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Carbon Leakage and Agriculture: A Literature Review on Emissions Mitigation Policies

Theodoros Arvanitopoulos, Grégoire Garsous, and Paolo Agnolucci

The risks of carbon leakage associated with climate policies in the agricultural sector remains under-researched. Studies to date suggest that carbon pricing policies implemented by a single country, or small group of countries, reduce global emissions but also affect the international competitiveness of these countries' agricultural sectors and induce carbon leakage. While carbon leakage can be prevented with trade-related measures that adjust emissions prices at the border, such measures applied in developed countries could potentially lead to significant welfare losses for developing countries that heavily rely on agricultural exports. That said, important caveats apply to the reviewed studies: i) from an environmental perspective, estimations of carbon leakage rates alone do not offer a comprehensive assessment of how optimally agricultural activities are allocated across countries; ii) most of the studies estimate the effects of additional environmental policies, such as carbon taxes, and ignore the effects of existing policies, including market distorting and potentially environmentally harmful support for agricultural production.

Key words: Climate change, trade, environmental policies

JEL codes: F18, O13, Q15, Q17, Q54

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Table of Contents

Key messages

- The evidence in the reviewed studies suggests that carbon pricing policies reduce the international competitiveness of countries' agricultural sectors and induce carbon leakage.
- While carbon leakage can be prevented with trade-related measures that adjust emissions prices at the border, such measures applied in developed countries could potentially lead to significant welfare losses for developing countries that rely heavily on agricultural exports.
- Important caveats apply to the conclusions derived from the reviewed studies:
    - i) from an environmental perspective, estimations of carbon leakage rates alone do not offer a comprehensive assessment of how optimally agricultural activities are allocated across countries.
    - ii) most of these studies estimate the effects of additional environmental policies, such as carbon taxes, and ignore the effects of existing policies, including market distorting support to agricultural production.

1. Introduction

Environmental policies addressing agricultural activities will play a crucial role in climate change mitigation and adaption strategies in the coming years (IPCC, 2019[1]). Under the Paris Agreement, 80% of countries have set objectives to reduce greenhouse gas (GHG) emissions in agriculture (Richards et al., 2015[2]). Agriculture, forestry and other land use (AFOLU)[1] is estimated to account for 23% of global GHG emissions in 2007-2016, being the second largest emitting sector after electricity and heat production[2] (Smith et al., 2014[3]; IPCC, 2019[1]).

While the agricultural sector has so far been largely exempted from emissions mitigation policies such as carbon taxes and emissions trading schemes across the world, some countries are contemplating including agricultural activities in comprehensive climate packages. However, in an international context where countries act on climate change in a non-coordinated fashion and from a diverse agricultural policy base, concerns have been raised over the potential unintended consequences associated with the unilateral[3] implementation of such environmental policies. These concerns have been centred on the concept of carbon leakage, by which the implementation of stringent environmental policies targeting the reduction of domestic carbon emissions results in an increase of emissions generated by countries that do not implement similar policies (Copeland and Taylor, 2005[4]). In other words, carbon leakage can be defined as the additional amount of GHG emissions generated in non-implementing countries caused by implementation of stricter environmental policies leading to a decrease of GHG emissions in implementing countries (Karp, 2010[5]).

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[1] Agricultural activities are estimated to account for at least 90% of emissions due to land-use change (Bennetzen, Smith and Porter, 2016[81]).

[2] Excluding land-use change, agriculture accounted for 11% of global anthropogenic GHG emissions between 2000 and 2010 (Smith et al., 2014[3]).

[3] In this report, the term "unilateral" refers to a situation where one country or many countries implement environmental policies relatively more stringent than another group of countries. The terms "implementing countries" and "non-implementing countries" thus refer to the (group of) countries that implement and do not implement these relatively more stringent policies, respectively.

The present study reviews the literature that discusses the risks of carbon leakage associated with climate policies and their implications for the agricultural sector. This review will cover studies on: (i) supply-side mitigation policies in the agricultural sector imposing a price on emissions such as carbon taxes, emissions trading schemes and abatement subsidies and; (ii) demand-side mitigation policies in the agricultural sector applying taxes on the final products, potentially modifying consumer choices. Trade-related measures that aim to limit potential carbon leakage are also reviewed. In particular, two types of measures will be discussed: (i) border carbon adjustments and; (ii) other trade-related measures such as environmental standards for imported goods.[4] This literature review includes both economic modelling and econometric studies that shed light on the underlying mechanisms of carbon leakage and the channels through which it occurs. There are important caveats to these studies which are discussed below.

Because only a limited number of studies discuss climate policy implications for the agricultural sector, this literature review also incorporates papers focusing on other sectors – e.g. manufacturing and power generation – in order to provide a greater breadth of analysis and examples of emissions mitigation policies that may lead to carbon leakage. However, because of comparatively higher barriers in agricultural markets – such as high tariffs, sanitary and phytosanitary measures, and other quantitative restrictions – trade in agriculture is likely to be even more frictional than other sectors, which may in fact complicate implications for carbon leakage outcomes.[5] Similarly, some studies do not always directly assess carbon leakage but rather investigate the effect of emissions mitigation policies on domestic competitiveness[6] or economic welfare. These studies are also included in this literature review as they provide useful insights about the relationship between climate policies and their net effects on global emissions.

Overall, the evidence in the reviewed studies suggests that the implementation of carbon pricing policies by a single country, or small group of countries, reduces the international competitiveness of these countries' agricultural sectors and induces carbon leakage. Modelling exercises tend to show that leakages resulting from unilateral climate policies can be prevented with trade-related measures that adjust emissions prices between implementing and non-implementing countries at the border. Nonetheless, they also show that such measures – e.g. border carbon adjustments – applied in developed countries could potentially lead to significant welfare losses for developing countries that heavily rely on agricultural exports. In addition, border carbon adjustments are unlikely to have much effect on controlling leakage from carbon pricing policies that target export-oriented sectors.

The literature further suggests that abatement subsidies could reduce agricultural emissions while avoiding leakage. Nonetheless, abatement payments are found to be less effective in reducing GHG emissions in comparison to carbon pricing because, unlike the latter, they do not create incentives for emission-intensive producers to exit the industry. In addition, these abatement payments to farmers would be made in a sector already heavily subsidised in many OECD and a number of developing countries. In this context, the reallocation of existing distortionary subsidies to instead support abatement practices could be an economically sensible approach for reducing farm emissions.

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[4] This literature review focusses on trade-related policies to minimise carbon leakage and therefore, does not provide a discussion of (non-trade-related) alternative instruments. Such instruments include distributing free permits to firms subject to an emissions trading system and setting preferential rates – e.g. setting a lower or zero carbon tax for specific users. Their use involves trade-offs as they typically imply a lower level of domestic climate ambition and are often incompatible with ambitious long-term climate objectives.

[5] This literature review shows that *ex ante* modelling exercises find larger estimates of carbon leakage than *ex post* empirical assessments. To the extent possible, *ex ante* models restrict trade flows – and thereby carbon leakages – in response to policy changes by imposing a limit on both the substitutability of imported and domestically produced commodities and the capacity to develop new trade relationships. Despite this, real-world adjustments in trade are likely to be even more frictional than the results of these models. Reasons for this include the conversion of trade quantitative restrictions – i.e. quotas on imports – into price-based equivalents, as well as the exclusion of other non-tariff measures – e.g. sanitary and phytosanitary requirements.

[6] Throughout this study, the term "competitiveness" is used in a narrow sense and refers to cost efficiency of firms (and by extension sectors) relative to competitors on international markets. Cost efficiency is defined as the ratio of total costs to output.

Important caveats apply to the conclusions derived from these studies. First and foremost, the notion of carbon leakage is an incomplete concept to assess the net impact of unilateral climate policies. A carbon leakage rate – defined as the percentage of the decrease in emissions in implementing countries that is offset by an increase in emissions in non-implementing countries – lower than 100% shows that some emissions reduction has been achieved at the global scale albeit an increase in agricultural production in non-implementing countries.[7] In addition, the reallocation of agricultural production in non-implementing countries could be environmentally sound if the latter are less emission-intensive because, for example, of geographic characteristics such as the availability of water and land, and favourable temperature and precipitation patterns. Thus, estimations of carbon leakage rates alone do not offer a comprehensive indicator that assess the effects of policy changes on the optimality of the allocation of agricultural activities across countries from an environmental perspective.

Relatedly, agricultural markets are currently heavily distorted by policies – such as quantitative restrictions to imports, high tariffs, and various forms of government support to domestic agriculture production, some of which can be environmentally harmful (OECD, 2020[6]). Estimating the effects of additional environmental policies – e.g. carbon taxes – on top of these existing policies is informative but provides, again, an incomplete assessment from which policy recommendations can be derived. A broader discussion that also addresses the environmental impact of current market-distorting policies is necessary to define a first-best coordinated effort towards a more sustainable agriculture.

Finally, these studies focus on current emissions flows and do not account for emissions stocks, which can have important policy implications in terms of how responsibilities for tackling climate change are shared.

The remainder of this paper is structured as follows. Section 2 provides a formal definition of the concept of carbon leakage and discusses its underlying mechanisms. Section 3 reviews the literature that assesses the extent to which emissions mitigation policies lead to carbon leakage. Section 4 discusses how trade measures – i.e. border carbon adjustments and other requirements on non-product-related processes and production methods – can mitigate carbon leakage effects. Finally, Section 5 summarises key insights and concludes.

2. The concept of carbon leakage

The concept of leakage originates from the seminal studies of (Grossman and Krueger, 1991[7]; Copeland and Taylor, 1994[8]; Copeland and Taylor, 1995[9]) on the linkages between pollution and international trade.[8] The motivation for these studies was to assess the environmental impact of the North American Free Trade Agreement (NAFTA) and, more generally, the effects of trade liberalisation on polluting activities when trading countries have different environmental standards. Their work highlighted the possibility of pollution leakage or what is sometimes referred in the literature as the "pollution haven effect". A pollution haven effect (PHE) occurs if stricter environmental policies and a resulting reduction of emissions in some countries – the so-called implementing countries – leads to an increase of emissions in countries with laxer environmental regulation – the so-called non-implementing countries (Larch and

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[7] For instance, if new climate rules induce an emissions reduction of 100 tonnes of CO_2 in implementing countries and, consequently, an emissions increase of 20 tonnes of CO_2 in non-implementing countries, the resulting carbon leakage rate is 20%. However, a net emissions abatement of 80 tonnes of CO_2 is still achieved. Typically, a leakage rate is lower than 100% as domestic production is not entirely replaced by production to non-implementing countries. This is because trade frictions – e.g. existing trade barriers and transport costs – create incentives to keep production local. In addition, domestic products are not perfectly substitutable with foreign products and some demand for the former persists despite a price increase due to carbon pricing policies.

[8] Cherniwchan, Copeland and Taylor (2017[15]) provide a helpful review of the literature linking international trade to the environment.

Wanner, 2017[10]).[9,10] A related concept is “energy-market leakage”. Strict environmental policies can reduce energy demand in implementing countries – because of carbon pricing for instance –, which then leads to a reduction in world energy prices, thereby encouraging production in energy-intensive sectors in non-implementing countries (Babiker, 2005[11]; McAusland and Najjar, 2015[12]).

Carbon leakage can occur through two channels. First, increasing costs in the production processes of implementing countries results in the modification of relative prices between countries: products from non-implementing countries become comparatively cheaper and, provided international trade is sufficiently liberalised,[11] they end up being exported to implementing countries. Second, domestic firms in pollution-intensive sectors have incentives to migrate to countries with laxer environmental policies.[12] Once relocated, these firms can produce the same goods at lower cost and export them back to implementing countries. In essence, domestic firms of implementing countries “offshore” their emissions to other countries, a process analogous to that of offshoring labour (Levinson, 2010[13]).

For a given country, changes in pollution levels can be decomposed into a scale, composition and technique effect (Levinson, 2009[14]). The scale effect is the increase in pollution due to a growing production volume, ceteris paribus – that is, maintaining production techniques and output composition constant.[13] The *composition* effect is the change in pollution due to changes in the range of goods produced by a country therefore capturing changes in the composition of economic activity. The *technique* effect is the change in pollution levels due to changes in production techniques.[14]

The two channels of carbon leakage – i.e. *movement of trade and movement of production* – therefore imply changes in pollution levels accounted for by the composition effect, since the composition of traded goods between implementing and non-implementing countries changes: non-implementing countries might end up exporting more carbon-intensive goods to implementing countries. Note, however, that determinants other than environmental policies can induce a composition effect on pollution emissions (e.g. changes in the availability of production factors such as capital or other policies). It is therefore empirically challenging to disentangle the role of each of these determinants.

Drivers of the technique effect can be market share reallocations, reorganisation within firms, innovation on abatement technologies (driving abatement costs down) and technological upgrades (Cherniwchan,

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[9] A related but different concept from the pollution haven effect is the pollution haven hypothesis. The pollution haven hypothesis is the prediction “that when trade barriers are reduced, pollution-intensive industries will shift from countries with stringent environmental [policies] to countries with lax environmental [policies]” (Taylor, 2005, p. 4[64]). The pollution haven hypothesis is therefore a prediction about the effects of trade liberalisation on the environment, whereas the pollution haven effect addresses how changes in environmental policies result in changes in trade flows. “The existence of a pollution haven effect is necessary, but not sufficient, for the pollution haven hypothesis to hold” (Ibid, p.4).

[10] The PHE can also occur with other types of pollution (water pollution, NOx and SOx emissions, etc.). Strictly speaking, the carbon leakage effect is a special case of the PHE. In the context of this literature review focussing only on climate policies, these two concepts are equivalent.

[11] Note that this is a strong assumption in the case of agricultural markets because of the large number of measures that restrict access to markets.

[12] Cross-country differences in agricultural emissions intensities are not only accounted for by farming management practices but also by geographic characteristics such as the availability of water and land, and temperature and precipitation patterns. Therefore, in the context of agricultural commodities, countries with laxer environmental regulation are not necessarily those with carbon-intensive production practices.

[13] Therefore, policies that increase production also increase pollution if one considers the scale effect only and ignores the composition and technique effects. Copeland and Taylor (1994[8]) analyse the interaction of these three effects in the context of trade liberalisation.

[14] In the literature, the technique effect is usually treated as a residual effect once scale and composition effects are accounted for and it identifies the reduction of emissions due to an increase in the overall productivity (Cui, Lapan and Moschini, 2012[68]; Cui, Lapan and Moschini, 2016[67]). Similarly to the empirical framework used for the estimation of Total Factor Productivity (Van Beveren, 2012[69]), one possible approach to capture the technique effect is to calculate it as the residual once scale and composition effects are identified. As a result, the residual captures the increase in overall productivity in relation to the emissions produced during the production process. Alternatively, changes in emissions intensity can be estimated with the use of a bottom-up approach that captures management practices and biophysical characteristics (Carlson et al., 2016[85]). The latter process is more widely used in the literature.

Copeland and Taylor, 2017[15]). It is important to note that the introduction of stringent environmental policies does not necessarily lead to pollution leakages. A more stringent environmental policy may also create incentives for firms to innovate and absorb the associated compliance costs, which ultimately leads to efficiency gains and new comparative advantages influencing trade patterns.[15] In the context of agriculture, such innovations include the transition to technologies like anaerobic digesters, feed supplements, nitrogen inhibitors etc. (Beach et al., 2015[16]). For example, the New Zealand Government has proposed the development of a methane vaccine to mitigate on-farm emissions associated with dairy products by 30% and sheep and beef by 20% (Ministry for the Environment, 2018[17]). Other practice changes involve more fundamental adjustments, such as changes in the management of the production processes – e.g. decreased flooding period of rice paddies – and reallocation of agricultural production across regions and through trade (Havlík et al., 2014[18]).[16]

3. Emissions mitigation policies

Agriculture has so far been largely exempted from emissions pricing policies such as carbon taxes and emissions trading systems – across the world. Perhaps this is because the measurement, reporting and verification (MRV) of diffuse heterogeneous sources of emissions – at both sector and landholder scales – is particularly challenging and constitutes an obstacle for the implementation of mitigation policies (Beach et al., 2008[19]; Beach et al., 2015[16]; OECD, 2019[20]; Henderson, Frezal and Flynn, 2020[21]).

In addition, concerns about producer incomes, food prices, and food security may also explain some of the lack of progress in pricing agricultural emissions. In fact, agriculture is one of the most heavily supported sectors, which may be a testament to these concerns.[17] However, government support can also work against the effects sought with emissions pricing policies as it may significantly raise emissions (Henderson and Lankoski, 2019[22]).[18] Therefore, to reach mitigation targets in line with the Paris Agreement, a reform of potentially environmentally harmful agricultural support policies is important in addition to other climate policies.[19]

In this section, existing policy instruments that may cause carbon leakage are reviewed. These policy instruments can be distinguished into two categories: (i) emissions mitigation policies that focus on the supply side of the agricultural sector by pricing GHG agricultural emissions and; (ii) emissions mitigation policies that focus on the demand side by applying taxes on final products with high GHG footprints paid by final consumers. Both *ex ante* and *ex post* studies on agriculture and carbon leakage are considered and their main results is summarised in **Error! Reference source not found.**.

3.1. Supply side

A ***carbon tax*** is a price on carbon emissions[20] that aims to internalise the associated negative environmental externalities. Such a levy creates incentives for agents – farmers in the case of agriculture – to abate emissions at the lowest possible cost. A carbon tax is most cost-effective when applied directly to emissions, although its application to emission-intensive inputs – e.g. fertilisers, fossil fuels, and ruminant animals – may be more feasible in practice. A carbon tax can adversely affect the terms of trade in implementing countries, by raising production costs. Non-implementing countries can therefore gain a

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[15] This effect is known as the Porter hypothesis. It has been investigated in the context of manufacturing industries. No studies addressing the Porter hypothesis for the agricultural sector has been found.

[16] For an overview of agricultural innovation systems in a selected sample of countries, see (OECD, 2019[82]).

[17] In 2018-20, all OECD countries, the European Union and thirteen emerging and developing economies provided net transfers to their agricultural sectors of USD 720 billion per year (OECD, 2021[63]).

[18] Note that other restrictions to agricultural markets – such as quotas and tariffs – also affect the location and scale of agricultural production, which can result in a suboptimal outcome from an environmental perspective.

[19] Few studies however discuss the relevance of such reforms in the context of current climate negotiations, an important gap in the literature for this policy debate.

[20] Or on GHG emissions converted in tonnes of CO_2 equivalent.

comparative advantage and may increase their exports and associated agricultural emissions.[21] Such a leakage of emissions can be mitigated using policies that preserve the profitability of producers. For instance, revenues raised by the tax can be returned to producers in the form of tax reductions or lump sum transfers so that their overall production costs are not significantly altered when implementing production practices that reduce emissions (Tol et al., 2008[23]).

A few *ex ante* studies have investigated the effect of a carbon tax on agricultural production and, by extension, on carbon leakage for the US agricultural sector. Focusing on emissions embodied in trade, these studies find that the implementation of a large carbon tax – i.e. USD 100 per tonne of CO_2 – would result in a decline of the US agricultural production unless domestic demand were inelastic to prices, which would allow producers to entirely pass the tax on consumers.[22] [23] Lee et al. (2007[24]) find that a unilateral implementation of agricultural GHG emissions mitigation policies decreases US agricultural production while it increases production in the rest of the world, therefore potentially resulting in carbon leakage. Peters et al. (2001[25]) estimate the economic impacts of carbon charges on energy intensive inputs such as fuels, fertilisers (nitrogen, phosphorous and potash), pesticides and electricity. A modest carbon charge of USD 14 per metric ton of carbon results in price increases and production declines equal to less than 1%. On the other hand, a carbon tax of USD 100 caused the production of commodities such as rice, barley, sorghum and cotton to decline by 4.1%, 2.2%, 2.2%, and 1.8%, respectively, while livestock production declined by 2.1%. Whereas these studies do not assess the level of carbon leakage, they show that a carbon tax causes a decrease in agricultural production, which might be compensated by an increase in imports resulting in more emissions in the countries of origin.

In 2008, the province of British Columbia (BC) introduced a carbon tax on fossil fuels – for all sectors, including agriculture.[24] This intervention provides a natural experiment for *ex post* analyses of the potential effects of climate policies on domestic agricultural competitiveness. Using aggregated data on imports and exports for a number of agricultural commodities from 1990 to 2011, (Rivers and Schaufele, 2015[26]) did not find evidence that the implementation of carbon tax in BC reduced net agricultural exports. However, fossil fuel emissions comprise a very small share of overall emissions from agriculture, which might explain why the policy had a negligible impact on aggregate exports. Moreover, (Rivers and Schaufele, 2015[26]) point out that it is possible that farms experienced a decline in their profits – even if international exports were relatively unaffected by the tax. They therefore suggested that the government compensate any negative effects of the carbon tax on farm income, with lump sum rebates or output-based rebates.[25] Relying on farm-level surveys, (Olale et al., 2019[27]) estimate that the BC carbon tax is directly related to higher production costs and an overall decline in net farm incomes. Thus, although these findings do not support the argument that carbon taxes on fossil fuels would reduce net exports and affect the trade competitiveness of the domestic sector, they do show a welfare loss for producers because of higher production costs. This welfare loss can be mitigated by payments in the form of lump sum transfers so that relative prices of inputs change – and internalise externalities – but aggregate production costs of farmers remain unchanged.

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[21] Such effect assumes that all goods from different countries are perfect substitutes. This is a reasonable assumption for commodities although some agricultural products are differentiated based on production methods such as organic, GMO, etc.

[22] Or unless producers are compensated for the increase in their production costs.

[23] These studies are based on the ASMGHG model, which is mathematical-programming-based model that estimates the economic effects of carbon pricing on energy intensive US agricultural inputs. See (McCarl and Schneider, 2001[70]; Schneider and McCarl, 2005[71]; Lee et al., 2007[24]) for details.

[24] However, agriculture has been exempted from the tax since 2012 due to increased concerns from sector representatives about losing competitiveness in relation to Californian and Mexican producers (Murray and Rivers, 2015[72]).

[25] These conditional rebates are an alternative policy instrument to lump-sum rebates and depend on firm performance. Output-based rebate payments can be calculated based on a measure of physical or economic output (Fischer and Fox, 2009[73]). The province of British Columbia currently has an output-based rebate programme called the CleanBC Industrial Incentive Program, which supports emissions reductions and industrial competitiveness by providing incentives for cleaner industrial operations, including in the greenhouse sector. https://www2.gov.bc.ca/gov/content/environment/climate-change/industry/cleanbc-industrial-incentive-program#who.

By comparison, implementation of a similar carbon tax at a global level[26] or multinational level (for developed countries) can significantly reduce global emissions.[27] Using a general equilibrium model, (Golub et al., 2013[28]) find that an international carbon tax equal to USD 27/tCO_2eq[28] in developed countries can significantly reduce livestock emissions but that 25% to 35% of this reduction would be offset by carbon leakage in developing countries. They argue that this leakage effect can be eliminated by forest carbon sequestration incentives in developing countries – although food security concerns can arise because sequestration encourages forestland to expand and agricultural land to contract. (Key and Tallard, 2012[29]) examine the implementation of a USD 30/tCO2eq on livestock methane emissions in developed countries and find that two-thirds of the emissions reduction is leaked to developing countries – a leakage that is two times larger than in (Golub et al., 2013[28]). In a more recent CGE analysis, (OECD, 2019[20]) finds that 34% of the emissions reduction from a carbon tax applied to agriculture in all OECD countries is leaked because of subsequent increases in agricultural emissions in non-OECD countries.

An ***emissions trading scheme*** (or cap-and-trade scheme) is an instrument that caps emissions to a pre-determined level and allocates emissions permits among agents (e.g. firms or farms) in sectors under the scheme, allowing these agents to trade permits. Firms with low abatements costs can therefore sell permits to firms with high abatement costs. The former then abate more than the latter and the pre-determined level of pollution (i.e. the cap) is achieved at a lower cost than imposing non-tradeable abatement quotas on all firms. In the absence of uncertainties on marginal benefits and costs of abatements, this approach is equivalent to a carbon tax and is therefore equally efficient at mitigating emissions and internalising the environmental externalities associated with pollution (Weitzman, 1974[30]). Emissions trading schemes exist in many jurisdictions including Korea, New Zealand, Quebec, and the European Union.[29] These cap-and-trade schemes have focused on industrial and energy generation sectors and have so far excluded agriculture, with the exception of emissions from energy and fuel use for some large-scale producers in some cases.[30]

Empirical evidence suggests that the EU ETS significantly reduced carbon emissions without adversely affecting European industries' competitiveness or reducing overall economic performance. Dechezleprêtre, Nachtigall and Venmans (2018[31]) show that firms subject to the EU ETS performed relatively better in terms of revenue than exempted firms. Branger, Quirion and Chevallier (2016[32]) did not find strong evidence that the EU ETS has increased EU net imports of cement and steel. Calel and Dechezleprêtre (2016[33]) find a 30% increase of innovation activity in low carbon technologies for companies under the EU ETS. Martin et al. (2014[34]) find no evidence that the introduction of the EU ETS resulted in the relocation of firms to non-European markets – although substantial variability between sectors and individual firms was observed – and argue against granting allowances to firms with the seemingly highest propensity to relocate overseas. However, one potential explanation for the empirical evidence that firms were not adversely affected by the introduction of the EU ETS is precisely that firms operating in sectors deemed at risk of carbon leakage were granted free allowances – thereby considerably relaxing the stringency of the EU ETS instrument in these sectors.

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[26] At the global level, (Havlík et al., 2014[18]) apply the GLObal BIOsphere Management (GLOBIOM) economic partial equilibrium land use model and finds that a carbon price of USD 10/tCO_2eq results in an abatement of 3.2 GtCO_2eq per year. (Frank et al., 2018[74]), which use the same model as (Havlík et al., 2014[18]), find that a USD 25/tCO_2eq and a USD 100/tCO_2eq reduce non-CO_2 emissions by around 1 GtCO_2eq and 2.6 GtCO_2eq per year until 2030 respectively.

[27] This is a comparative static model and therefore it assumes constant production (Golub et al., 2013[28]).

[28] Tonnes of CO_2 emissions equivalent.

[29] The EU emissions trading scheme (EU ETS) is currently the largest cap-and-trade system in terms of emissions coverage (Hood, 2010[65]; Dechezleprêtre, Nachtigall and Venmans, 2018[31]).

[30] The New Zealand Government had initially planned the introduction of the New Zealand ETS (NZ ETS) for all sectors including agriculture (Jiang, Sharp and Sheng, 2009[76]). Nevertheless, agriculture was eventually excluded from the scheme because of concerns that it would undermine competitiveness and lead to carbon leakage in non-implementing countries (Bullock, 2012[75]). However, the pricing of farm-level emissions in New Zealand might be implemented in 2025. In preparation for this, the reporting of farm-level emissions will become mandatory by 2024. A final decision on the implementation of farm-level pricing on emissions will depend on the outcome of a government study into its feasibility (Ministry for the Environment, 2019[83]).

Since agriculture has not yet been included in any cap-and-trade system, there is no natural experiment allowing for an *ex post* estimation of the economic impacts and potential carbon leakage effect of such a scheme on agricultural activities. An *ex ante* analysis by (Kerr and Zhang, 2009[35]) finds that including agriculture in the New Zealand ETS would result in relatively limited carbon leakage. Additional *ex ante* findings are available from studies that use the CAPRI model, which assesses the impact of agricultural, environmental and trade policies for EU and non-EU countries (Britz and Witzke, 2014[36]; Torbjörn, Pérez Domínguez and Britz, 2010[37]; Fellmann et al., 2012[38]; Van Doorslaer et al., 2015[39]; Fellmann et al., 2018[40]). These studies suggest that policies targeting emissions reductions with tradable emissions permits across EU countries perform better in reducing leakage than an equivalent scheme with non-tradable quotas.

Studies relying on the CAPRI model explore four scenarios of emissions reduction targets in agriculture coupled with non-tradable emissions quotas. Two assume spatially homogenous emissions reduction targets equal to 19% (HOM19) and 28% (HOM28). The other two scenarios assume spatially heterogeneous emissions reduction targets equal to 19% (HET19) and 28% (HET28). Under the HOM19 and HOM28 scenarios with no tradable permits, 67% and 81% of the emissions reduction in the EU are neutralised by carbon leakage respectively (Van Doorslaer et al., 2015[39]). Under the HET19 and HET28 scenario with no tradable permits, 77% and 91% of the emissions reduction in the EU are neutralised by carbon leakage respectively (Van Doorslaer et al., 2015[39]). The CAPRI model shows that producers meet the emissions cap not only by reducing emissions intensities, but also by cutting production. The latter must be offset by increasing imports (mainly from Africa), which creates a leakage. In contrast, the introduction of the emissions trading scheme “dampens leakage” as it leads to 13% less leakage than the equivalent scenarios without tradable permits. Under an ETS, regions with low marginal abatement costs sell permits to regions with high marginal abatement costs, leading to an efficient allocation of the mitigation burden, which by extension reduces the need for imports and thus attenuates leakage.

Unlike carbon taxes that rely on the “polluter pays” principle, abatement payments for emissions reduction is a policy instrument that relies on the government paying agricultural producers to reduce their emissions. In essence, producers can use this financial support to invest in technologies and management techniques that help them mitigate emissions while keeping production costs down.[31] Therefore, by providing abatement payments governments may be able to both reduce emissions from agriculture[32] while preserving domestic competitiveness. Depending on the funding mechanism, payments may exactly compensate producers for their mitigation costs – e.g. via an auction system where farmers who propose the lowest bids receive them for the abatements they would provide – or may more than compensate producers if payments are uniformly provided irrespective of their actual abatement costs. The limitation of this policy is that it is financed by the government – in contrast to carbon taxes and cap-and-trade systems that raise government revenues. As agriculture is already heavily supported in many OECD countries and in some emerging economies, redirecting this (a priori) distortive support to GHG mitigation could improve economic welfare.

An *ex ante* study focusing on the Canadian livestock sector suggests that producer subsidies would result in a lower emissions reduction at a higher social cost than a producer tax on emissions. Using a partial equilibrium model, (Slade, 2018[41]) estimates that a CAD 50/tCO$_2$eq tax[33] on beef producers is associated with 23-50% reduction in emissions at a social cost[34] of between CAD 10.40 and CAD 21.50[35] per tonne abated. An equivalent producer subsidy would achieve a 16-43% reduction in emissions and be associated

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[31] Note that if producers abate by producing less and abatement payments compensate for their associated lost income, imports from other countries might increase. In such case, abatement payments might not reduce leakage.

[32] Compared to “polluter pays” instruments, abatement payments have a positive effect on the entry-exit margin, which can encourage production to expand, making them less effective at abating emissions for a given carbon price.

[33] The Canadian Government has set carbon prices at CAD 20/tCO$_2$eq in 2019 and proposes to increase the carbon price by $15 per year, starting in 2023, rising to $170 per tonne of carbon emissions in 2030 (https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/climate-plan/healthy_environment_healthy_economy_plan.pdf).

[34] The social cost of the policy is the sum of the change in producer surplus, consumer surplus, and taxpayer benefits.

[35] Similarly, Schaufele (2018[84]) finds that a CAD 40/tCO$_2$eq carbon tax would result in loss of producer surplus by approximately 3.5% of revenues.

with a social cost between CAD 28.7 and CAD 30.8 per tonne abated. The author argues that a producer subsidy would result in lower carbon leakage than a producer tax because the former would increase domestic production, thereby adding to global supply and putting downward pressure on production and emissions in the rest of the world. A producer tax would have the opposite effect. In sum, the subsidy provides a larger producer surplus – which may make it more politically feasible – but achieves a lower emissions reduction target at a higher social cost than a carbon tax.

Other studies addressing the effect of a subsidies-oriented emissions mitigation strategy on carbon leakage rely on the CAPRI emissions model. Without a predefined emissions reduction target, three scenarios are explored: the allocation of abatement payments to agricultural producers equal to 30% (SUBS30), 60% (SUBS60) and 90% (SUBS90) of the unit cost of their mitigation. Thanks to abatement payments, emissions reduction is achieved solely by technique improvements – i.e. reduction in emissions intensities – and no reduction in the EU agricultural production is required, thereby implying no additional imports and no leakage – in contrast to emissions reduction targets with or without tradable emissions quotas discussed above. Nonetheless, abatement payments may be half as effective at reducing non-CO_2 emissions as GHG tax policies. Their effectiveness can be further reduced if land-use change emissions are also taken into consideration (OECD, 2019[20]). Finally, abatement payments are expected to have a global cost of USD 31 billion in 2050, which is very small compared to the amount of government support currently provided to producers for non-environmental purposes (OECD, 2019[20]).

3.2. Demand side

A few studies have explored the implications of consumer taxes applied to ruminant meat[36] and dairy products, which have higher emission intensities compared to other agricultural products (Wirsenius, Hedenus and Mohlin, 2011[42]; Ripple et al., 2013[43]). Wirsenius, Hedenus and Mohlin (2011[42]) estimate that a tax on animal food products equivalent to EUR 60 per tCO_2eq in the EU countries could result in the mitigation of 32 $MtCO_2eq$ per year – an outcome that corresponds to a reduction of 7% of European agricultural emissions and a reduction of 15% in emissions associated with the ruminant meat production.[37] In principle, carbon leakage could be limited (or even avoided), if consumer-based taxes are applied in a non-discriminatory way to both domestic and imported sources of food.

Nevertheless, other effects play out. First, a reduced demand for meat in the EU countries could potentially depress global meat prices and lead to increased levels of meat consumption in non-EU countries (Wirsenius, Hedenus and Mohlin, 2011[42]).[38] This could eventually generate emissions in other countries – even though the magnitude of these emissions is expected to be considerably lower than a leakage that would occur under a carbon-pricing instrument. In addition, recent studies show that producer-based taxes are much more effective at reducing GHG emissions than consumer-based taxes (OECD, 2019[20]; Henderson et al., 2021[44]). Finally, consumer taxes are also likely to be associated with higher prices for food products – especially those with an inelastic demand – which could disproportionately affect low-income households.

4. Trade policies

In this section, existing trade policy instruments that aim to prevent leakage are reviewed and discussed. They can be distinguished into two categories: (i) border carbon adjustments (BCAs) and; (ii) other trade-related measures such as environmental standards for imported goods.

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[36] Dietary changes might have a rather large global effect on emissions reduction, while also potentially having positive impacts on human health and life expectancy in developed countries where increased levels of meat consumption are strongly related to a number of diseases (such as obesity, diabetes, heart disease, cancer) (Fraser, 2009[77]; Stehfest et al., 2009[78]).

[37] Although (Herrero et al., 2016[79]) and (Golub et al., 2013[28]) estimate the effect of carbon pricing on food consumption and food prices – the former on a global level while the latter on a multinational level – they do not estimate the direct effect of a consumer tax on agricultural carbon emissions.

[38] For the least developed countries, this could represent an improvement in nutrition and a welfare gain.

4.1. Border carbon adjustments (BCAs)

A border carbon adjustment is as a measure that adjusts prices of imports in destination markets so that they include the costs they would have incurred had they been subject to the destination market's greenhouse gas emission regime (Cosbey et al., 2012[45]).[39] Such a measure could reduce leakage as domestic products and imports would be subject to climate policies of identical stringency.[40] The compatibility of BCAs with WTO rules has been at the centre of an intense debate in international trade law literature.[41] In summary, the legal validity of BCAs depends on their "specific design features and the modalities of [their] application and implementation" (Mehling et al., 2019, p. 457[46]). Cosbey et al. (2012[45]) point out that, to be compatible with WTO law, at a minimum, BCAs should meet the following conditions: i) focus only on preventing leakage and not on preserving competitiveness; ii) be preceded by *bona fide* attempts at negotiating a multilateral solution; iii) allow foreign individual producers to challenge any benchmark imposed by providing their own data; iv) allow exemptions for countries with comparable climate action.

In addition, the implementation of BCAs raise practical challenges, especially in the agricultural sector. Given the heterogeneous and diffuse nature of agricultural production, the accurate measurement, reporting and verification (MRV) of emissions from the sector is a significant technical challenge. For BCA schemes, this challenge is amplified because it entails the additional MRV burden of accounting for all GHG emissions embodied in imported and domestic and agricultural and food commodities.

The literature suggests that the implementation of BCAs in the agricultural sector can reduce carbon leakage, though the extent of this reduction varies significantly with country characteristics. In particular, for the livestock sector, the implementation of BCAs could neutralise carbon leakage. Nonetheless, such a measure implies significant welfare losses for developing countries as they experience a decrease in their exports – and by extension their output – to countries applying BCAs.

Several studies use a CGE framework to evaluate the effect of BCAs on leakage.[42] Elliott et al. (2010[47]) show that the implementation of a carbon tax accompanied by full BCAs – including both import tariffs and export subsidies – in the Annex B countries of the UNFCCC[43] reduces carbon leakage because, compared to a scenario with a carbon tax alone, production rises in Annex B and decreases in the rest of the world. However, it has no significant effect on global emissions, as higher prices depress consumption in Annex B countries but export subsidies boost it elsewhere. Elliott et al. (2013[48])[44] further show that full BCAs result in half as much leakage as carbon import tariffs alone (Table 1). Similarly, (Böhringer, Carbone and Rutherford, 2018[49]) find that the implementation of embodied carbon tariffs (ECTs)[45] reduces carbon leakage but has no effect on global emissions because carbon intensive output from non-implementing countries is redirected to other non-implementing markets to avoid penalties imposed by the tariffs – i.e. a trade diversion effect. In addition, ECTs increase the cost of global emissions reduction and disproportionately shift the emissions reduction burden to non-OECD countries. Böhringer, Carbone and Rutherford (2018[49]) find that imposing carbon tariffs on energy-intensive and trade-exposed industries

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[39] Although much of the discussion in literature on BCAs has focussed on imports, the measure could also apply on exports with a rebate equivalent to the emissions charges levied in the country of origin.

[40] Note that BCAs would come on top of other trade barriers on imports.

[41] See Mehling et al. (2019[46]) for a recent survey.

[42] These studies derive general results on the effects of BCAs. (Elliott et al., 2010[47]; Böhringer, Carbone and Rutherford, 2018[49]) and (Babiker and Rutherford, 2005[66]) do not include the agricultural sector in their analysis. Agriculture is included in Böhringer, Müller and Schneider (2015[80]).

[43] Annex B or Annex I countries are mostly developed countries that have signed the Kyoto protocol and are subject to caps on their GHG emissions. The difference between Annex B and Annex I countries is that the former is an adjusted list that contains countries that have formally stated their reduction targets.

[44] Elliott et al. (2013[48]) develop an extension of Elliott et al. (2010[47]) in which they exclude export subsidies from the CGE model. Although Elliott et al. (2013[48]) take into account sugar as an agricultural commodity, the study does not incorporate any other agricultural commodity in the analysis.

[45] ECTs mean that the taxation is on the carbon emissions embodied in imported goods.

avoid leakage but may result in more expensive imported intermediate goods, thereby hurting the competitiveness of some domestic industries.

The effectiveness of BCAs in reducing leakage is negatively related to the size of the coalition (Burniaux, Chateau and Duval, 2013[50]; Irfanoglu et al., 2012[51]). Under small coalitions (e.g. EU countries), carbon leakage occurs mainly through international trade losses, with emissions intensive sectors in implementing countries losing market share to competitors in non-implementing countries. In contrast, under large coalitions (e.g. all developed countries), leakage mostly occurs through declining world fossil fuel prices, a process known as energy-market leakage (discussed in Section 2). By definition, BCAs are able to address the former channel but not the latter.

A limited number of empirical studies assess the effects of BCAs on leakage and competitiveness[46]. Larch and Wanner (2017[10]) apply a multi-factor structural gravity model, which allows for the decomposition of emissions changes into scale, composition and technique effects. Under the scenario that Annex I countries of the Copenhagen Accord[47] implement their national emissions targets, they find that the carbon leakage rate is equal to 13.4%. If carbon tariffs are introduced in these countries, the carbon leakage rate falls to 4.14%. Nonetheless, carbon tariffs reduce leakage at the expense of decreasing international trade flows, which is associated with a substantial welfare loss for developing countries.

Only a couple of studies have addressed BCAs with a focus on agriculture. The first study, (Ghosh et al., 2012[52]), finds that when policies are based on all GHGs, implementing BCAs in the European agricultural sector increases the European agricultural output by 0.76% – resulting in a negative leakage[48] of approximately -8% in comparison to alternative scenarios where no BCAs are applied to agricultural imports. Nonetheless, shielding European agriculture against leakage affects non-implementing countries that export agricultural products. For instance, agricultural exports from Brazil would decrease as they become more expensive to European consumers. Next, Irfanoglu et al. (2012[51]) find that the implementation of BCAs in developed countries results in a negative emissions leakage of -14% in the livestock sector – although the leakage rate for all sectors is estimated to be 2%. This is because livestock imports become more expensive, which reduces domestic demand and associated emissions in non-implementing countries. Applying BCAs in the EU countries only would imply a negative livestock emissions leakage rate of -53% – and of 4% for all sectors.

4.2. Other trade-related measures to prevent leakage

Requirements on non-product-related processes and production methods (nprPPMs)[49] are other instruments that are used to promote environmental sustainability, including climate change mitigation. They include mandatory and voluntary environmental standards. Requirements on nrpPPMs can take two forms (Moïsé and Steenblik, 2011[53]). First, they can refer to the specification of technologies allowed or prohibited in the PPMs of the targeted products. Second, they can be the specification of an emissions level – or any other environmental performance indicator, such as resource efficiency – to be achieved, leaving free choice on the technologies to be used to produce the relevant products.

These instruments could reduce carbon leakage, provided the same requirements were applied to both domestic agricultural products and imports. Just as with BCAs, the WTO compatibility for nprPPM requirements is uncertain and will primarily depend on their design. Moïsé and Steenblik (2011[53]) point out that the notions of transparency, predictability, feasibility, and trade effects should matter in determining consistency with WTO rules, but in no way prejudges it. For instance, if a measure requires a technology that is unavailable, unsuitable or prohibitively expensive for trading partners, it will likely be deemed discriminatory and at odds with WTO rules. In addition, the costs of proving compliance with the requirements – i.e. the costs of verification and certification – might be disproportionally high for small

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[46] Condon and Ignaciuk (2013[59]) have developed a very helpful literature review on BCAs and their effect on carbon leakage and competitiveness.

[47] Copenhagen accord was an international attempt to set binding emissions reduction commitments.

[48] Conceptually, a negative leakage occurs when emissions actually decrease non-implementing countries.

[49] See Annex 1 for an overview the existing studies assessing the impact of emissions mitigation policies on carbon leakage.

producers in developing countries where assessment and certification infrastructure is deficient (Moïsé and Steenblik, 2011[53]). This could adversely affect these producers (Brenton, Edwards-Jones and Jensen, 2009[54]; Bowlig and Gibbon, 2009[55]; Edwards-Jones et al., 2009[56]).

Examples of nprPPMs requirements are standards for biofuels in the European Union, Switzerland and the United States. In these countries, domestically produced and imported biofuels must meet minimum reduction targets for life-cycle GHG emissions. Voluntary nprPPMs requirements include product carbon footprint (PCFs) labelling – e.g. the French Casino Carbon Index, the Carbon Reduction Label, the Swiss Climatop label, and the CarboNZero label.[50] Some countries have also adopted government procurement guidelines relating to life-cycle environmental impacts that give preferences to goods and services with low environmental footprints. Notable examples of related nprPPMs provisions can be found in the United States, Switzerland and the EU Member States. The US Energy Independence and Security Act directs that, on a lifecycle basis, GHG emissions from alternative fuels purchased by federal agencies must be lower (or equal) to emissions from conventional petroleum sources. The Swiss sustainable procurement recommendations, issued in 2010, guide procurement services to take into consideration environmental and social concerns, while ensuring value for money in public purchases. The EU regulatory framework for green procurement covers areas such as energy efficient computers and buildings, office furniture made from environmentally friendly wood products, and recyclable paper (Moïsé and Steenblik, 2011[53]).

5. Discussion and conclusion

Agriculture is a GHG intensive sector and scenarios indicate that its share of global emissions could grow substantially in the coming decades if it continues to be exempted from carbon mitigation policies across the world. As with all trade-exposed sectors, carbon leakage may undermine the effectiveness of mitigation policies when the latter are unilaterally introduced. The literature reveals that estimates of carbon leakage rates vary considerably.

Although a *carbon tax* is one of the most cost-efficient policy instruments to mitigate agricultural emissions, the literature suggests that its unilateral application will most probably result in carbon leakage. Studies have estimated that the implementation of a carbon tax in the European Union would result in a leakage rate that ranges from 12.29% to 26.25% depending respectively on whether policies focus on GHG emissions or solely on CO_2 emissions. The leakage rate for OECD countries and for the Annex I countries of the UNFCCC is estimated to vary between 5.2% and 34% and between 13.44% and 55% respectively. Studies done thus far have shown that the magnitude of the leakage effect depends on the level of the tax – with a higher tax resulting in a higher leakage rate.

The unilateral implementation of a carbon tax in agriculture has been shown to reduce the competitiveness of the implementing countries, as compliance costs reduce net exports and impose economic welfare losses on domestic producers. This finding seems to be especially relevant to the livestock sector, which has higher emission intensities compared to other agricultural products. More specifically, a carbon tax in the livestock sector is estimated to generate a leakage rate of 67% if implemented in the Annex I countries and of 54% if implemented in the European Union.

In theory, the literature indicates that a combination of a carbon tax and *BCAs* could prevent leakage. The effectiveness of BCAs is found to be negatively related to the size of the coalition of countries, simply because the bigger the coalition, the smaller the carbon leakage. However, BCAs are expected to disrupt international trade flows and lead to significant welfare loss in countries with less stringent environmental standards that export agricultural products – i.e. the least developed countries. In addition, the difficulty of accurately measuring emissions embodied in imported goods can make BCAs instruments technically challenging – see (OECD, 2020[57]) for a discussion. Therefore, from a global perspective, this cannot be seen as an optimal strategy.

Consumer taxes have been shown to be potentially effective in supplementing supply-side emissions mitigation policies. They can be effective in limiting leakage when applied to both domestic and imported food products. Findings however suggest that they do not provide producers with the same level of

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[50] A potential issue with PCFs labelling is the lack of robust and internationally agreed methodology to estimate the carbon footprint at the product level.

incentives for adopting abating practices as producer-based taxes. In addition, consumer taxes are not as effective as producer-based taxes at incentivising dietary shifts because of the low elasticity of demand to price changes for agricultural goods (OECD, 2019[20]). One (important) exception seems to be ruminant meat and dairy products (Wirsenius, Hedenus and Mohlin, 2011[42]). However, consumer taxes translating into higher prices for such products are likely to disproportionately affect low-income households, which raises equity issues.

Emissions mitigation can also be approached with *abatement payments*, where the government can compensate producers for the costs associated with their agricultural abatements. Considering that many OECD countries and a number of emerging economies already subsidise the agricultural sector, governments could redirect existing distortive support to address environmental externalities and improve economic welfare. As a result and in contrast to carbon taxes, the literature suggests that abatement payments could both preserve domestic comparative advantage and prevent carbon leakage in the implementing countries. Nonetheless, evidence shows that abatement payments are less effective in reducing non-CO_2 emissions compared to GHG taxes.

Overall, a thorough analysis of the existing literature on carbon leakage in the agriculture sector reveals that studies using *ex ante* models tend to provide larger estimates of carbon leakage compared to empirical papers (Branger and Quirion, 2014[58]; Condon and Ignaciuk, 2013[59]). This conclusion echoes the findings of the literature on the pollution haven effect that focuses on industrial sectors only. Studies on industry find that implementing ambitious environmental policies is associated with statistically significant adverse effects on trade, employment, plant location and productivity in the short run. However, the magnitude of these effects are small compared to other determinants of trade and investment location choices such as capital abundance, labour force qualification, customer proximity, or infrastructure quality (Dechezleprêtre and Sato, 2017[60]). One potential reason, as pointed out by (Branger and Quirion, 2014[58]), is that these parameters are not easily modelled in *ex ante* studies. For example, the latter do not include non-tariff trade barriers such as nprPPMs, which potentially could reduce leakage. In addition, modelling studies often impose unrealistic policy assumptions such as compulsory emissions constraints rather than carbon price policies, which may lead to high rates of leakage not found in empirical assessments.

Additional research is required to fill large gaps in the literature. First, more evidence is needed on the potential validity of the Porter hypothesis in the agricultural sector. A few studies suggest that regulation can have positive effects on productivity at the same time as improving environmental performance and that on-farm innovation – e.g. feed and nutrition, animal genetics, pasture management, and animal health – plays a determining role in such performance (DeBoe, 2020[61]). However, Hardelin and Lankoski (2018[62]) point out that information necessary to undertake cost-benefit assessments of environmental regulations in agriculture – including positive or negative impacts on farm productivity – is currently lacking. Data collection efforts and case studies analyses should therefore be ramped up to better understand the relationships between regulation and innovation in agriculture. For example, results-oriented mechanisms seem to be more efficient to stimulate on-farm innovation and adaptation of environmental management practices to local conditions than practice-based mechanisms (DeBoe, 2020[61]).

Second, the literature suggests that environmental standards – i.e. nprPPMs – could potentially reduce leakage and minimise trade distortions. However, as no studies have explored this issue, the exact effects of these standards on agricultural production and leakage remain unclear. Estimating these effects– assuming that producer-based taxes are the main policy instrument used to mitigate emissions – would be relevant.

Third, it would also be relevant to better understand and reconcile the apparent discrepancies in the estimated outcomes between the modelling exercise and the empirical work. Further modelling exercises, with more complex trade structures, are needed to more realistically simulate the impacts and interactions of climate mitigation policies on environmental, economic, and trade outcomes and to better reflect the results of the empirical results.

Finally, only a limited number of studies address the role of government support and other policies affecting agricultural markets in increasing global GHG emissions. More evidence on these issues is needed to properly inform the policy debate on sustainable agriculture and how to reach mitigation targets at the least cost. In particular, a discussion on reforming government support to agriculture seems relevant since it can be potentially environmentally harmful (Henderson and Lankoski, 2019[22]; OECD, 2021[63]), thereby likely contributing to an existing misallocation of agricultural activities across countries.

Annex A. Overview of existing studies assessing the impact of emissions mitigation policies on carbon leakage

Paper	Model	Emissions mitigation policies	Leakage (livestock)	Leakage	Regional coverage	Policy scenario	Agriculture included
Babiker and Rutherford (2005)	CGE	Carbon tax + voluntary export restrains		17%	Global	Kyoto emissions targets for 2010 relative to 1995	No
		Carbon tax + carbon tariffs		11%			
Boringer et al (2018)	CGE	Carbon pricing (emissions tax or ETS)		14.10%	OECD	20% uniform emissions reduction across all OECD relative to 2011	No
		Carbon pricing (emissions tax or ETS) + Carbon tariffs		5.20%			
Boringer et al (2014)	CGE	Carbon pricing (emissions tax or ETS)		30.75%	Switzerland	20% emissions reduction relative to 2011	Yes
		Carbon pricing (emissions tax or ETS) + carbon tariffs		3.88%			
		Carbon pricing (emissions tax or ETS)		4.12%	USA		
		Carbon pricing (emissions tax or ETS) + carbon tariffs		1.98%			
Burniaux et al (2010)	CGE (ENV-Linkages)	Carbon tax $74\$/\text{tCO}_2$		5.90%	Annex I	20% emissions reduction by 2020 and 50% by 2050 relative to 2005	No
		Carbon tax $74\$/\text{tCO}_2$ + BTA		3.40%			
		Carbon tax $63\$/\text{tCO}_2$		7.90%	EU		
		Carbon tax $63\$/\text{tCO}_2$ + BTA		1%			
Elliot et al (2013)	CGE (CIM-EARTH)	Carbon tax $30\$/\text{tCO}_2$ + BTA		4%	Global	2020 relative to 2004	No
		Carbon tax $30\$/\text{tCO}_2$ + import tariffs		8%			
Ghosh et al (2012)	CGE (EC-MS-MR)	CO_2 based abatement policies		26.25%	EU	20% emissions reduction relative to 2004	Yes
		CO_2 based abatement policies + BTA		9.44%			
		GHG based abatement policies		12.29%			
		GHG based abatement policies + BTA		-7.75%			
Gollub et al (2013)	CGE (GTAP-AEZ-GHG)	Carbon tax $27\$/\text{tCO}_2\text{eq}$ + carbon sequestration		25%-55%	Annex I	2020 relative to 2001	Yes
		Carbon tax $27\$/\text{tCO}_2\text{eq}$ + carbon sequestration		Nearly eliminated	Global		
		Carbon tax $27\$/\text{tCO}_2\text{eq}$ + carbon sequestration/Compensation for carbon tax payment		0%	Global/non-Annex I		
Key and Tallard (2012)	Partial equilibrium model (AGLINK-COSIMO)	Carbon tax $30\$/\text{tCO}_2\text{eq}$	67%		Annex I	2013 relative to 2008	Yes
Irfanoglou et al (2012)	CGE (GTAP-AEZ-GHG)	Carbon tax $27\$/\text{tCO}_2\text{eq}$ + carbon sequestration subsidy	47%	11%	Annex I	2020 relative to 2004	Yes
		Carbon tax $27\$/\text{tCO}_2\text{eq}$ + carbon sequestration subsidy + BTA	-14%	2%			
		Carbon tax $27\$/\text{tCO}_2\text{eq}$ + carbon sequestration subsidy	54%	19%	EU		
		Carbon tax $27\$/\text{tCO}_2\text{eq}$ + carbon sequestration subsidy + BTA	-53%	-4%			

Paper	Model	Emissions mitigation policies		Leakage (livestock)	Leakage	Regional coverage	Policy scenario	Agriculture included
OECD (2019a)	CGE (MAGNET)	40$/tCO$_2$eq, 60$/tCO$_2$eq and 100$/tCO$_2$eq for 2021-2030, 2031-2040 and 2041-2050, respectively	Carbon tax		0%	Global	2050 relative to 2011	Yes
			Carbon abatement payment		0%			
			Carbon tax		34%	OECD		
			Carbon abatement payment		0%			
			Carbon tax and food subsidy		0%	Global		
Larch and Wanner (2017)	Structural Gravity model	Carbon tax			6.01%	Global	Implicit carbon tax for each country equal to energy expenses/carbon emissions relative to 2007	Yes
		Carbon tax + carbon tariffs			1.41%	Global	Carbon tariffs equivalent to implicit carbon tariffs relative to 2007	Yes
		Carbon tax			13.40%	Annex I	Emissions reduction targets set in Copenhagen Accord relative to 2007	Yes
		Carbon tax + carbon tariffs			4.14%	Annex I	Emissions reduction targets set in Copenhagen Accord relative to 2007	Yes
Van Doorslaer et al (2015)	CAPRI	HET19			77%	EU	2030 relative to 2005	Yes
		HET28			91%			
		HOM19			67%			
		HOM19ET			64%			
		HOM28			81%			
		HOM28ET			77%			
		SUBS30			-2%			
		SUBS60			-1%			
		SUB90			-1%			

Notes: **Paper** shows the name of the authors and the date that the study was published. Studies are listed in alphabetical order. For more information, check the References section.

Model indicates the model that the study used to estimate leakage. CGE stands for computable general equilibrium.

Emissions mitigation policies specify the policy instrument assumed in each scenario, which can range from carbon pricing mechanisms to trade policies. BTA stand for border tax adjustments and includes both import tariffs and export subsidies. Otherwise, if the scenario assumes only import tariffs then it is indicated as carbon tariffs. HOM19 and HOM28 stand for spatially homogenous emissions reduction targets equal to 19% (HOM19) and 28% (HOM28), respectively. HET19 and HET28 stand for spatially heterogeneous emissions reduction targets equal to 19% (HET19) and 28% (HET28), respectively. HOM19ET and HOM28ET stand for spatially homogenous emissions reduction targets across EU countries equal to 19% (HOM19ET) and 28% (HOM28ET) with emissions trading, respectively. SUBS30, SUBS60 and SUBS90 stand for the allocation of abatement payments to agricultural producers equal to 30% (SUBS30), 60% (SUBS60) and 90% (SUBS90) to the unit cost of their mitigation, respectively. ETS stands for emission trading scheme. CO2eq stands for tonnes of CO2 emissions equivalent.

Leakage shows the share of emissions reduction that is estimated to be neutralised by emissions leakage.

Regional coverage shows the geographical area that the emissions mitigation policy is implemented at. The Copenhagen accord was an international attempt to set binding emissions reduction commitments. Annex I are mostly developed countries that have signed the Kyoto protocol and are subjected to caps on their GHG emissions. Annex II are mostly developing countries.

Policy scenario indicates the time horizon or emissions reduction target of the policy scenario relative to a specific base year.

Agriculture included indicates whether the agricultural sector is included in the model or not.

Source: Authors' elaboration.

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