Q Open, 2024, **5**, qoae015
https://doi.org/10.1093/qopen/qoae015
Advance access publication date: 12 June 2024
Article

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Border carbon adjustments in agri-food markets: Not as effective as one might think

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Received: February 16, 2024. **Accepted:** June 4, 2024

Abstract

Using the EU as case study, we simulate the impact of border carbon adjustments on agri-food markets. While border carbon adjustments alleviate adverse carbon price impacts on EU agricultural competitiveness and emission leakage, our simulation results also reveal that (i) border carbon adjustments may diminish domestic mitigation efforts, thereby partly offsetting benefits from reduced emission leakage, and (ii) trade diversion further undermines global emission reduction. The results indicate that border carbon adjustments on agri-food products in major exporting countries with emission-efficient production systems may not reduce global emissions as effectively as commonly assumed, highlighting the importance of emission efficiency improvements especially in developing and emerging countries.

Keywords: Border carbon adjustments, Agriculture, Climate policy, Competitiveness, Carbon tax.

JEL codes: Q17, Q18, Q54, Q56

1. Introduction

Implementing policies to reduce domestic greenhouse gas (GHG) emissions can lead to a reallocation of production to countries with less stringent or no mitigation targets, resulting in emission increases in these countries (i.e. emission leakage). From a global perspective, emission leakage undermines mitigation efforts (Perez Domínguez and Fellmann 2015) and may even result in a net increase in global emissions (Babiker 2005). Accordingly, unilateral climate policies may raise concerns of harming the local economy while at the same time not efficiently reducing global emissions (Elliott et al. 2010). These concerns about emission leakage and competitiveness can lead to special treatment or complete exemption

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of emission-intensive trade-exposed sectors from carbon pricing (Juergens, Barreiro-Hurle, and Vasa 2013). Although the Paris Agreement expands the commitment to combat climate change to almost all nations, individual signatories retain discretion regarding the stringency of their mitigation targets, specific mitigation policies employed, and the targeted sectors. Due to these varying domestic actions across countries, concerns about competitiveness losses and emission leakage persist.

One policy option that can be implemented to alleviate concerns about emission leakage and competitiveness is border carbon adjustments (BCAs). BCAs are intended to level the competitive landscape between producers in countries implementing carbon pricing (i.e. where governments implement a price on GHG emissions) and in non-carbon pricing countries. Particularly in times of disparate climate action, BCAs are gaining growing political traction (Mehling et al. 2018). For example, the EU initiated in October 2023 the transitional phase of a Carbon Border Adjustment Mechanism (CBAM). This BCA aims to impose a carbon price on the emissions generated during the production of certain carbon-intensive goods that are entering the EU and have a significant risk of carbon leakage (EC 2021; EU Regulation 2023/956). While the current CBAM excludes agriculture, the European Parliament's Committee on Agriculture called for assessing the possibilities to include agricultural products by 2030 (EP 2022), and also the representation of European farmers and agri-food cooperatives generally supports the idea of BCAs on agricultural products (Copa-Cogeca 2021).

The effectiveness of BCAs in reducing emission leakage has been assessed in several scientific papers. Reviewing 25 studies, Branger and Quirion (2014) conclude that BCAs can reduce leakage from 5 to 25 per cent to −5 to 15 per cent. Furthermore, the extent of leakage reduction correlates with the size of the coalition implementing carbon pricing and the sectors covered. Böhringer, Carbone, and Rutherford (2018) show that BCA covering the full carbon content of imported goods is effective in reducing carbon leakage resulting from unilateral OECD policies. However, the literature also reports cases where BCAs are not effective, as for example Fouré, Guimbard, and Monjon (2016) found that BCA applied to energy-intensive imports has negligible impacts on EU competitiveness and only minimal effects on global emissions.

The literature mainly tends to support the potential of BCAs to moderate the negative consequences of unilateral climate policy, but is focused on industrial sectors. There is a notable gap in assessing the performance of BCAs in the agricultural sector. Given that agriculture's non-CO_2 GHG emissions cause about 10–12 per cent of global GHG emissions (Smith et al. 2014), and the susceptibility of agri-food products to trade dynamics, examining the potential impacts of BCAs in this sector seems important. Moreover, the agricultural sector holds a largely unused potential to reduce GHG emissions, and its contribution is considered essential to limit the temperature increase to below 2°C (Rogelj et al. 2018a; Nabuurs et al. 2022).

Against this background, we assess the potential impacts of a BCA on GHG emission mitigation, emission leakage, and competitiveness. We conduct simulations to evaluate the pricing of domestic non-CO_2 GHG emissions solely within the EU agricultural sector and in combination with BCAs implemented as regionally differentiated carbon tariffs.

2. Border carbon adjustments

BCA measures are based on the quantification of GHG emissions associated with the production of a good, and they are typically implemented through import tariffs, export rebates, obligations for importers to surrender domestic carbon allowances, or a combination thereof (Kuik and Hofkes 2010). The practical implementation of BCAs requires addressing three key considerations:

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1. Compliance with World Trade Organization (WTO) regulations and implementation feasibility.
2. Definition of the adjustment base for carbon content and calculation rules for related indicators (such as determining the carbon content of goods).
3. Specification of policy parameters for BCA measures (e.g. import tariff rates).

As BCA policies affect trade dynamics, they may be challenged under the WTO principle of treating imported and domestically produced goods equally. However, under the WTO's national treatment principle (GATT Article III), BCAs can be permissible if they aim to ensure trade neutrality in national taxation. Additionally, BCAs may be justified on environmental grounds (GATT Article XX) (Di Leva and Xiaoxin 2017; Mehling et al. 2017; Odell 2018). In ensuring adherence to WTO regulations, the selection and specific design of BCA measures become crucial. Export rebates, for example, may be challenged as a form of export subsidy, and their WTO compatibility significantly depends on the overall policy design (Fischer and Fox 2012; Holzer 2014; Böhringer et al. 2022). Conversely, BCAs designed around import tariffs are generally considered more WTO-compliant, particularly when they result in similar treatment of domestic and imported goods. Furthermore, several studies found that import tariff-based BCAs potentially outperform output-based rebating in terms of emission abatement and leakage prevention (Monjon and Quirion 2011; Fischer and Fox 2012; Böhringer, Fischer, and Rosendahl 2014; Ward et al. 2015; Böhringer et al. 2022). Given these considerations, we do not further explore export rebates in the subsequent analysis.

Determining the carbon content of goods and related indicator calculation can be based on three approaches: (i) actual emissions, (ii) product-specific benchmarks based on best available technology (BAT), or (iii) product-specific average emission levels. In practice, BCAs based on actual emissions imply high transaction costs due to information requirements, and WTO compatibility issues (Holzer 2014; Fouré, Guimbard, and Monjon 2016; Böhringer et al. 2022). BAT approaches, using product-specific benchmarks, may align with WTO rules (Ismer and Neuhoff 2007), but their practicability and effectiveness in reducing carbon leakage are debatable (Sakai and Barrett 2016). Alternatively, product-specific benchmarks based on average emission levels from the importing or exporting region can be considered. While the former adheres to the WTO's national treatment principle, the latter benefits exporters from countries with emission-efficient production, which is justifiable under WTO rules on environmental grounds.

Once the carbon content is determined, BCAs entail either imposing tariffs on imports based on the carbon content of the products (tariff-based system) or obligating importers to surrender domestic carbon allowances equivalent to the imported goods' carbon content (allowance-based system). To adhere to the national treatment principle (i.e. the similar treatment of domestic and imported goods), the choice between the two systems seems to depend mostly on the specific domestic GHG mitigation policies. Accordingly, an allowance-based system aligns more with cap-and-trade measures, whereas a tariff-based system better suits national carbon taxes (Monjon and Quirion 2011). Given the complexity of implementing a cap-and trade policy in the EU's highly fragmented agricultural sector with many small farms, a tariff-based BCA system seems more feasible and practical in the context of our analysis.

Aligned with these considerations, our assessment focuses on scenarios where we apply a carbon tax on agricultural non-CO_2 emissions on EU domestic agricultural products, and a comparable BCA in form of import tariffs determined by product and region-specific average emission levels, contingent upon the origin of the imports.

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3. Methodological framework

For the policy simulations we use the CAPRI (Common Agricultural Policy Regional Impact Analysis) modelling system (Britz and Witzke 2014). CAPRI is a global, economic, comparative-static, partial equilibrium model for agriculture and primary processing sectors. CAPRI comprises two interconnected modules, integrating a set of regional mathematical programming models of EU agricultural supply with a spatial multicommodity model for global agri-food markets (Jansson and Heckelei 2011). Changes in bilateral trade flows and attached prices are modelled based on the Armington assumption (i.e. imports are differentiated by place of origin). Bilateral import prices consider trade policy measures at the border, such as tariffs, tariff rate quotas, and variable levies. The behavioural functions for supply, feed, processing, and human consumption in the market model represent supply and demand for primary agricultural and processed commodities (Britz and Witzke 2014; M'barek et al. 2017). CAPRI is frequently used for ex-ante impact assessment of agricultural, environmental, and trade policy options, including the analysis of climate change mitigation policies in the agricultural sector in the EU (Fellmann et al. 2018; Jansson and Säll 2018; Himics, Fellmann, and Barreiro-Hurle 2020; Stepanyan et al. 2023) and at global level (Hasegawa et al. 2018; van Meijl et al. 2018; Frank et al. 2019).

The CAPRI model endogenously calculates agricultural non-CO_2 GHG emissions (methane and nitrous oxide) directly related to the United Nations Framework Convention on Climate Change (UNFCCC) common reporting category 'agriculture'; CO_2 emissions and removals of other categories (e.g. land use, land use change, and forestry), are not included in the model version used for this paper. For the EU, the calculation of non-CO_2 emissions is based on the input and output of production activities mostly following a Tier 2 approach from the IPCC guidelines (IPCC 2006). GHG emissions for the rest of the world are calculated on a commodity basis (i.e. per tonne of each product and type of GHG) for each non-EU region and emission category individually (Domínguez et al. 2016; Himics et al. 2018; Jansson and Säll 2018; Jansson et al. 2021). For more information on the model and how it captures GHG emissions see the supplementary material.

4. Scenario assumptions

The analysis covers two main policy scenarios that are compared to a business-as-usual reference scenario. In the first policy scenario, we implement a carbon tax on agricultural commodities produced within the EU, based on their non-CO_2 GHG emission intensity (CO_2 equivalent [CO_2e] emissions per kg/product).[1] The focus on non-CO_2 is warranted by the focus on agriculture, where most emissions are methane and nitrous oxide, whereas CO_2 emissions are typically attributed to—and in the case of fossil fuel use often taxed—in other sectors. In the second policy scenario, BCA tariffs are added in addition to the EU carbon tax, based on the average emission intensity in the country of origin. We selected the combination of an EU carbon tax and a BCA tariff based on the considerations of WTO conformity (see Section 2). It needs to be mentioned that while the agricultural sector is included in the EU's Effort Sharing Regulation, which establishes national targets for GHG emission reduction by 2030 for each member state, there are currently no carbon pricing mechanisms in place for agricultural emissions or products within the EU. Denmark, however, is taking pioneering steps towards implementing carbon pricing in agriculture, as the first country in the EU to do so, although the details of the implementation are not yet decided (Danish Council on Climate Change 2023).

The target year for all scenarios is 2030, with the major scenario assumptions outlined as follows:

– *Reference scenario (REF):* This scenario considers agricultural, environmental, and trade policies as ratified by 2016, and is calibrated to the European Commission's

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Table 1. Scenario details.

Scenario	Emission intensity considered for the EU carbon tax	Emission intensity considered for the BCA (non-EU)	Carbon price (EUR/t CO_2e)
REF	None	None	0
Tax	MS specific[a]	None	120
Tax & Tariff	MS specific[a]	Exporting region specific[b]	120

Notes: All tax and tariff rates are computed per commodity based on non-CO_2 GHG emission intensities in the reference scenario.
[a]Carbon tax rate based on average non-CO_2 GHG emission intensity for each EU member state (MS).
[b]Carbon tariff rate based on non-CO_2 GHG emission intensity for each region in the world exporting to the EU.

outlook for agricultural markets and income, which itself is based on the OECD-FAO agricultural market outlook. Both outlooks rely on data from OECD and FAO databases, supplemented by additional data and analysis from country experts and national administrations. These outlooks provide medium-term projections in a consistent international framework, underpinned by exogenous assumptions on macroeconomic developments (GDP growth, exchange rates, world oil prices, and population growth).

- *Tax scenario:* Building upon the REF scenario, this scenario introduces a carbon tax of 120[2] EUR/t CO_2e on all EU agricultural commodities. The tax is levied based on actual average agricultural emission intensities per product, differentiated by the EU member state, and is applied at farm gate (i.e. it also encompasses tradable feed, such as feed cereals).[3]
- *Tax & Tariff scenario:* This scenario, layered atop the Tax scenario, integrates a BCA in the form of a carbon-based import tariff, using the EU carbon tax as CO_2e price, applied to country or region[4] and commodity-specific agricultural emission intensity, which include emissions from tradeable feed. The BCA tariff is applied to both primary products and processed goods[5] to encompass all trade activities, and it is implemented in addition to existing tariffs (as of 2016) in a two-step procedure: first, a reference scenario is simulated without any shock to the model, and the ad-valorem equivalent of all tariffs, global and bilateral tariff rate quotas, minimum border prices and trigger prices combined is computed for each commodity imported to the EU from each trading partner. Then, the existing tariff structure of the EU is replaced by two measures: one ad-valorem tariff equivalent to the computed ad-valorem equivalent in the reference scenario, and one specific tariff calculated as the carbon tax rate of the EU multiplied by the emission intensity in the country of origin of each imported commodity.[6]

The carbon taxes and tariffs are determined based on product-specific average emission levels per region of origin. In general, the most emission intensive products are those from ruminant animals (beef, sheep and goat meat, and dairy), whereas, for example, crops have much lower emission intensities. Consequently, higher taxes are levied on ruminant meat relative to crops. Table 1 provides an overview on the scenarios and their key mitigation policy assumptions, while Table 2 presents the resulting taxes and tariffs for the EU in 2030 for key products.

5. Results

In the following we focus on key results with respect to EU and global agricultural non-CO_2 emissions and explore the changes in production, prices, and trade patterns driving

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Table 2. Average EU taxes and non-EU BCA tariffs for selected products (EUR/t).

	Cereals	Beef	Dairy	Pork	Poultry	SGMT
EU tax	21	2,277	153	255	79	2,449
BCA	12	4,359	639	479	175	4,226

Notes: All amounts in nominal value for 2030. SGMT = sheep and goat meat. Dairy means 'raw milk' for the tax, and the weighted average of all dairy products for the BCA. BCA values are weighed averages for imports to the EU from all non-EU origins.

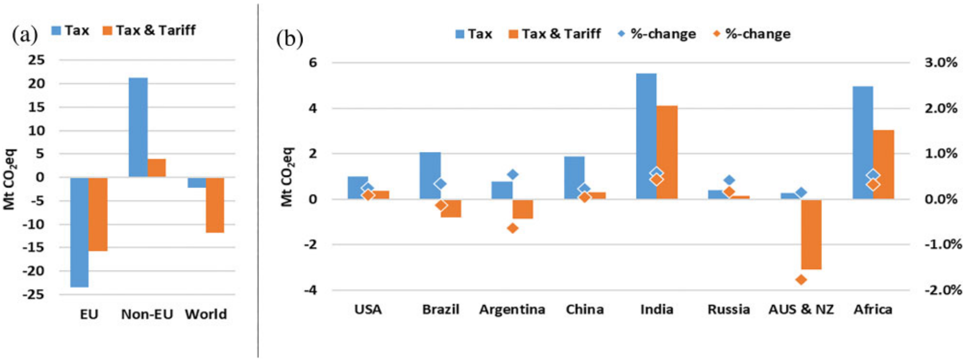

Figure 1. Change in agricultural non-CO_2 GHG emissions compared to the reference scenario by 2030.
Notes: AUS & NZ = Australia and New Zealand.

the emission dynamics. Unless explicitly stated otherwise, all scenario results are compared to the reference scenario in 2030.

In the Tax scenario, EU agricultural non-CO_2 emissions decrease by 5.7 per cent, i.e. 23.4 million tonnes (Mt) CO_2e (Fig. 1a). However, the effectiveness of this mitigation effort is low, as emission increases in non-EU countries (21.2 Mt, +0.4 per cent) almost offset the EU decrease (resulting in a leakage rate of 91 per cent).[7] Globally, agricultural emissions decline by 2.2 Mt CO_2e, corresponding to a net mitigation of 0.5 per cent in the EU. In the Tax & Tariff scenario, the emission increase in non-EU countries is reduced to 4 Mt (+0.1 per cent). However, EU domestic abatement is also considerably lower compared to the Tax scenario, amounting to 15.8 Mt CO_2e (−3.9 per cent). Consequently, the introduction of BCAs limits emission leakage to 25 per cent of the EU's emission decrease, resulting in a total global net mitigation of 11.8 Mt CO_2e, corresponding to an effective 2.9 per cent decrease in EU emissions. Fig. 1b illustrates emission changes for the most affected non-EU countries and regions.[8] While none of these countries experience agricultural emission increases surpassing 0.6 per cent, absolute increases can be substantial, in the Tax scenario particularly in India (+5.5 Mt CO_2e), the African continent (+5 Mt), Brazil (+2.1 Mt), and China (+1.9 Mt). In the Tax & Tariff scenario, the increase in emissions across non-EU countries is generally lower than in the Tax scenario, with several countries and regions (e.g. Brazil, Argentina, Australia and New Zealand [AUS & NZ]) showing emission decreases compared to the reference scenario.

Emission changes in both scenarios are the result of the interplay between changes in production, prices, and trade flows, alongside disparities in emission intensities across products and regions. Understanding the impact of the domestic EU emission tax is essential in comprehending developments in both scenarios. Therefore, we first present and analyse the changes in the Tax scenario in detail.

Fig. 2 presents changes in (a) emissions and (b) production across agricultural product groups in the EU and non-EU regions. In the EU, about half of the emission reduction in both

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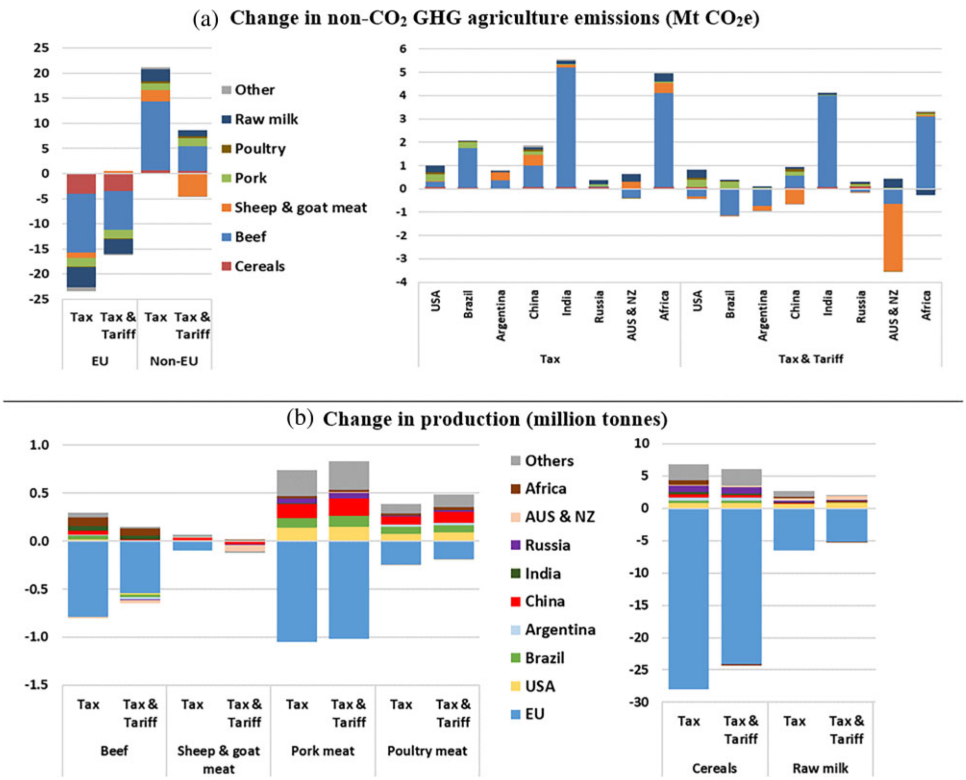

Figure 2. Changes in emissions and production by sector and region compared to REF by 2030.
Notes: Beef in India refers to water buffalo meat; AUS & NZ = Australia and New Zealand.

scenarios is due to a decline in beef production. Specifically, in the Tax scenario, emissions related to the EU beef sector decrease by 11.7 Mt CO_2e (−9.3 per cent), followed by raw milk (−3.9 Mt CO_2e; −2.6 per cent), cereals (−3.9 Mt CO_2e; −9.8 per cent), pork meat (1.8 Mt CO_2e; −4.3 per cent), and sheep and goat meat (−1.1 Mt CO_2e; −7.7 per cent). The production and related emission decreases in the EU are primarily a direct consequence of imposing the domestic carbon tax, while secondary effects arise from reduced demand for feed crops. In general, the tax affects EU competitiveness, inducing production decreases as long as the tax burden exceeds the profit margins of the production activity.

The substantial decline in emissions within the EU beef, sheep, and goat meat sectors can be attributed to their high emission intensities and comparatively narrow profit margins, which, compounded by the increased cost from the tax, lead to significant relative production decreases. Despite a relatively high emission intensity associated with raw milk production, profit margins in several EU member states remain favourable compared to ruminant meats. This economic disparity explains the comparatively smaller production and emission declines in the dairy sector. Conversely, pork and poultry production, characterised by lower emission intensities, are less impacted by the carbon tax, translating to smaller relative reductions in both production and emissions. The substantial reduction in EU cereal emissions is a combination of the effect of lower feed demand from the livestock sector and, to a lesser extent, the direct tax impact on cereal production itself.

Following the production changes in the EU, the increase in emissions outside the EU is mostly due to increases in beef production and the related emissions, accounting for 65 per cent (13.7 Mt CO_2e) of the total non-EU emissions increase in the Tax scenario. Emissions

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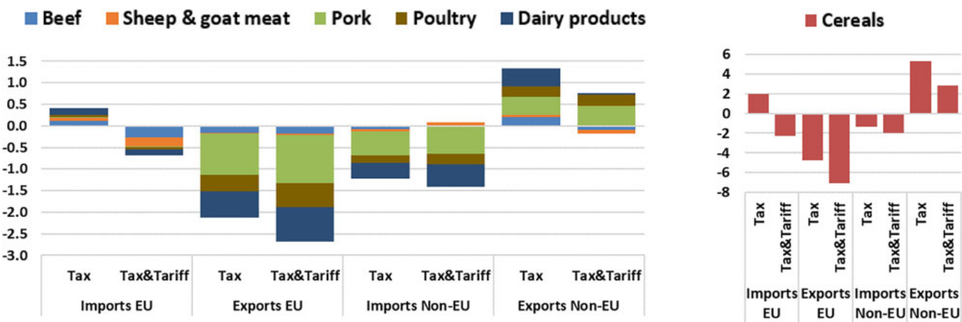

Figure 3. Change in trade compared to the reference scenario by 2030 (million tonnes).

related to raw milk production follow with an increase of 2.4 Mt CO_2e, and sheep and goat meat with 2.2 Mt CO_2e. While the overall emission increase in non-EU regions almost equals the total EU emissions decline, the production increases outside the EU do not come close to compensate the respective production declines in the EU (with the exception of poultry meat) (Fig. 2b). This disparity primarily arises from differences in emission intensities between regions, with EU production being relatively emission-efficient compared to most non-EU production.

The discrepancy in emissions per product between the EU and non-EU is most pronounced for beef, where the non-EU production increase compensates only 35 per cent of the EU production decline, yet the associated rise in non-EU emissions by 117 per cent surpasses the EU emissions decline. Most of the beef-related emission increase comes from India, Africa, and Brazil. While India's prominence in this context may appear surprising initially, it underscores the intricate interplay between emission intensities, production dynamics, and trade patterns. India's beef exports exclusively consist of water buffalo meat as the slaughter and export of cow meat is prohibited.[9] India is the world's second largest beef (buffalo) exporter after Brazil (OECD-FAO 2019), and remains in this position in 2030 under the REF scenario. In the Tax scenario, the contraction in EU beef production leads to changes in trade flows, since the EU worsens its net trade position by both increasing imports and decreasing exports (Fig. 3). This prompts India to increase exports not to the EU but to some countries that import less either from the EU or from countries redirecting exports to the EU. The resultant production increase, coupled with India's high beef emission intensities (more than three times higher compared to the EU), drives the substantial emission increase. African countries in the African, Caribbean and Pacific (ACP) group of states expand beef exports to the EU due to increased EU prices and preferential trade access, achieved by both increasing production and rerouting exports. Mercosur countries expand beef production to increase exports to the EU (particularly Brazil) and non-EU markets, while China increases production for its own use to (partially) compensate for diminished beef availability on the world market. Conversely, beef emissions in AUS & NZ decline following reduced production in favour of the also mostly grass-based milk and sheep meat production. Despite AUS & NZ augmenting sheep meat exports to the EU, its increased dairy exports partly compensate other countries for declining EU exports. As a consequence of reduced availability on the world market, China and Africa also show increases in milk, sheep, and goat meat production and emissions. Although the quantities involved in production and export changes in non-EU countries are rather modest, their emission ramifications are significant due to generally higher emission intensities compared to the EU. The surge in non-EU pork meat production and emissions are a direct consequence of diminished EU exports. The production of poultry, the least costly meat, increases in non-EU countries mainly to compensate

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for lower availability and higher prices of other meats on the global market. However, due to their low emission intensities, the associated emission increases are limited.

In the Tax & Tariff scenario, the introduction of BCAs makes it more expensive for non-EU countries to export to the EU, triggering a dual effect: (i) within the EU domestic market, EU production gains competitiveness, resulting in substantial reductions in imports and exports—as domestic prices increase, the declines in EU production lessen, resulting in lower emission reductions compared to the Tax scenario; (ii) for non-EU countries, exporting to the EU becomes less attractive, resulting in diminished exports to the EU, trade diversion, and subsequently lower production and emission increases. These overarching effects manifest across all sectors. Concerning emission leakage, the effect of reduced EU imports exceeds the reduction in EU exports (i.e. while trade diversion still occurs to compensate for fewer EU exports, the resultant increases in non-EU emissions are smaller than in the Tax scenario).

As most non-EU countries reduce especially beef exports to the EU, their total emissions decrease even compared to the reference scenario (e.g. Brazil and Argentina). With the BCA, EU beef imports decrease by 89 per cent, a strong contrast to the 41 per cent increase in the Tax scenario. The reduction in EU beef imports translates to considerably smaller increases in beef-related emissions in non-EU countries compared to the Tax scenario. However, as some countries step in to fill the export gaps vacated by the EU, coupled with the aforementioned differing emission intensities, the overall rise in non-EU emissions is still dominated by relatively modest beef production increases in India (due to exports) and Africa (for domestic consumption). Consequently, the net effect is an increase of 4.9 Mt CO_2e in non-EU beef emissions compared to REF. Notably, increased pork and milk production emerge as the second and third largest contributors to rising non-EU emissions, which in both sectors is a direct consequence of decreased EU exports. AUS & NZ, the major exporter of sheep meat to the EU in the reference scenario, almost completely stop these exports to the EU with the BCA. Although exports are partly diverted to other countries (mainly China, which subsequently decreases its own production and emissions), total AUS & NZ sheep meat exports and net production decrease, almost entirely constituting the drop in total AUS & NZ emissions. Conversely, with imports plummeting by 97 per cent and substantial price increases, sheep and goat meat is the only sector where EU production and emissions experience a slight increase compared to REF.

The differences in production and trade effects between the Tax and the Tax & Tariff scenarios are driven by and manifested in price changes (Fig. S1a). The drop in domestic production leads to higher EU producer and consumer prices across all agricultural commodities in both scenarios. EU producer price increases generally correlate with emission intensities and production declines due to taxes. In the case of milk, the price increase offsets the production impact of the tax more than for the other commodities, resulting in lower production decreases. Non-EU producer prices increase only moderately (around 1 per cent), and are highest for beef, pork, and dairy products, which for the latter two reflects the EU's substantial exports of these commodities. As imports decrease due to the BCA, EU producer prices increase further in the Tax & Tariff scenario, resulting in diminished EU production decreases compared to the Tax scenario. Conversely, reduced EU imports lead to lower producer price increases in non-EU countries compared to the Tax scenario, but most prices are higher than in the reference scenario as EU exports are still lower due to the tax. Consumer price changes show similar absolute magnitudes, but relative changes are much lower due to high consumer margins (assumed constant).

Consumption decreases are limited (Fig. S1b), with dairy products experiencing the highest absolute decline in the EU (−1.8 kg/capita and year; −1.6 per cent) and beef experiencing the greatest relative decline (−0.8 kg; −6 per cent), with poultry partially serving as substitute for beef (+0.3 kg; +1.3 per cent). With the BCA, EU consumption further declines for beef (−1 kg; −7.6 per cent) and, in relative terms, most for sheep and goat meat

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Table 3. Scenario assumptions for emission intensities and carbon prices in the sensitivity analysis.

Scenario code	Emission intensities compared to original REF		Emissions to which carbon price is applied (120 EUR/t CO_2e)		
	EU	non-EU	REF	Tax	Tax & Tariff
SA1	−20%	−20%	None	EU	EU and non-EU
SA2	−20%	Reduction to equal the EU emission intensities of original REF			
SA3	No change				

Notes: All tax rates computed per commodity based on non-CO_2 GHG emission intensities as defined in the left column.

(−0.3 kg; −15.7 per cent), partially substituted by the cheaper poultry (+0.5 kg; +2.4 per cent) and pork (+0.2 kg; +0.7 per cent). The impacts on non-EU consumption are small; decreased EU exports lead to slight declines in non-EU per capita consumption of cereals (−0.06 kg/capita and year), pork, and dairy products (each −0.03 kg) in the Tax scenario. Conversely, in the Tax & Tariff scenario, the reduction in EU imports has a small positive effect on non-EU per capita beef consumption (0.01 kg; +0.15 per cent), whereas dairy and cereal consumption decrease less, but the lower EU exports of pork lead to consumption decreases comparable to those in in the Tax scenario. Poultry meat consumption in non-EU is virtually unaffected by these policies.

6. Sensitivity analysis

The main results highlight the significance of emission efficiency and, hence, the emission intensities of products in shaping the emissions developments within the scenarios. While our projections suggest a continued improvement trend in EU and non-EU emission intensities until 2030, it is important to acknowledge that the announcement and implementation of mitigation policies can incentivise farmers to further enhance the GHG efficiency of their production. This enhancement can be achieved, for example, through the adoption of technical and management-based mitigation options (Fellmann et al. 2018; Frank et al. 2019). Moreover, the policy implementation could also stimulate accelerated technological advancements in mitigation technologies.

To assess the potential impacts that technological development and adoption could have on the effectiveness of BCAs, we conduct a sensitivity analysis using alternative emission intensities for EU and non-EU countries. Combining different assumptions on improved emission intensities, we analyse three sets of alternative scenarios (see Table 3). SA1 assumes a 20 per cent reduction in emission intensities for both EU and non-EU production by 2030 compared to the reference and policy scenarios. The 20 per cent rate was chosen as this represents a significant change, but still does not assume all possible options that, for example, the adoption of a wide range of technological (i.e. technical and management-based) GHG mitigation options could achieve (see, for example, Himics, Fellmann, and Barreiro-Hurle 2020; Fellmann et al. 2021; Rosa and Gabrielli 2023). SA2 assumes that all non-EU countries would reach at least the average emission intensity of the EU in the original reference scenario, unless they are already lower than in the EU, while the EU would further improve its emission intensities by 20 per cent. SA3 explores the effects of non-EU countries improving emission intensity levels to at least equal to EU emission intensities in REF (as in SA2), with no additional improvements in the EU (as in the main scenarios).

Fig. 4a illustrates the impact of the altered emission intensities on reference emissions in the sensitivity scenarios compared to the original reference scenario. While the reduction in non-EU emissions in SA2 and SA3 is extreme, and although it is unlikely that all

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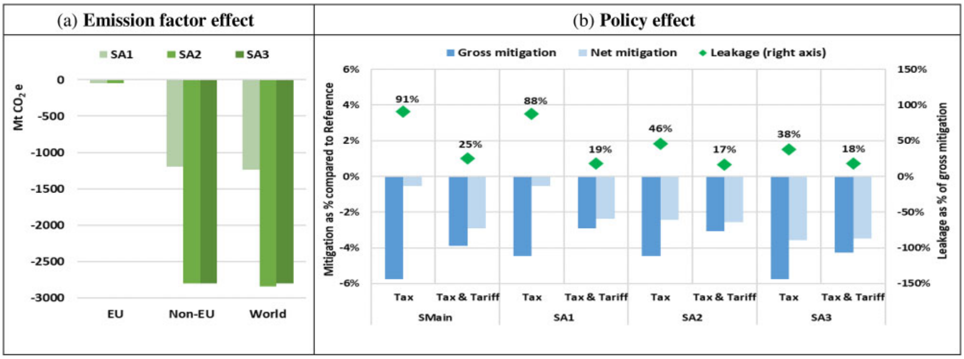

Figure 4. Sensitivity analysis: change in agricultural non-CO_2 GHG emissions and leakage by 2030. (a) Change in the reference emissions SA_REF compared to the original REF. (b) Change in emissions compared to the respective SA_REF. *Notes*: SMain refers to the main scenarios of the study.

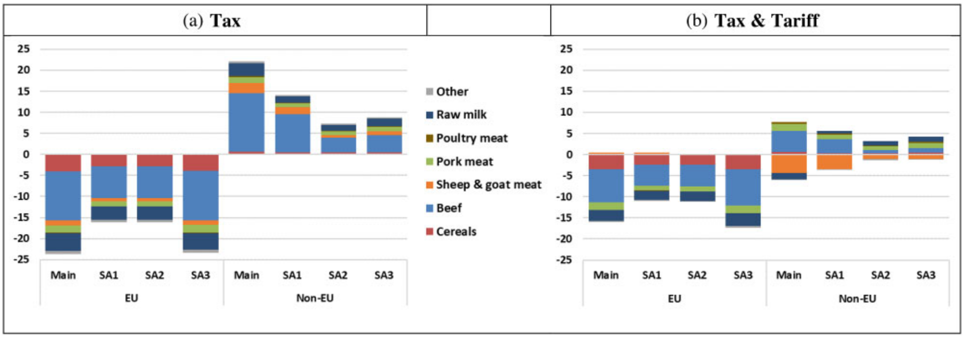

Figure 5. Sensitivity analysis: change in agricultural non-CO_2 GHG emissions (Mt CO_2e) by sector and country. *Notes*: Beef in India refers to water buffalo meat; AUS & NZ = Australia and New Zealand.

non-EU countries could reach the EU's emission efficiency by 2030, this assumption allows highlighting the potential impact of emission intensities on the effectiveness of BCAs. To isolate the effects of emission intensities from the policy effects (EU Tax and Tax & BCA), each sensitivity scenario set is compared with its corresponding reference scenario. Fig. 4b presents EU gross and net emission mitigation, along with leakage as percentage of gross mitigation by 2030.

The results of the sensitivity scenarios generally align with the observations from the main scenarios, although the magnitude of the effects varies depending on the assumptions about further emission efficiency developments in the EU and non-EU. By scenario design, EU emission reductions in the Tax scenario are the same between SA1 and SA2 (−16.1 Mt CO_2e; −4.5 per cent), and between SA3 and the main Tax scenario (−23.4 Mt CO_2e; −5.7 per cent) as each pair assumes the same development in EU emission intensities, and hence the domestic tax affects EU emissions to the same extent (Fig. 5). The 20 per cent decrease in EU emission intensities in SA1 and SA2 means lower emissions per unit of product, which reduces the tax burden and subsequently results in lesser EU production reductions and, therefore, lesser emission reductions compared to SA3 and the main Tax scenario relative to REF. Consequently, less production increase in non-EU countries is needed to compensate for EU production declines. This, combined with the assumption of lower emission intensities, leads to lower emission increases in non-EU. Nonetheless, in SA1, with an assumed

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20 per cent increase in non-EU emission efficiency, emission leakage is substantial at 88 per cent, corresponding to an effective EU net mitigation of only 0.5 per cent. In contrast, the BCA leads to EU net mitigation of 2.4 per cent. Due to lower EU production decreases, EU exports of all products decrease less compared to the main Tax & Tariff scenario (Fig. S2), resulting in reduced trade diversion, an effect that contributes more to lowering the emission increase in non-EU than the improved emission intensities.

In SA2, where EU emission efficiency improves by 20 per cent while non-EU countries reach EU emission intensities of the original REF, non-EU emissions increase by approximately half the amount seen in SA1. This translates to 46 per cent emission leakage and corresponds to 2.4 per cent EU net mitigation (mirroring the SA1 Tax & Tariff scenario). In SA2 Tax & Tariff, the further enhanced emission efficiency in non-EU implies a lower relative tariff burden for exporters to the EU compared to SA1, prompting reduced EU production and increased imports, particularly beef, and sheep and goat meat, compared to SA1 Tax & Tariff. Consequently, emission leakage decreases to 17 per cent, resulting in an EU net mitigation of 2.6 per cent.

In SA3, with EU emission efficiency remaining consistent with the main scenarios and non-EU assumed to reach EU emission intensities of the original reference (as in SA2), EU emissions decrease by 5.7 per cent in the Tax scenario. Non-EU emissions increase less than in the main Tax scenario due to improved emission efficiency, resulting in 38 per cent emission leakage, equivalent to an EU net mitigation of 3.6 per cent. However, non-EU emissions increase 21 per cent more than in the SA2 Tax scenario, mainly due to the higher decrease in EU production compared to SA2, which triggers a higher increase in non-EU production. In SA3 Tax & Tariff, EU imports and exports decrease less than in the other Tax & Tariff scenarios, and production and trade diversion in non-EU due to increased imports and decreased exports of the EU are only slightly augmented compared to the main Tax & Tariff scenario. However, due to the strongly improved emission intensities in non-EU, the emission effect of these adjustments is much lower compared to the main Tax & Tariff scenario, resulting in 18 per cent emission leakage and corresponding to 3.5 per cent EU net mitigation. Thus, SA3 is the only scenario in which net emission reduction in Tax & Tariff is (albeit only slightly) lower than in the respective Tax scenario, despite SA3 Tax exhibiting the largest net mitigation. This observation suggests that for global emission reduction, the BCA may become counterproductive once emissions of imported goods attain the same emission efficiency as domestic products.

7. Discussion and policy implications

In this paper we present simulations examining the effectiveness of a border carbon adjustment (BCA) implemented in the agricultural sector, in the form of a carbon-based import tariff, to counteract carbon leakage resulting from a domestic carbon tax in the EU. The simulated tax and BCA are based on country or region and commodity-specific emission intensities, with a carbon price set at 120 EUR/t CO_2 equivalent (CO_2e) on non-CO_2 agriculture emissions. In both scenarios, the tax on EU agricultural emissions leads to lower EU production. Conversely, many non-EU countries increase agricultural production to compensate for EU supply changes, partially fulfilling the increased EU import demand and decreased EU exports, thus leading to increased non-EU emissions. Therefore, the EU production reduction induced by the domestic carbon tax triggers four main trade-related responses: (i) increased EU imports and decreased EU exports, (ii) increased production in non-EU countries to augment exports to the EU, (iii) increased production and trade between non-EU countries to compensate for lower EU exports or redirected exports to the EU, and (iv) increased production for domestic markets in non-EU countries, either directly affected by decreased EU exports or indirectly by lower agricultural goods availability on the world market. Collectively, these responses result in an emission leakage rate

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of 91 per cent in the Tax scenario. This outcome is consistent with previous applications for unilateral climate action with similar scenario assumptions (Fellmann et al. 2018; Jansson et al. 2023), but considerably higher than the results found in studies allowing the adoption of endogenous mitigation technologies, which can decrease the emission intensity of production activities in response to the carbon tax (Domínguez et al. 2016; Himics et al. 2018).

The BCA increases the costs of exporting to the EU, leading to higher domestic EU prices. The higher prices partially offset the carbon tax burden for EU farmers, resulting in a less pronounced decrease in EU production and related emissions. Concurrently, the BCA diminishes opportunities for non-EU countries to expand their exports to the EU due to the additional import tariff, thereby limiting the rise in production and agricultural emissions outside the EU. Additionally, a third (indirect) effect arises from the reduction in EU exports, triggering additional secondary effects that stimulate production and trade, and hence emissions, in non-EU countries. Overall, these effects enhance the competitiveness of EU agricultural production compared to solely implementing a domestic emission tax. Although the BCA reduces emission leakage to 25 per cent, it adversely impacts total global emission reduction efforts. Our results indicate that the BCA partially undermines the efforts to decrease domestic EU emissions, resulting in a lower EU contribution to global emission reduction compared to the Tax scenario (3.9 per cent EU mitigation versus 5.7 per cent in the Tax scenario). Depending on the evolution of emission efficiency in non-EU regions, this effect could even prevail reduced emission leakage, as shown by a sensitivity analysis (SA3) assuming non-EU emission intensities equal to EU levels. The range of assumed improvements in non-EU emission intensities considered in our sensitivity analysis spans from partial implementation of technological mitigation potentials to substantial changes for certain scenarios and regions. This underscores the importance of fostering emission intensity improvements and confirms that the effectiveness of the BCA diminishes as emission efficiency in non-EU regions increases. In addition, enhancing emission efficiencies through the adoption of technical and management-based mitigation options can have further benefits, such as yield increases, improved fertiliser efficiency, and potential cost savings.

Emission intensities vary significantly across countries and products, and our simulations underline the significance of production location for global emission trends. Notably, EU agricultural production demonstrates higher emission efficiency compared to most non-EU countries. Accordingly, global emissions are further increased outside the EU due to production rises in non-EU countries with higher emission intensities. Beef meat emerges as a primary driver of emission leakage across all scenarios, given its high emission intensity. While our sensitivity analysis reveals a substantial decline in beef-related emission increases in non-EU regions with improved emission efficiency, they remain a major driver of non-EU emission developments. In this context it is also important to highlight that consumer price elasticities are generally low in developed countries, and our EU results indicate challenges in achieving substantial and balanced decreases in (global) emissions with the modelled measures, particularly in the absence of significant changes in consumption patterns, notably concerning beef meat consumption (see also, for example, Frank et al. 2019).

A major consideration surrounding BCAs is their compatibility with WTO rules. In our scenarios, we implement a policy design (BCA as import tariffs differentiated by exporting country in combination with a domestic carbon tax) that is generally considered to comply with WTO rules (Di Leva and Xiaoxin 2017; Mehling et al. 2017; Odell 2018; Cosbey et al. 2019). The carbon tax in our scenarios is levied on marketed agricultural products, based on average CO_2e emissions occurring throughout the production process. This approach facilitates the practical implementation and monitoring of a domestic carbon tax and allows to implement the same approach for the BCA tariff, hence aligning with WTO compliance considerations. However, using average benchmark emissions as an anchor point provides individual farmers with ambiguous incentives to enhance emission

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efficiency at farm level, such as by implementing more emission-efficient technologies and management options. With tax reductions based on a regional average, efficiency improvements at individual farms may not necessarily result in proportional reductions in carbon taxes. If the carbon tax would instead be based on emissions measured at the individual farms, the incentive for emission efficiency improvements would be straightforward. The explicit link between the carbon tax that farmers pay and their actual emissions is a crucial aspect in designing an emission tax and a related BCA. In practical terms, both carbon taxes and import tariffs under the BCA would need to be recalculated regularly (e.g. following the annual reporting of emissions to the UNFCCC). Such recalculations would provide clearer incentives for farmers to enhance their emission efficiency and allow for the consideration of these improvements in imported goods.

A targeted distribution of tax and tariff revenues from BCAs could further improve the climate change mitigation potential of BCAs. Redistributing (at least partly) the revenues from the domestic carbon tax back to the farming sector, for example, in the form of direct subsidies for farmers to adopt GHG emission mitigation technologies and management practices, could stimulate additional improvements in emission efficiency. Previous studies with the CAPRI model have shown that such subsidies could lead to improvements in EU emission efficiencies similar to those in our sensitivity scenarios SA1 and SA2 (20 per cent), thereby reducing the negative EU supply response and resulting in smaller emission leakage effects compared to those simulated in our main scenarios (Domínguez et al. 2016; Himics, Fellmann, and Barreiro-Hurle 2020). Likewise, at least part of the BCA tariff revenues could be transferred to relatively less emission-efficient (developing) countries as direct support for technology improvements to enhance emission efficiency in non-EU countries (Matthews 2022). This would have positive effects on curbing emission leakage, as indicated in our sensitivity analysis, and underscore the global emission mitigation objective of a BCA (Barreiro-Hurle et al. 2016).

Several limitations and areas for further research can be identified from our analysis. Firstly, our analysis only considers agricultural non-CO_2 emissions (i.e. CO_2 emissions and removals from land use and land use change are not covered). While the EU production decreases in our scenarios might lead to land use changes that benefit the reduction of EU CO_2 emissions, the emission leakage effects could be amplified if the production increase in non-EU countries leads to the release of land use change-related CO_2 emissions. Therefore, future research should also take CO_2 emissions and removals into account. Secondly, our analysis is partial and does not address welfare effects. BCAs are often criticized for their potentially negative welfare effects for developing countries (Frankel 2008; Stavins et al. 2014). However, our scenario results suggest that excluding developing countries from BCAs could be counterproductive in terms of global emission reduction, given their higher emission intensities in agricultural production. Our sensitivity analysis shows the importance of enhancing emission intensities in developing and emerging countries, even if BCAs are introduced unilaterally in a developed country (such as the EU). Therefore, promoting the improvement in emission efficiency in developing countries is recommended, for example through technology transfer and adoption.

8. Conclusions

Based on our scenario results, we conclude that BCAs in the agricultural sector could be a measure to enhance the competitiveness of domestic producers and reduce emission leakage resulting from unilateral GHG mitigation policies. However, the increase in competitiveness leads to adverse effects on domestic mitigation efforts, partially counteracting the reduction in emission leakage. Furthermore, the focus on imports alone overlooks other intensities, particularly in the case of major emission-efficient net exporters in agricultural commodities, such as the EU. In these cases, emissions associated with trade diversion further undermine

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global emission reduction efforts. Therefore, our results indicate that BCAs on agri-food products in major exporting countries with emission-efficient production systems may not reduce global emissions as effectively as commonly assumed. This underscores the critical importance of improving emission efficiencies, and highlights the necessity of multilateral agreements and the implementation of complementary policies beyond BCAs for achieving effective global emission mitigation in the agricultural sector.

Supplementary material

Supplementary data are available at *Q Open* online.

Declarations

This paper has not been submitted elsewhere in identical or similar form, nor will it be during the first 3 months after its submission to the publisher.

Funding

This work was partially supported by the Swedish Energy Agency (project number 40727-1).

Conflicts of interest

The authors have no relevant financial or non-financial interests to disclose. The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

Data availability

Data and model code can be provided on request.

End Notes

1. Our emission intensities are fixed, even though it would be economically efficient to have endogenous emission intensities. We made this choice for two reasons: (i) a fixed tax per commodity and country would be relatively simple to implement, 'VAT-style' without any need for on-farm certification or measurements, and (ii) it treats imports (with BCA) and domestically produced goods in a similar way.
2. Modelling results on global emission pathways compatible with the Paris Agreement indicate that carbon prices well above 100 USD/t CO_2e are necessary to achieve the goals (Rogelj et al. 2018a,b; Roe et al. 2019). Consistent with these findings and with one of the currently implemented carbon prices, the Swedish CO_2 tax on fossil fuels, we have selected a carbon price of 120 Euro/t CO_2e for our scenarios (in 2018 price level, inflated to 2030 using the same inflation rate applied to all other prices in CAPRI).
3. Emission intensities for animal products used to base the tax on exclude the implicit content of tradable feed (as the feed is taxed when it is produced by the farm), but the final price of meat product includes tradable feed.
4. Some of the non-EU countries are aggregated to regions, for example Africa LDC (least developed countries).
5. The processed goods are dairy products, vegetable oils and cakes, refined sugar, milled rice, and biofuels. The tariff was based on the embedded content of primary outputs. In the EU, only primary outputs are taxed (not processed goods), to avoid double taxation.
6. The motivation for the conversion to ad-valorem equivalents is to avoid complex interaction with measures such as tariff rate quotas (TRQs). If, for instance, a TRQ is binding, and the import price is between the preferential rate and the MFN rate, adding a BCA may have no effect other than changing

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the dual value of the TRQ. This could be a real effect, depending on the details of the actual BCA implementation, but would distract from the purpose of our analysis.

7. Leakage in percentage terms is calculated as emission increase outside the EU/emission decrease in the EU.
8. Non-EU countries and regions with at least a change of 0.4 Mt CO_2e in one of the policy scenarios compared to REF. This selection covers 68 per cent of total non-EU agricultural emissions in REF, and 80 and 82 per cent, respectively, in the Tax and the Tax & Tariff scenario.
9. India exports buffalo meat produced primarily from culled, or non-productive, dairy animals, which makes it low-cost meat and particularly attractive for low- and middle-income developing countries. Moreover, Indian law requires buffalo meat to be produced in accordance with halal standards, which makes it competitive in the markets of developing countries in Southeast Asia, Middle East, and North Africa with Muslim populations (Landes, Melton, and Edwards 2016). Indian buffalo meat production is characterised by extensive production systems, with low feed digestibility, relatively poor animal husbandry, and low carcass weights (Gerber et al. 2013).

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