scenarios induce production reductions in the EU, lower EU exports, higher EU imports, and agricultural GHG emission expansion outside the EU. The livestock sector is affected most strongly, in line with earlier model-based studies. We also find evidence that points to potential food security implications due to a decline in EU wheat exports to developing countries (Fujimori *et al* 2022, Jansson *et al* 2024).

Advantage of coupling framework:

Our approach is able to combine granular representation of agricultural and forestry markets, while allowing for cross-sectoral dynamics and global feedbacks. This reconciles the limitation of PE models, unable to capture cross-sectoral feedbacks and macroeconomic responses, with the limitation of CGE models, often lacking the precise representation of production systems and sub-products within sectors. This integration allows for a more consistent representation of macroeconomic dynamics and cross-sectoral interactions, although it does not fully eliminate structural and parametric uncertainties inherent in both modelling approaches.

Limitations

This study is subject to several limitations. First, the analysis relies on a scenario-based framework in combination with two different equilibrium models. As is common in this class of models, behavioral parameters are calibrated using historical data, and the product structure reflects current and past market conditions. The models do not endogenously capture structural transformations, technological disruptions, or idiosyncratic shocks that may emerge in the future. In addition, the quality of the input data constitutes a further source of uncertainty. Data used in global modelling exercises are often heterogeneous and subject to measurement errors, which can propagate through the modelling framework and affect the robustness of the results. Second, the results are inherently dependent on exogenous assumptions embedded in the scenarios, including projections of population growth, GDP development, and policy pathways. The plausibility and accuracy of these assumptions cannot be assessed ex ante, and alternative assumptions could lead to substantially different outcomes. This contributes to a broader uncertainty surrounding the results. Thirdly, we use simplifying assumptions that are likely to affect leakage implications. We assume that no climate policies are implemented outside the EU, that technological abatement measures are only implemented in the EU, and that no leakage-mitigating policies such as border adjustment mechanisms, are installed. Fourthly, the representation of technological abatement options in MAGNET is methodologically constrained. The raw data of US EPA (2013) only supplies static estimates for mitigation technology adoption for 2030, which disregards dynamic technology scale-up. Additionally, MAGNET's MACC implementation assumes a linear functional form, which deviates from similar studies that feature discrete MACC curves or from models that allow for endogenous technology adoption like CAPRI. Despite these limitations, our approach provides valuable insights into potential future developments in agricultural and wood product markets. By systematically exploring a range of plausible scenarios, the study contributes to a better understanding of key drivers and uncertainties, thereby supporting informed decision-making and evidence-based policy development.

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