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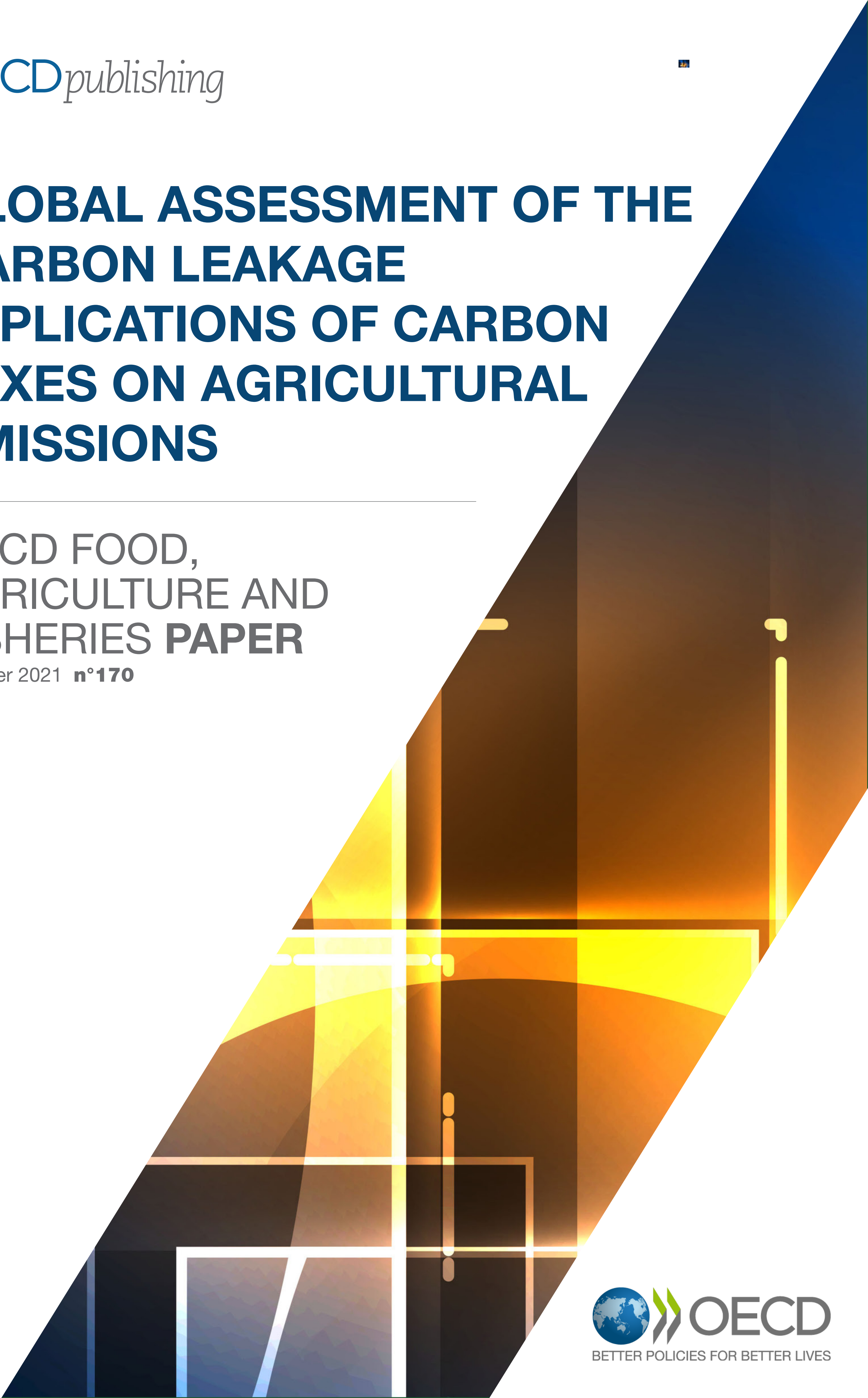

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Global Assessment of the Carbon Leakage Implications of Carbon Taxes on Agricultural Emissions

Ben Henderson and Monika Verma

Carbon leakage arises when emission reductions in countries applying a carbon tax are offset, partially or completely, by emission increases in countries that do not apply the tax or any other greenhouse gas (GHG) mitigation policies. Analysis using the MAGNET computable general equilibrium model indicates that a carbon tax always lowers global GHG emissions from agriculture, even when it is applied in a small group of countries, provided that producers facing the tax can make use of GHG abatement technologies. This suggests that mitigation policies should be considered in conjunction with investments in research and development on abatement practices and technologies. When a small number of countries adopt a carbon tax, about half of the direct reduction in emissions in adopting counties is offset by higher emissions in non-adopting countries; the rate of carbon leakage declines as the group of countries implementing a carbon tax expands. Higher tax rates stimulate larger global emissions reductions, but also induce higher rates of emissions leakage, thus limiting the mitigation benefits from setting higher tax rates in contexts where few countries adopt the policy.

Key words: Climate change, mitigation, trade, environmental policies

JEL Codes: C68, F18, O13, Q11, Q17, Q54

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Key points

The global modelling results in this study indicate that:

- A carbon tax always lowers global greenhouse gas (GHG) emissions from agriculture, even when it is applied to a small group of countries, as long as producers facing the tax can make use of GHG abatement technologies.
- With a small number of countries adopting a carbon tax, about half of the direct reduction in emissions in adopting counties is offset by higher emissions in non-adopting countries.
- Increasing the number of countries adopting carbon pricing policies is an effective means of controlling the leakage of emissions.
- GHG mitigation policy packages that include investments into the research and development of abatement technologies significantly enhance the effectiveness of carbon pricing policies, and help to minimise carbon leakage.
- Higher carbon prices stimulate larger global emission reductions, but also induce higher rates of emission leakage, thus limiting the mitigation benefits from setting higher carbon prices in contexts where few countries adopt the policy.

Executive Summary

The objective of this study is to assess the mitigation potential of carbon taxes applied to agricultural (non-CO_2) greenhouse gas (GHG) emissions from a selection of countries, taking into account carbon leakage. Carbon leakage arises when reductions in emissions from countries applying the tax are offset, partially or completely, by increases in emissions from countries not applying the tax.

A computable general equilibrium model was used to assess a total of 20 carbon tax scenarios, varying across three different dimensions—the level of the carbon tax, the number of countries implementing the tax, and the availability of abatement technologies. Results from these scenarios show that the net reductions in global agricultural emissions from using carbon taxes are always positive, as long as agricultural producers have access to and adopt abatement technologies. In other words, carbon leakage is never likely to be high enough to fully offset the reduction in emissions from a group of countries applying carbon taxes.

The extent of carbon leakage from carbon taxes is much reduced by the availability of abatement technologies and practices, which allow producers to lower their emissions per unit of agricultural commodity. Moreover, the availability of these measures is more effective at mitigating emissions than increasing the price of carbon alone, for any group of countries. Hence, a key policy conclusion is that mitigation policies should be considered in conjunction with investments for the research and development of abatement practices and technologies.

At the same time, the degree of carbon leakage is also lower if the group of countries implementing a carbon tax is larger. Thus political efforts to widen the use of carbon pricing policies among countries, especially those that are large emitters and producers, would also be effective in reducing global emissions and controlling leakage.

If both Australia and New Zealand or Northern European countries as a group, were to implement a carbon tax of USD 100 $tCO_2\text{-eq}^{-1}$ by 2050, then about half of their emission reductions would be offset by carbon leakage. Increasing the number of countries applying the tax to include all OECD countries, plus Brazil, the People’s Republic of China (hereafter “China”) and other non-OECD countries from East Asia would cause the leakage rate to fall to 21%, enabling total global non-CO_2 emissions from agriculture to fall by

605 $MtCO_2$-eq or 9.6% compared to baseline emissions (i.e. global agricultural non-CO_2 emissions would fall from 6 307 to 5 702 $MtCO_2$-eq, in 2050).

Doubling the carbon tax from USD 100 tCO_2-eq^{-1} to USD 200 tCO_2-eq^{-1} for OECD countries as a whole, would cause large increases in mitigation by these countries from 391 to 505 $MtCO_2$-eq, in 2050. However, the price increase was found to increase the leakage of emissions from 31% to 44%, resulting in far more modest gains in global mitigation from 268 to 307 $MtCO_2$-eq in 2050. In contrast, maintaining the carbon price on OECD country emissions at 100 tCO_2-eq^{-1}, while assuming abatement technologies are unavailable, sees the leakage rate double (from 31% to 64%) and global mitigation fall from 268 to 83 $MtCO_2$-eq, in 2050.

There are some important factors that these models do not capture, which may cause them to overestimate carbon leakage. For instance, countries may reap marketing and market access benefits by taking the early initiative in implementing carbon pricing policies. New Zealand is one country moving cautiously, but positively in this direction with plans to price agricultural emissions by 2025.

Further work could also usefully assess the impact of removing distorting agricultural support policies on agricultural emissions and leakage, in the context of mitigation policy development. The quantification of such effects would be particularly valuable given the high levels of support that agriculture receives globally.

1. Rationale and objectives

Agriculture is one of the main sectors responsible for climate change. Between 2007 and 2016, the sector directly contributed approximately 12% of global anthropogenic greenhouse gas (GHG) emissions (6.2 ± 1.4 GtCO2eq) and was responsible for an additional 9% of global GHG emissions each year (4.9 ± 2.5 GtCO2eq) from changes in land use (i.e. the conversion of forestland to cropland and grassland (IPCC, 2019[1])).

With the exception of emissions from energy use for large-scale facilities in a small number of countries, the agricultural sector has been exempted from mitigation policies that apply the "polluter pays principle", such as carbon taxes or emissions trading schemes. To date, a limited number of mainly voluntary policies, including those that involve paying farmers to abate emissions, have been the main policy options employed to lower agriculture's net GHG emissions. This is due, in part, to a reluctance to impose costs on producers (OECD, 2019[2]).[1] As a consequence, mitigation efforts in agriculture are lagging behind other sectors, and stronger mitigation policies in the sector are needed to efficiently tackle climate change. In addition, reforms to reduce agricultural support policies that can raise GHG emissions will also need to be part of an efficient policy strategy to lower GHG emissions in the sector (Henderson and Lankoski, 2019[3]).

Despite the slow pace of mitigation policy progress, some countries are contemplating ambitious mitigation targets for the agricultural sector. However, concerns about the carbon leakage effects, which occur when country efforts to reduce GHG emissions are, partially or completely, offset by increased emissions from countries without mitigation policies, may continue to hinder progress towards more ambitious policy development. These leakages stem from cross-country differences in the stringency of climate policies, which cause unequal compliance costs between foreign and domestic producers, undermining the net global impact of these policies. As shown in OECD (2019[2]), the leakage of emissions is mainly associated with mitigation policies based on the "polluter pays principle", as these policies impose costs on producers.

The agricultural sector is facing a complex triple challenge of: providing food security and nutrition to a growing work population; generating livelihoods for farmers and others connected to the sector; while using resources sustainably and contributing to GHG mitigation targets. An understanding of the potential for national GHG mitigation policies to result in carbon leakage, in the form of higher emissions in other countries, is a pre-requisite for understanding how these multiple objectives can be reconciled at the national and global levels. This study aims to build knowledge on the importance of carbon leakage effects

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[1] The OECD report by Henderson, Frezal and Flynn (2020[10]) provides a survey of GHG mitigation policies in the AFOLU sector.

in the agricultural sector, by quantitatively assessing the potential for emissions leakage as a consequence of applying a tax on agricultural GHG emissions, for a selection of countries. The relationship between: net global mitigation; carbon leakage; the level of the carbon tax; the number of countries taxing emissions; access to abatement technology; and agriculture's exposure to trade, is explored.

The study is exploratory and, as with all *ex ante* models, it includes a number of generalisations and assumptions (outlined and discussed in Sections 2 and 3, and in the Annex). Given the global scale of the assessment, it does not consider farmer-level risk preferences and their impacts on production. It also does not consider market or non-market risks that may occur outside of the policy experiments, such as those related to disease epidemics, climate change and natural disasters. Nevertheless, it is well-founded in general equilibrium theory and offers a rigorous assessment of policy changes and impacts that is well-suited to the scale of the assessment.

2. Modelling approach and scenarios

2.1. Model and data

This analysis builds on previous work presented in Chapter 2 of OECD (2019[2]) and uses the same Modular Applied GeNeral Equilibrium Tool (MAGNET) model (Woltjer et al., 2014[4]). This model, developed and managed by Wageningen Economics Research (part of Wageningen University and Research), is a recursive dynamic multi-sector, multi-region Computable General Equilibrium (CGE) model that covers the global economy. There are eleven primary production sectors in agriculture, including eight crop sectors (paddy, wheat, other grains, oilseeds, sugar beet and cane, fruits and vegetables, other crops, other plants and fibres) and three livestock sectors (ruminants, pigs and poultry and dairy cattle). As in (OECD, 2019[2]) countries are aggregated into 21 global regions and countries.[2]

MAGNET uses the GTAP 9.2 database (Aguiar, Narayannan and McDougall, 2016[5]), which has a base year of 2011, but is updated in this assessment to create a dynamic baseline, from 2011 to 2050, with yield, economic and population growth assumptions that conform to the 'middle of the road' Shared Socioeconomic Pathway, SSP2 (Fricko et al., 2017[6]). The model also incorporates emissions from the latest GTAP non-CO_2 database (Irfanoglu and van der Mensbrugghe, 2015[7]), including methane (CH_4) and nitrous oxide (N_2O). Livestock non-CO_2 emissions and Rice CH_4 emissions are tied to the output variables of these respective sectors within the MAGNET model. Whereas N_2O emissions from crop fertiliser use are tied to the fertiliser input variable in these sectors. Additional details about the integration of emissions into the production structure of the model are provided in Annex A.

2.2. Experiment design

A summary of all 20 of the policy scenarios, including their names and characteristics is provided in Table 1. These scenarios differ according to two different carbon tax rates, five different geographic regions, and two different abatement technology settings (i.e. with and without the availability of abatement technologies). The 2050 prices are indicated in the first column, the five country groupings are shown in the top row, and the availability of abatement technologies is noted in the second column of Table 1. More specifically, two different carbon tax pathways were applied. The first involved initially setting the carbon price to USD 40 tCO_2eq^{-1} in 2020-2030, and increasing this to USD 60 tCO_2eq^{-1} in 2030-2040, then increasing it to USD 100 tCO_2eq^{-1} for the final 2040-2050 period. The second carbon price pathway simply involved doubling these carbon taxes in each simulation period, to reach a rate of USD 200 tCO_2eq^{-1} in the final 2040-2050 simulation period. The carbon taxes are applied directly to agricultural non-CO_2 emissions and a total of 20 policy scenarios were assessed relative to a baseline scenario from 2020 to 2050, without any carbon taxes.

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[2] United States, Canada and rest of North America, Brazil, Mexico, Chile, Latin America, Japan-Korea, China-Hong Kong (China), India, South Asia, South-east Asia, Russian Federation, Caribbean, North EU, Central EU, South EU, Rest of Europe, Israel and Turkey, Middle-east and North Africa, Sub-Saharan Africa, Australia and New Zealand.

As mentioned, the carbon tax is only applied to the non-CO_2 emissions (described in Section 2.1). The reasons for focusing on these emissions are two-fold. First, the scope of the assessment is limited to the agriculture sector which, from a UNFCCC inventory accounting perspective, does not include CO_2 emissions from on-farm fuel and energy use, and also does not include downstream emissions from post-farm food processing and upstream emissions from the production of agricultural inputs. Second, non-CO_2 emissions account for the vast majority of emissions from the agriculture sector, with a share of 83% of all on-farm emissions from agriculture 2018. For OECD countries as a whole, this share is slightly lower, at 79% (FAOSTAT, 2021[8]).

Introducing a price on carbon incentivises producers to adopt abatement technologies and practices, which reduce the GHG emissions generated for each unit of agricultural product. To incorporate these responses into the model, data from the US EPA (2013) on the marginal abatement costs (MACs) associated with practices and technologies were used. These include measures for lowering the main non-CO_2 emission sources including CH_4 from enteric fermentation by ruminants (i.e. cattle, sheep and goats), N_2O and CH_4 from livestock manure, CH_4 emissions from paddy rice and N_2O emissions from soil associated with fertiliser use by crops. Accordingly, it is these emission sources that are targeted with mitigation policy instruments in this study. It should be noted that the MACs used in this assessment do not include assumptions about technological change, from the development and adoption of new technologies which are likely to lower the costs of mitigation over time. Consequently, the MAC data used in this assessment are conservative with respect to their assumed GHG mitigation potential, especially over the longer term. More details about both the MAGNET modes and the approach for incorporating the abatement technology responses in the model are provided in Annex A.

The leakage rate for the purpose of this study is defined as the sum of the increases in agricultural emissions in countries without carbon tax policies, divided by the sum of the reductions in agricultural emissions in countries that implement mitigation policies. Thus, a leakage rate of less than 1 signifies a net reduction in global GHG emissions from agriculture.

Table 1. Summary of mitigation policy scenarios

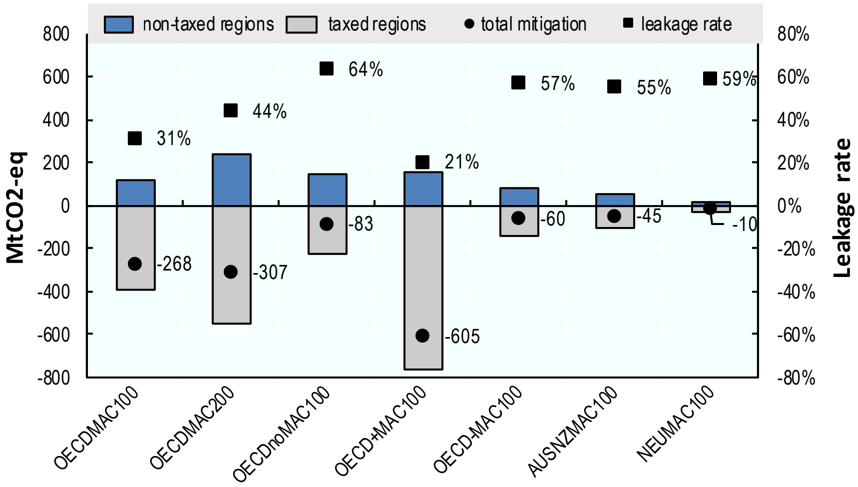
Tax	Abatement technology[a]	OECD, Brazil, China	OECD	Australia-New Zealand, Northern Europe, Canada	Australia-New Zealand	Northern Europe
100	Yes	OECD+MAC100	OECDMAC100	OECD-MAC100	AUSNZMAC100	NEUMAC100
200	Yes	OECD+MAC200	OECDMAC200	OECD-MAC200	AUSNZMAC200	NEUMAC200
100	No	OECD+noMAC100	OECDnoMAC100	OECD-noMAC100	AUSNZnoMAC100	NEUnoMAC100
200	No	OECD+noMAC200	OECDnoMAC200	OECD-noMAC200	AUSNZnoMAC200	NEUnoMAC200

a. This feature of MAGNET model, developed in OECD (2019[2]), enables the use of abatement technologies and practices to be employed, thereby allowing the emission intensity of agricultural production to decline.

3. Scenario results and discussion

A snapshot of the changes in global GHG emissions from agriculture in the year 2050 is shown for a selection of the scenarios in Figure 1. Net global emissions decline in all scenarios, with access to abatement technology and the size of the country groups implementing the tax playing the most decisive roles. Doubling the tax rate used — comparing OECD100MAC and OECD200MAC — does not make much difference to total mitigation because the rate of leakage increases as the carbon price increases. While the increase in the carbon price causes emissions among the OECD countries implementing the tax to fall a further 40%, increases in carbon leakage wipe out most of the additional mitigation. This is because the carbon tax has the dual impact of lowering emissions per unit of output (due to the adoption of abatement technology) and lowering production, due the costs they impose on producers – and as the carbon price doubles, this latter impact becomes relatively larger. This suggests that in the absence of increased participation by countries in the tax policy, the additional gains in net global mitigation from OECD countries adopting a more aggressive carbon price would be limited.

Figure 1. Mitigation of agricultural GHG emissions (million tonnes CO2-eq) in 2050 (left) and leakage rates (right)



Note: As mentioned, the leakage rate is defined as the sum of the increases in agricultural emissions in countries without carbon tax policies, divided by the sum of the reductions in agricultural emissions in countries that implement mitigation policies. Thus, a leakage rate of less than 100% signifies a net reduction in global GHG emissions from agriculture.

The absence of abatement technologies (OECDMAC100 vs. OECDnoMAC100) has a big influence on both the total emission reduction and the leakage rates, causing the leakage rate to more than double (from 31% to 64%) and total mitigation to fall dramatically. As expected, the expansion of regions covered by the tax works in the other direction, lowering the rate of leakage. For instance, in addition to substantially increasing total mitigation, expanding the coverage of countries beyond the OECD to also include Brazil, and China – other East Asia[3] regions (comparing OECDMAC100 to OECD+MAC100) causes leakage to fall from 31% to 21%. In contrast, restricting the tax to three OECD regions (comparing OECD-MAC100 to OECDMAC100), causes a near doubling of the leakage rate compared to the scenario in which agricultural emissions in all OECD countries are covered by the carbon tax. However, further reductions of the size of the implementing coalition do not appear to further increase the leakage rate, despite the coalition's share of global market share of agricultural production shrinking from just over 4% to less than 2% when moving from the OECD-MAC100 scenario (which includes Northern Europe, Australia-New Zealand and Canada) to either Australia-New Zealand (AUSNZMAC100) or the Northern Europe (NEUMAC100) scenarios (Table 2).

A combination of demand and supply responses underlie net production and leakage outcomes. The carbon tax causes the supply of the affected commodities to fall in the country (countries) with the tax, which raises world prices and stimulates the production of these commodities in untaxed countries. The extent to which untaxed countries can offset the shortfall in supply will depend on how much their marginal production costs increase as they expand output, and also on the capacity of consumers to bear the ensuing price increases. This in turn depends on the size of the aggregate supply reduction in taxed countries. As the pool of taxed countries and supply shortfall increases, so too does the production needed from smaller pool of untaxed countries to offset the shortfall. Thus, leakage rates decline because the capacity and resources available to respond to the shortfall also decline. The extent to which consumer markets can bear the increase in prices associated with the higher marginal production costs induced by the carbon tax also depends on the price elasticities of demand for these commodities. The more inelastic that demand is, the larger the capacity of the consumer market will be to absorb any price increases and, consequently, the smaller the net reduction in taxed commodities and their associated leakage rates will be, putting aside the effect of regional variations in emission intensities.

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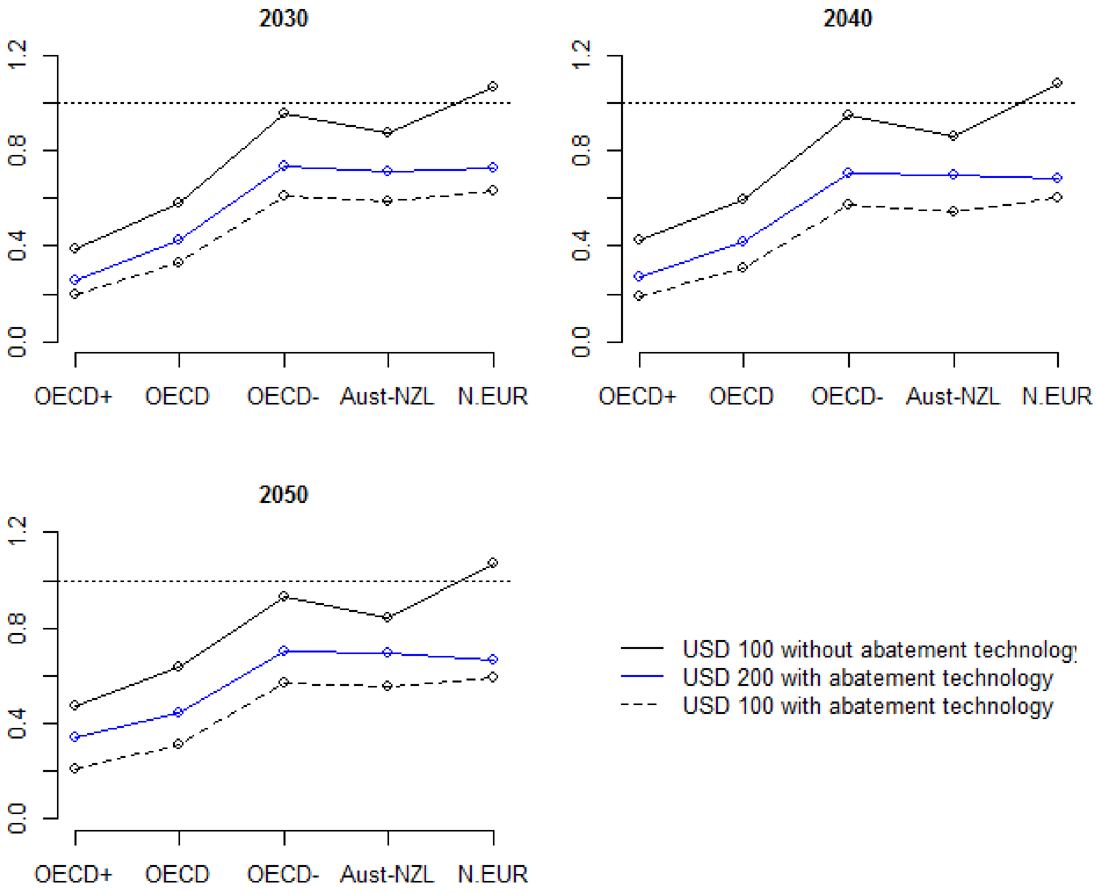
[3] This includes China-Hong Kong (China), Mongolia, Macau (China), Chinese Taipei, and the Democratic People's Republic of Korea.

Figure 2. Leakage rates for the different carbon tax scenarios



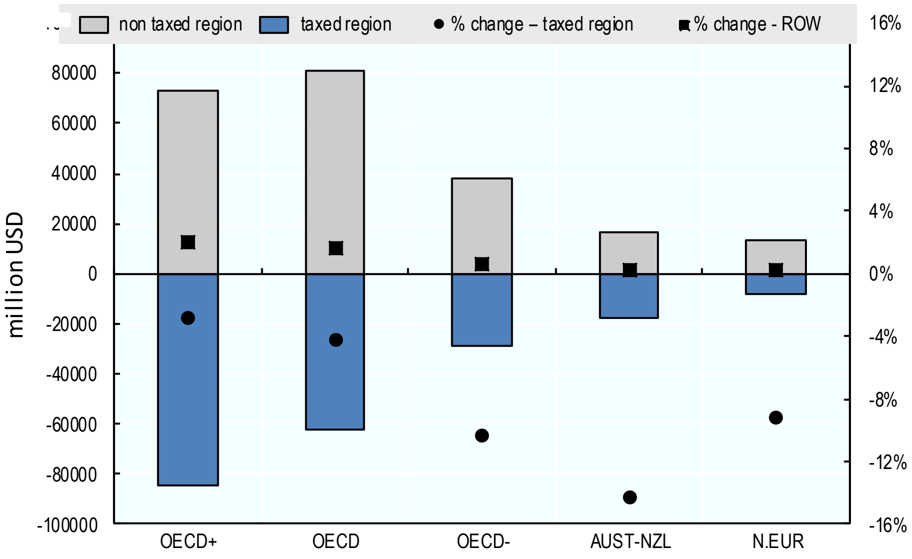
Looking more closely at the leakage rates across the different simulation years, the impacts of global agricultural production share, the carbon tax rate and the availability of abatement technology are shown more clearly in the panel of line graphs displayed in Figure 2. These results clearly demonstrate that for all regional groupings and years, the adoption of abatement technology is a more significant factor affecting carbon leakage than the level of the carbon price. In fact, a lack of abatement technology inflates the leakage rate to between 84% and 108% across all simulation years for the three smallest country groups. Further, the leakage rate for Australia-New Zealand is slightly lower than for the OECD- coalition (containing Australia-New Zealand, Northern Europe and Canada) in all simulation years. This again demonstrates that the coalition shares of global production, shown in the third column of Table 2, are important, but not always decisive.

Table 2. Shares of global agricultural output in 2050

	Composition of agriculture within regional group		Share of global production
	Crops	Livestock	Agriculture
World	68%	32%	100%
OECD+	57%	43%	45%
OECD	60%	40%	22%
OECD-	51%	49%	4.2%
AUST-NZL	47%	53%	1.8%
NEU	43%	57%	1.3%

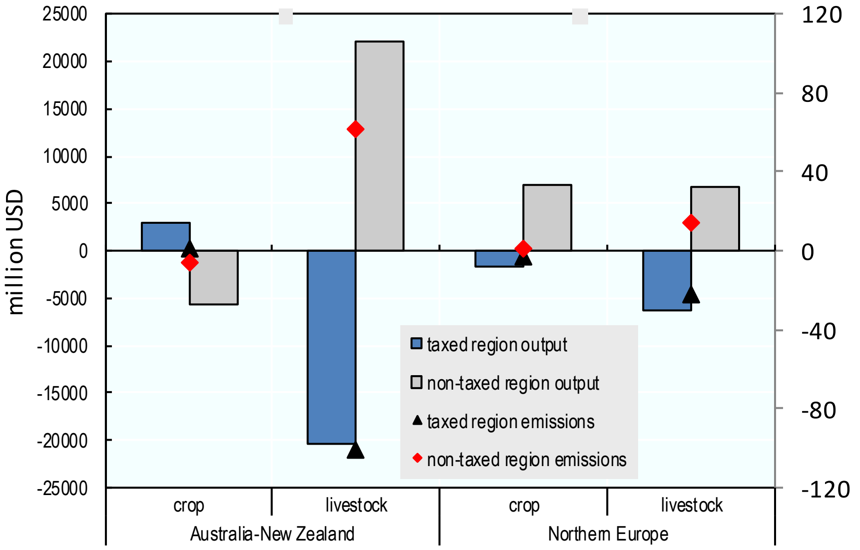
The impact of trade and production displacement from taxing emissions at USD 100 tCO_2-eq is shown below for the different implementing regional groups in 2050 (Figure 3). As expected, the reductions in aggregate agricultural production in the taxed regions are offset by increases in the non-taxed regions. These aggregate adjustments capture some of the mechanics that underpin the leakage responses, but they only provide a partial explanation for the leakage rates associated with each scenario.

Figure 3. Changes in agricultural output relative to baseline in 2050 at USD 100 tCO2-eq^{-1}, with access to abatement technology



A more detailed presentation of the changes in agricultural commodities underlying the changes in aggregate agricultural production in Figure 3, is shown for Australia-New Zealand and Northern Europe in Figure 4. Additional attention is given to these two implementing regions, because they have the smallest global shares of agricultural production and similar rates of leakage, but there are differences in the mechanics underpinning the leakages they experience. The results show that the change in aggregate output in Australia-New Zealand is underpinned by substantial reductions in livestock production within the region and similarly large increases in livestock outside of the region, with corresponding changes in livestock emissions moving in line with these adjustments. Although not reported in Figure 4, the reduction in livestock output in Australia-New Zealand represents a 32% reduction against the baseline in 2050. The carbon tax causes a similar pattern of changes in livestock output and emissions in Northern Europe, however the swings in production are more muted in both absolute and percentage terms. For instance the fall in livestock output in Northern Europe represents a 13% reduction against baseline livestock production in that region in 2050.

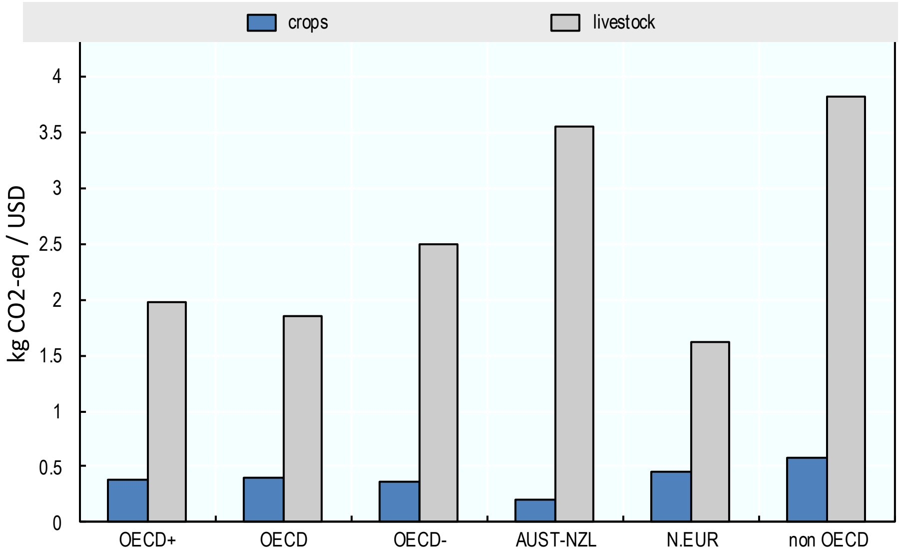
Figure 4. Changes in crop and livestock output in Australia-New Zealand and Northern Europe relative to baseline in 2050 at USD 100 tCO2-eq^{-1}, with access to abatement technology



The reasons for the large reduction in livestock production in Australia-New Zealand are two-fold. Firstly, the impact of the carbon tax is primarily dependent on the economic emission intensity of the agricultural commodities in each region (i.e. the amount of GHG emissions from a sector divided by the economic value of its output). The emission intensities reported in Figure 5 vary across the different regional groups, however they are by far the highest for the livestock commodities. Among the different groups, the livestock emission intensities are notably highest in Australia–New Zealand and in non-OECD countries, due to the presence of more extensive ruminant livestock production systems in these regions. The average emission intensity of livestock production in the Australia–New Zealand grouping is slightly in excess of 3.5 $kgCO_2$-eq per USD across all simulation periods (mainly due to the high contribution of livestock products from extensive ruminant production systems in Australia), compared to the lower global average figure of 3 $kgCO_2$-eq per USD. For Northern Europe, the average emission intensity is considerably lower at 1.6 $kgCO_2$-eq per USD. The livestock sector is also more reliant on crop as feed source for livestock in Northern Europe than in Australia–New Zealand. In 2050, crop products account for 35% of livestock production costs in Northern Europe, whereas they only account for 15% of livestock production costs in Australia–New Zealand. As explained below, these differences help to explain differences in the size and direction of changes in crop and livestock production in Australia–New Zealand and Northern Europe.

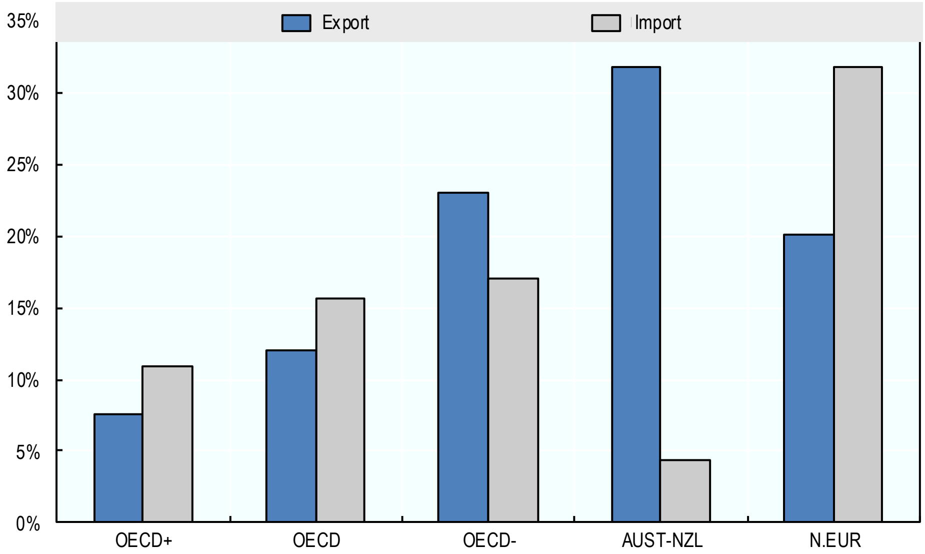
In contrast to the movements in livestock production, the changes in crop production in both regions move in opposing directions. The relationship between the changes in livestock and crop production are governed by two counteracting influences: competition effects between livestock and crops for land and production resources; and complementary production effects from the use of crops as a source of feed for livestock. Australia–New Zealand, where livestock production is significantly more emission intensive, is less reliant on crops as a source of livestock feed than in Northern Europe. Hence, the effect of the tax on releasing production resources from livestock production for crop production dominates, causing crop production to increase. In Northern Europe, where livestock have a greater reliance on crop for feed, the tax causes both livestock and crop production to fall. The increase of crop production in Australia–New Zealand is the main reason that the leakage rate in in this region is slightly lower than in Northern Europe. Another factor behind these differences in leakage rates, is the higher emission intensity of livestock in Australia–New Zealand relative the rest of world.

Figure 5. Baseline emission intensities of agricultural production kgCO_2-eq per USD of primary agricultural production in 2050



Note: The emission intensities are derived by dividing the non-CO_2 emissions associated with the production of crop and livestock commodities, by the value of these commodities at world prices. World (fob) prices are used to remove the impact of subsidies and taxes from distorting the comparisons between regions. The emissions are from the non-CO_2 emissions database prepared by Irfanoglu and van der Mesnbrugghe (2015[7]) for use in computable general equilibrium models. These emissions are, in turn, drawn from the FAOSTAT GHG emissions database (FAOSTAT, 2021[8]), which calculates these emissions based on the Tier 1 IPCC Guidelines for national GHG Inventories. Further details about the approach used for calculating these emissions can be found in Irfanoglu and van der Mesnbrugghe (2015[7]) and FAOSTAT (2021[8]). It should be noted that most OECD countries compute their own GHG emissions using more sophisticated and accurate calculation methods, and they report these emissions each year in their national GHG inventory reports submitted to the UNFCCC. The agricultural GHG emissions calculated in these reports will differ from those used in this modelling study. Furthermore, the emission intensities reported here for aggregate regions will differ from those calculated for individual countries. For New Zealand, emissions intensity figures calculated using emissions estimates from their GHG inventory (which is submitted to the UNFCCC) are more accurate than the aggregate figures used in this report and show a lower level of emissions intensity than in this study.

Figure 6. Baseline import and exports of livestock commodities as a share of livestock production in 2050



A further explanation behind the large displacement of livestock production in Australia – New Zealand is the relatively high degree of trade exposure of livestock commodities (Figure 6). Exports in particular account for high share of livestock production (including both primary and processed livestock products) in Australia–New Zealand, but also in the larger regional group of OECD (which again includes Australia–New Zealand, Canada and Northern Europe). This also suggests that the main avenue for leakage in these regions is via the displacement of their livestock products from export markets, rather than from competition with imports. For Northern Europe competition with imports is likely to be an additional important factor.

The study is exploratory and, as with all *ex ante* models, it includes a number of generalisations and assumptions that influence the results. For instance, some aspects of the model used in this assessment may cause higher leakage rates than would be observed in reality. On the one hand, model specifications that limit both the substitutability of imported and domestically produced commodities, and the capacity to develop new trade relationships, restrict trade flows in response to policy changes. Despite this, real-world adjustments in trade are unlikely to be as frictionless as they are in the CGE model used in this assessment. Reasons for this include the conversion of quantity-based trade measures, such as those that impose quotas on imports, into price-based equivalents, as well as the exclusion non-tariff measures, such as sanitary and sanitary and phytosanitary requirements that can restrict trade flows. Nevertheless, the mitigation and carbon leakage rates calculated in this study are within the range results from other studies in literature that use *ex ante* economic models. However, *ex ante* models such as the one used in this assessment have a tendency to calculate higher leakage rates compared to those found in *ex post* empirical assessments (OECD, 2020[9]).

Furthermore, there are two assumptions underlying the MACs used in the assessment, which increase the cost of abatement and, consequently, the leakage rate. First, the assumed absence of technological change will upwardly bias these costs, especially over the longer term. Second, setting the segments of the MAC curves that have negative costs (associated with abatement technologies that are calculated to be profitable to implement) in US EPA (2013) to zero in the model (Annex A) also upwardly biases abatement costs. More importantly, there are potential marketing and market access benefits for countries with the initiative to become early movers in implementing stringent mitigation policies in agriculture. However, these benefits are neither certain or easy to quantify. New Zealand is one country moving cautiously, but positively in this direction with plans to with plans to introduce a price on agricultural emissions by 2025, but not necessarily through the New Zealand Emissions Trading Scheme. The sector-government partnership (He Waka Eke Noa) will work to establish an approach to price agriculture emissions by 2025 (Henderson, Frezal and Flynn, 2020[10]). As explained in Gruère and Henderson (2020[11]), concerns about non-mitigating competitors encroaching on New Zealand's export market share do not appear to have outweighed expectations about the potential benefits of this important policy step, such as encouraging other countries to take action and the potential for global consumers to increase their preference for New Zealand's agricultural products.

In addition to the assumptions discussed above, the data inputs used in the model will also affect the results. For example, some countries have detailed emissions data, which could alter the results if used instead of the emissions data from the global database employed in the assessment. The aggregation of countries also prevents some country-specific insights. For example, the same commodity produced in Australia and New Zealand will have different emission intensities. Therefore, the regionally aggregated policy results for these countries would differ from the country-specific results that would be obtained if the same policy experiments were applied to each county separately. Similarly, there are alternative MAC data to those employed in this assessment (USEPA, 2013[12]). Due to time and budget constraints, more recent MAC data from US EPA (2019) or other sources were not included in the assessment. The model results are also affected by the decision to limit the carbon tax to non-CO_2 emissions from agriculture. As explained, these account for the vast majority of emissions from agriculture. Nevertheless, applying the carbon tax to CO_2 emissions from on-farm fuel and energy use, would increase the costs of the carbon tax for agriculture and potentially increase the leakage rate estimates in this study. For countries such as Australia and New Zealand, where emissions from on-farm fuel and energy only comprise 6% of (non-CO_2 + CO_2 emissions fuel and energy use) agricultural emissions, this increase would be slight. For Northern Europe, where this share increases 15% (FAOSTAT, 2021[8]), the increase in leakage rates is likely to be slightly larger.

Future work could be done to decompose the carbon leakage results according to different trade channels, under a broader range of mitigation policies. This could include policy formulations that can lower cost of a carbon tax on producers by using tax revenue to offset the costs of adopting abatement technologies. Further insights about leakage could be gained by considering scenarios in which all sectors of the economy are included in the tax policy. Future assessments with this methodology would also benefit from a sensitivity analysis with respect to the value of elasticities between domestic and imported commodities, and with respect other assumptions such abatement technological change, to provide more comprehensive insights about the drivers of leakage. An additional important area of work would be to assess the impact of removing distorting agricultural support policies on agricultural emissions and leakage, in the context of mitigation policy development. As concluded in previous OECD assessments (OECD, 2019[2]; Henderson and Lankoski, 2019[3]), the economic efficiency of mitigation policies could be enhanced if they are implemented alongside reforms to agricultural support policies that can raise GHG emissions.

Annex A. Additional Details on the Model and Approach for Incorporating Abatement Technologies

MAGNET is based on the Global Trade Analysis Project (GTAP) database and model that has been developed at Purdue University in the United States (Hertel and Tsigas, 1996[13]). MAGNET and GTAP were originally designed to model the effects of trade policies, such as the Uruguay Round of multilateral trade negotiations, especially on the agricultural sectors. MAGNET has been extended and updated with several modules to improve the modelling of land markets and agricultural policies, biofuel policies, socio-economic and environmental impacts of environmental policies.

As mentioned in Section 2, the model incorporates non-CO_2 emissions data, including methane (CH_4) from enteric fermentation and manure management in the livestock sectors and from paddy rice production, as well as and nitrous oxide (N_2O) from livestock manure and urine, and from crop fertiliser use. Livestock non-CO_2 emissions and Rice CH_4 emissions are tied to the output variables of these respective sectors within the MAGNET model. Whereas N_2O emissions from crop fertiliser use are tied to the fertiliser input variable in these sectors. Data on the percentage reductions of these main non-CO_2 emission sources for a given GHG price, along with the costs of abatement at that price, were obtained from the MAC curves reported in (USEPA, 2013[12]). The measures for reducing enteric fermentation in the EPA study include the use of antibiotics, bovine somatotropin, propionate precursors, anti-methanogens, and intensive grazing, while the measures for reducing emissions from manure management focus on different technologies for anaerobic digesters suited to different scales of production, with smaller scale low-tech options used in developing country settings. For dryland crop production, the measures focused on those used for reducing N_2O emissions from fertiliser, including optimal fertilisation, split fertilisation, no-tillage, nitrification inhibitors, and residue incorporation. To reduce CH_4 and N_2O emissions from rice production, a combination of water-(midseason drainage, continuous flooding, alternative wetting/drying, dry seeding, and dryland rice), residue (100%/50% residue incorporation and no tillage), and fertiliser management (ammonium sulphate fertiliser, increased/reduced fertilisation, optimal fertilisation, slow release fertiliser, and nitrification inhibitors) were used (USEPA, 2013[12]).

These MAC curve data have a global coverage and they were aggregated to match the 21 regions used in the MAGNET for this assessment. The MAC curve data for livestock non-CO_2 emissions and rice CH_4 emissions were incorporated into the MAGNET model by applying the same percentage changes from the USEPA MAC curves within the relevant agricultural sectors of the MAGNET model. The corresponding abatement costs were included by using negative total factor productivity shocks, which require each of the livestock and rice sectors to use more production resources to produce the same amount of output. The additional costs imposed by these shocks were set at a level that matched the positive portion of the abatement costs reported in the USEPA MAC curves.

A caveat related to this approach is that the input resource changes associated with implementing the abatement practices in the USEPA MAC curves will not be precisely matched to the agricultural input changes in MAGNET. Importantly, however, the approach used in this assessment incorporates costs that match the positive costs in the USEPA MAC curves, and ensures that the abatement responses in MAGNET entail the use of additional input resources. The USEPA MAC curves also include negative costs for the initial levels of abatement in each sector, however, these negative costs were assumed to be zero in this assessment. This conservative assumption inflates the costs of the abatement options in this model relative to the USEPA MAC curves. A similarly conservative approach is applied in other CGE studies that use USEPA MAC data (Golub et al., 2009[14]; Golub et al., 2013[15]). The USEPA MAC curves were available for the years 2020 and 2030, and these were matched to the corresponding simulation years in the MAGNET model. The year 2030 marginal abatement cost data from USEPA (2013) were also applied for the 2040 and 2050 simulation years in MAGNET. For N_2O emissions from fertiliser use by crops, the standard substitution relationships between fertilisers and other intermediate inputs, and between intermediate inputs and value-added, which are governed by the price elasticity of substitution parameters in the model, where considered to provide an adequate representation of the abatement responses and costs in the model. Therefore, no additional abatement structure was added to the model to manage the abatement responses of this emission source. Similar assumptions were also used in CGE assessments by Golub et al. (2009[14]) and Golub et al. (2013[15]).

Specification of trade flows and taxes

MAGNET assumes that products traded internationally are differentiated by country of origin following the Armington assumption. This assumption generates smaller and more realistic responses of trade to price changes than implied by models of homogeneous products (Armington, 1969[16]). The Trade or Armington elasticities are taken from the GTAP database (Aguiar, Narayannan and McDougall, 2016[5]).

Additional taxes and subsidies (including the GHG taxes modelled in this study), are not *a priori* (by design) redistributed within the economy, but they induce a higher government deficit or surplus. The GHG taxes lead to a lower deficit or higher surplus.

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