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Please cite this paper as:

Henderson, B. *et al.* (2021-01-28), “Policy strategies and challenges for climate change mitigation in the Agriculture, Forestry and Other Land Use (AFOLU) sector”, *OECD Food, Agriculture and Fisheries Papers*, No. 149, OECD Publishing, Paris.
http://dx.doi.org/10.1787/47b3493b-en

OECD Food, Agriculture and Fisheries Papers No. 149

Policy strategies and challenges for climate change mitigation in the Agriculture, Forestry and Other Land Use (AFOLU) sector

Ben Henderson,

Stefan Frank,

Petr Havlik,

Hugo Valin

OECD

OECD FOOD, AGRICULTURE AND FISHERIES PAPERS

The report was declassified by the OECD Joint Working Party on Agriculture and the Environment in October 2020 and was prepared for publication by the OECD Secretariat.

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Policy Strategies and Challenges for Climate Change Mitigation in the Agriculture, Forestry and Other Land Use (AFOLU) Sector

Ben Henderson (OECD)
Stefan Frank, Petr Havlik and Hugo Valin
(International Institute for Applied Systems Analysis – IIASA)

This study uses GLOBIOM – the most detailed global economic model of agriculture, land use and greenhouse gas (GHG) emissions – to assess the effectiveness of different policies in cutting net emissions from the Agriculture, Forestry and Other Land Use (AFOLU) sector, with a view to helping limit long-term global temperature increases to 1.5°C and 2°C. Trade-offs between emission reductions and impacts on food producers, consumers and government budgets are also evaluated for each policy package. A full complement of policy options is deployed globally across AFOLU, comprising emission taxes for emitting AFOLU activities and subsidies rewarding carbon sequestration. Using a carbon price consistent with the 2°C target (1.5°C target), this is projected to mitigate 8 GtCO2 eq/yr (12 GtCO2 eq/yr) in 2050, representing 89% (129%) reduction in net AFOLU emissions, and 12% (21%) of total anthropogenic GHG emissions. Nearly two-thirds of the net emission reductions are from the Land Use, Land-Use Change and Forestry (LULUCF) component of AFOLU, mostly from reduced deforestation. A global carbon tax on AFOLU is found to be twice as effective in lowering emissions as an equivalently priced emission abatement subsidy because the latter keeps high emitting producers in business. However, a tax has trade-offs in terms of lower agricultural production and food consumption, which a subsidy avoids. A shift to lower emission diets by consumers has a much smaller impact on reducing agricultural emissions than any of the policy packages involving taxes on emissions.

Key words: GHG emission tax, abatement subsidy, Paris Agreement

JEL codes: C61, F18, Q11, Q18, Q54, Q56, Q58

Acknowledgements

The authors wish to acknowledge the valuable feedback provided by OECD delegations, which helped to improve the clarity and quality of this report. Thanks are also extended to Guillaume Gruère, Marcel Adenäuer, Jonathan Brooks, Jussi Lankoski, Santiago Guerrero, and Julia Neilson for their constructive comments and suggestions throughout the review process.

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Key points

- Modelling results suggest that a comprehensive policy strategy, comprising of agriculture and land use emission taxes and subsidies for carbon sequestration, at a carbon price consistent with a 2ºC (1.5ºC) objective could reduce global AFOLU emissions by 8 GtCO2 eq/year (12 GtCO2 eq/year) in 2050. This represents an 89% (129%) reduction in net AFOLU emission.
- 63% of the net emission reductions with the comprehensive policy package relate to land use and land use change and forestry (mainly avoided deforestation) emissions, 28% to agriculture emissions and 9% to soil carbon sequestration.
- The policy choices invoke different trade-offs: while a global carbon tax on AFOLU is found to be twice as effective in lowering emissions as an equivalently priced emission abatement subsidy, the use of emission taxes lowers agricultural production by 3-8% and per capital consumption by 2-4%, which emission abatement subsidies avoid. Taxes also raise revenues, while subsidies require government expenditures.
- A shift to lower emission diets by consumers is assessed to have a much smaller impact on reducing agricultural emissions than any of the policy packages that tax these emissions.

Executive Summary

The Agriculture, Forestry and Other Land Use (AFOLU) sector accounts for 23% of net global greenhouse gas (GHG) emissions and without strong policy action to lower these emissions, this share is likely to grow. Thus, the sector has an important role to play in stabilising global temperatures. Governments in a number of countries are taking steps to lower net AFOLU emissions, as part of their economy-wide GHG mitigation efforts, yet progress has been gradual and piecemeal and is occurring against a backdrop of increasing urgency for action on climate change. This inertia may reflect some of the challenges in identifying suitable goals for mitigation in the AFOLU sector, including the need for policies to accommodate concerns about potentially negative effects on food security and farmer livelihoods, particularly in least developed countries. It also reflects difficulties in designing efficient goals and policies for different AFOLU activities that take into account their often complex impacts on land use.

This study aims to help address this gap by helping to frame broad levels of ambition for the AFOLU sector in different world regions, within the context of economy-wide efforts to meet the climate stabilisation objectives of the Paris Agreement on Climate Change. Specifically, this study seeks to identify how much the AFOLU sector could contribute to limiting long-term global temperature increases to 1.5°C and 2°C, based on policy simulations made with the Global Biosphere Management Model (GLOBIOM).

The policy packages used in this assessment apply a combination of taxes and subsidies (set at the same carbon price) to AFOLU emissions and abatement sources. The taxes cover non-CO_2 emissions from agriculture (principally methane and nitrous oxide emissions from animals and crops), and CO_2 emissions from the Land Use, Land-Use Change and Forestry (LULUCF) mainly from deforestation. Subsidies, on the other hand, are used to reward carbon sequestration in forest biomass (e.g. through afforestation) and agricultural soils (from improved cropland and grazing land management), and the uptake of non-CO_2 abatement technologies in agriculture. These technologies include: dietary additives and feed quality improvements to reduce enteric methane from ruminants; anaerobic digester technologies for reducing methane emissions from manure management; agronomic practices to lower nitrous oxide emissions from fertiliser use on crops; and drainage management practices to lower methane emissions from paddy rice production.

Growing demand for bioenergy is assumed to be met from a combination of agricultural crops, dedicated tree plantations and forest biomass. These plantations and biomass can contribute to mitigation in the

AFOLU sector via the accumulation of carbon stocks in afforested land. By contrast, energy emission reductions associated with bioenergy use are not counted as AFOLU emission reductions and are therefore not included in this assessment. For all of the policy packages, carbon prices consistent with economy-wide efforts to stabilise global temperatures at 2°C or 1.5°C were used. To streamline the reporting of results, the main focus of the report is on the scenarios relating to the less ambitious 2°C stabilisation goal.

The main findings from the assessment are as follows:

- When the full complement of policy options is deployed globally across AFOLU, using a carbon price consistent with the 2°C target, the AFOLU sector is projected to mitigate 8 $GtCO_2eq\ yr^{-1}$ in 2050. This represents an 89% reduction in net AFOLU emissions, and 12% of total anthropogenic GHG emissions in 2050.
- The collective impact of the emission taxes is about twice as large as that of abatement subsidies reflecting an equivalent carbon price, given that the former significantly reduces emissions from land clearing, reallocates agricultural production towards less emission intensive commodities, and reduces overall consumption by raising the prices of agricultural products.
- By raising agricultural production costs, the policy packages that include emission taxes cause global per capita calorie consumption to be 2-4% lower relative to the baseline in 2050 and global agricultural output to be 3-8% lower. In contrast, the policy packages that only subsidise mitigation have negligible impact on agricultural production and food consumption.
- On the other hand, taxes deliver the double dividend of stronger mitigation and net increases to government budgets. In fact, the revenues from the emission taxes, particularly those applied to agriculture, were found to dwarf the costs of abatement subsidies in the AFOLU sector.
- Limiting the geographical scope of emission taxes lowers food security impacts at the cost of reducing their mitigation potential. Exempting least developed countries from paying emission taxes, while deploying the full complement of policy options across AFOLU in other countries attenuates, but does not eliminate, losses in per capita food consumption in least developed countries. At the same time, it lowers global mitigation by AFOLU from 8 $GtCO_2eq$ to 6 $GtCO_2eq$, in 2050 compared to the global application of the most comprehensive AFOLU-wide policy.
- A tax on LULUCF emissions, which was found to be the single most effective component of the AFOLU policy package, creates relatively low impacts on consumers and producers compared to the taxes on agricultural emissions. These impacts are lower because the tax on LULUCF emissions affects agricultural production indirectly, through raising the cost of converting forests and other natural land to agriculture, compared to the tax on non-CO_2 emissions which more directly raises agricultural production costs.
- Increasing the stringency of the global climate stabilisation goal from 2°C to 1.5°C involves a substantial increase in the global carbon price from USD 70/$tCO2eq^{-1}$ to USD 240/$tCO2eq^{-1}$ by 2050. This increases AFOLU's global mitigation potential from 8 to 12 $GtCO_2eq$, but it also generates much larger production and land use impacts.

Looking in more detail at the mitigation contributions to the central AFOLU-wide policy package, consistent with the 2°C target, which reduced net AFOLU emissions by 8 $GtCO2eq\ yr^{-1}$:

- The bulk of the emission reductions from the full package of policies are from non-agricultural LULUCF (63%), particularly from a reduction in the clearing of forests and other vegetation (41%).
- Reductions in non-CO_2 emissions from agriculture contribute 28% of AFOLU-wide reductions in 2050 despite agriculture accounting for the majority of AFOLU emissions.
- Soil carbon sequestration on agricultural land contributes a further 9%.
- Most of the emission reductions from avoided land clearing are located in Latin America, sub-Saharan Africa and, to a lesser extent, Southeast Asia. Afforestation also makes a sizeable contribution (22%), particularly in Latin America.

The tax and subsidy policies also have different implications for way that agricultural land is used to produce crops for food and bioenergy. In each mitigation policy scenario, increases in the demand for bioenergy cause similar increases in the agricultural land area devoted to energy crops. When agricultural emissions are taxed, agricultural land falls, but the land used for food production falls by more than land used for energy crops. In contrast, when abatement subsidies are applied on their own, there is a modest fall in agricultural land devoted to food production, which is more than offset by the increase in land used to produce energy crops. In this case, the increase in production of energy crops comes from the conversion of non-agricultural land.

Policy packages specifically targeted towards the agricultural sector or towards the LULUCF sectors can affect mitigation outcomes in the other sector, as a consequence of land use interactions For example, mitigation policies in the LULUCF sector reduce agricultural land use and production, which in turn slightly lowers the overall impact of agricultural mitigation policies, simply by lowering the amount of emissions which these agricultural policies can target. The reverse is also true, with agricultural mitigation policies also slightly reducing the impact of LULULF policies on reducing LULUCF emissions.

The mitigation potential of lowering the content of livestock products in consumer diets (except in least developed countries and India) which was also explored, is not as effective as the emission taxes. The strongest dietary shift, involving a 50% reduction in the consumption of these products by 2050, was only found to be half as effective at lowering agricultural emissions as the USD 70/tCO2eq-1 tax on these emissions. However, the dietary scenarios are not linked to a policy intervention, so cannot be compared directly with the policy packages assessed in this report. Furthermore, the mitigation potential of consumer-based policies is likely to be lower than suggested by the dietary shift scenarios modeled in this study.

The sensitivity of the main global results to changes in assumptions about climate change, progress in the development of non-CO2 abatement technologies, and macro-economic trends (i.e. Shared Socioeconomic Pathway assumptions) is also assessed. The impacts of these changes were compared to the central mitigation policy package targeting all AFOLU emission and abatement sources. The acceleration of abatement technology progress significantly improved the effectiveness of policies in lowering non-CO2 emissions. Changing the macroeconomic trends also had a large impact on the AFOLU mitigation outcomes. In contrast, these outcomes are less sensitive to alterations in the climate change pathway.

1. Background and objectives

The Agriculture, Forestry and Other Land Use (AFOLU) sector accounts for 23% of global greenhouse gas (GHG) emissions, with 11% coming from agriculture and 12% from the rest of AFOLU (IPCC, 2019[1]). Given its large and potentially growing contribution to total emissions and the availability of cost effective mitigation options (OECD, 2019[2]), the sector can make an important contribution, along with other sectors, to the climate stabilisation objectives of the Paris Agreement (Clark et al., 2020[3]). As outlined in Article 2 of the Paris Agreement, this involves limiting "the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UNFCCC, 2016[4]).

Current commitments and policy actions to mitigate net AFOLU emissions vary markedly among countries, but their overall impact is expected to be minor and not commensurate with the sector's contribution to climate change (OECD, 2020[5]). There are several challenges to scaling up mitigation policy efforts in AFOLU, including the need to consider the impacts of complex interactions between different land use activities on policy performance. Accommodating concerns about food security and farmers' livelihoods, particularly in least developed countries, present further challenges to policy makers. It also reflects difficulties in designing efficient goals and policies for different AFOLU activities with complex land use interactions. Global economic models can help to shed light on ways to address these challenges, by calculating the potential impact of mitigation policies, while incorporating these interactions and other important economic relationships.

A number of modelling studies have assessed GHG mitigation policies in the agricultural sector, providing useful insights about their effectiveness and their economic impacts on the sector (OECD, 2019[2]). However, these studies have tended to ignore important linkages between agriculture and other land uses and, in particular, the interactions between mitigation policies in the agriculture and Land Use, Land-Use Change and Forestry (LULUCF) sectors.

In this study, policy packages targeting mitigation across a broader range of AFOLU mitigation sources than in previous studies are considered. With this modelling framework, the primary objective of this study is to answer the following question: How much can the AFOLU sector contribute to the net global emission reductions needed across all sectors of the economy to limit average global temperature increase to 1.5°C and 2°C? The following sub-objectives both support and complement this primary objective:

- define and assess policy packages for AFOLU (i.e. both agriculture and LULUCF sectors), commensurate with economy-wide global efforts to limit global average temperature increases to 1.5°C and 2°C; and
- evaluate the impacts of these policy packages on food producers and consumers, and government budgets, to provide information which policy makers can use in developing mitigation strategies to manage these trade-offs.

To address these objectives, the Global Biosphere Management Model (GLOBIOM) was used. This modelling assessment adds to previous OECD work in this area (OECD, 2019[2]) by addressing the broader question as to how much the AFOLU sector could contribute to achieving the mitigation goals of the Paris Agreement. To do this it expands the coverage of mitigation measures and sectors within AFOLU beyond policies targeting non-CO_2 emissions in agriculture to include: policies to promote carbon sequestration in forestland and agricultural soils. It also incorporates the impacts of climate change on agriculture.

In addition to calculating the greater combined potential for emission reductions in this larger set of mitigation policies and measures, this expanded coverage also enables the assessment of policy interactions between sectors. In OECD (2019[2]) it was shown that a carbon tax in agriculture could leverage significant additional mitigation from the LULUCF sector, particularly through avoided deforestation. With the expanded sectoral coverage of mitigation sources in GLOBIOM, the impact of mitigation policies directly targeting the LULUCF sector on agricultural emissions and production can also be assessed.

GLOBIOM has previously been coupled to MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) to incorporate information and economic feedback from mitigation policies in the energy sector, particularly in relation to bioenergy demand. Together, GLOBIOM-MESSAGE is one of the main integrated assessment models (IAMs) that quantifies GHG mitigation potential in AFOLU sector for the IPCC special reports on climate change and land (IPCC, 2019[1]), and on global warming of 1.5°C (IPCC, 2018[6]). For consistency, this and the other IAMs included in these reports have typically relied on a simple uniform carbon price policy across different sectors, to determine the least cost contribution of each sector to economy-wide climate targets.

The GLOBIOM assessment in the present study also adds value to the above IAM assessments, by considering a broader range of mitigation policy options, including the possibility of subsidising abatement measures in agriculture in addition to taxing GHG emissions. Some of the value added in relation to previous OECD assessments that are discussed above also apply here. These include the addition of soil carbon sequestration on agricultural land, and forest management options for sequestering carbon within existing forest land. This latter feature comes from new model development as part of this project that allows for endogenous representation of afforestation, and the inclusion of additional drivers for deforestation outside agriculture in the model (Annex A).

The main strengths of GLOBIOM is its detailed representation of different land use sectors and their interactions and, through its many applications in climate change mitigation, significant capacity has been invested in the model for representing mitigation options and policies, as well as incorporating the impacts of climate change. Consequently, GLOBIOM incorporates a more detailed portfolio of mitigation options, covering both non-CO_2 and CO_2 emissions, than other global partial equilibrium models such as MAgPIE (Model of Agricultural Production and its Impact on the Environment), GCAM (Global Climate Change Analysis Model) and IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade). In addition, GLOBIOM also includes endogenous demand-side responses to mitigation policies. Moreover, a major strength of this latest version of GLOBIOM is the endogenous representation of the forestry sector. This is critical for realistically representing agricultural-forestry interactions and is missing from other global partial equilibrium models such as MAgPIE, GCAM, and IMPACT.

2. Modelling approach and scenarios

2.1. Modelling approach

The global economic assessment in this study is conducted with GLOBIOM (Global Biosphere Management Model), which is a partial equilibrium model that includes both the agricultural and forestry sectors. A detailed description of the model is provided in Annex A.

Marginal abatement costs (MACs) data from the US EPA (2013[7]) and Beach (2015[8]) are incorporated in the model, to reflect the use of mitigation technologies at different carbon prices for reducing non-CO_2 emissions from agriculture. Previous global modelling assessments by the OECD (OECD, 2019[2]) and others, including those that have used GLOBIOM (Frank et al., 2018[9]) have also relied on these sources of MAC data. Details about these MACs, the process used to incorporate them and the mitigation measures that they cover, are provided in Annex A. These include: dietary additives and feed quality improvements to reduce enteric methane from ruminants; anaerobic digester technologies for reducing methane emissions from manure management; agronomic practices to lower nitrous oxide emissions from fertiliser use on crops; and drainage management practices to lower methane emissions from paddy rice production. In addition, the MAC data used to represent soil carbon sequestration in agricultural soils, improved cropland and pastureland[1] management, are provided in Annex A.

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[1] In this assessment the term pasture includes both intensively managed planted pastures and more extensively managed grazing areas such as rangelands.

2.2. The baseline and mitigation policy scenarios assessed

A set of 20 scenarios were assessed, including 1 baseline scenario and 19 mitigation scenarios were implemented and quantified in GLOBIOM, from 2010 to 2050. The central baseline and policy scenarios includes yield and economic growth assumptions that conform to the “middle of the road” Shared Socioeconomic Pathway (SSP2) (Fricko et al., 2017[10]). This is one of five SSP scenarios[2] that have been developed by the climate change research community to facilitate the integrated analysis of climate change impacts, mitigation and adaptation. These pathways represent different narratives that describe plausible major global developments that will create different challenges for the mitigation and adaptation to climate change (Riahi et al., 2017[11]). The “middle of the road” SSP2 narrative used in this assessment is described as presenting medium challenges to mitigation and adaptation, and it describes a world in which economic, technological and social trends do not differ significantly from historical patterns (Riahi et al., 2017[11]).

The baseline scenario used corresponds to this SSP2 narrative and does not include any mitigation policies. Additional details about the baseline assumptions, including for the growth population, GDP per capita and agricultural productivity are provided in Annex A.

The purpose of these scenarios is to calculate the net GHG emission reductions possible in AFOLU, that are consistent with the 1.5°C and 2°C targets, under policy schemes with varying sector coverage and the policy approaches for applying carbon price incentives. For the climate change impacts under the mitigation scenarios, representative concentration pathway RCP2.6 is also used, because this is presently the best proxy for both the 1.5°C and 2°C impact pathways.

The AFOLU mitigation policies cover the following emission and abatement sources:

1. Agriculture[3]
    a. Non-CO_2 emissions: N_2O fertiliser and manure application, manure management, CH_4 from enteric fermentation, rice cultivation and manure management
    b. CO_2 removals from sequestration in cropland and grassland soils[4]
2. (Non-agricultural) LULUCF
    a. Above and below ground CO_2 emissions from forest management, deforestation, and other land use changes (e.g. conversion of natural vegetation and peatlands)
    b. CO_2 removals from the sequestration of carbon above ground and below ground, from afforestation and net removals (removals minus emissions) the establishment of dedicated energy plantations[5]

The specific emissions and abatement sources covered by each mitigation policy scenario are outlined in detail Table 1. The policy package in the first row (*2c_afolu*) is the most comprehensive, targeting the most number of mitigation sources in the AFOLU sector an emission tax on non-CO_2 emissions from agriculture and on CO_2 emission sources from LULUCF; and a subsidy for the adoption of non-CO_2 abatement

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[2] In addition to “the middle of the road” SSP2 used in this study, are the following SSPs: SSP1 - “Sustainability - Taking the Green Road (Low challenges to mitigation and adaptation)”; SSP3 – “Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)”; SSP4 – “Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)”; and SSP5 – “Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenge to adaptation)” (Riahi et al., 2017[11]).

[3] Direct CO_2 emissions from agriculture (from fuel and energy use) are not included in the assessment.

[4] IAMs currently do not explicitly capture soil carbon losses in their climate stabilisation pathways (Smith, 2016[48]). Nevertheless, agricultural soils are estimated to have lost significant amounts of carbon following conversion from native vegetation (according to Sanderman et al. (2018[49]) around 133 Pg C over the past 200 years) and global warming may further amplify carbon losses from soils (Crowther et al., 2016[51]).

[5] N_2O emissions from short rotation plantations (SRPs) for bioenergy are also included in this assessment. With respect to carbon stocks and CO_2 emissions SRPs Land converted to SRPs can either (depending on the original land cover) create emissions (e.g. if forests are converted) or (temporal) removals if the average carbon stock over the rotation period of the SRP is higher than that of the original vegetation. This (temporal) effect is only accounted for once in GLOBIOM when converting the land.

technologies in agriculture (e.g. anaerobic digesters, feed supplements etc.), and for carbon sequestered on agricultural land and from afforestation.

The rest of the policy packages cover fewer mitigation sources within the AFOLU sector. For example the AFOLU-wide tax policy package (*2c_afolu_tax*) includes taxes on non-CO_2 emissions from agriculture and on CO_2 emissions from LULUCF sources, but does not include subsidies for carbon sequestration or for the adoption of non-CO_2 technologies. Conversely, the AFOLU-wide subsidy policy package (*2c_afolu_sub*), includes these subsidies, but none of the taxes. The remaining policy packages target each the agriculture and LULUCF sectors separately, using either a combination of tax and subsidy policies (*2c_agri*, *2c_lulucf*) or just the tax policies (*2c_agri_tax*, *2c_lulucf_tax*) or only the subsidy policies (*2c_agri_sub*, *2c_lulucf_sub*) (Table 1).

One of the main purposes of modelling the agriculture- and LULUCF-specific scenarios is to calculate the extent to which the concessions in sectoral coverage lower the mitigation potential for the AFOLU sector as a whole. The sector-specific scenarios also help to reveal the respective contributions from each component of the AFOLU policy package, and the as well as the impact of policy and land use interactions between each sector on the mitigation outcomes.

Table 1. The GHG emission and abatement sources targeted in the AFOLU mitigation policy scenarios, as part of global sector-wide efforts to limit global warming to 1.5°C and 2°C

Scenario names	Mitigation policy schemes		Agriculture		(Non-agricultural) LULUCF	
			Non-CO_2 emissions	Soil carbon sequestration^a	CO_2 emissions^b	Carbon sequestration^b
2c_afolu, 1.5c_afolu	AFOLU	Tax	✓		✓	
		Subsidy		✓		✓
2c_afolu_tax,1.5c_afolu_tax		Tax	✓		✓	
		Subsidy				
2c_afolu_sub,1.5c_afolu_sub		Tax	✓	✓		✓
		Subsidy				
2c_agri, 1.5c_agri	Agriculture	Tax	✓			
		Subsidy		✓		
2c_agri_tax, 1.5c_agri_tax		Tax	✓			
		Subsidy				
2c_agri_sub, 1.5c_agri_sub		Tax	✓	✓		
		Subsidy				
2c_lulucf, 1.5c_lulucf	LULUCF	Tax			✓	
		Subsidy				✓
2c_lulucf_tax, 1.5c_lulucf_tax		Tax			✓	
		Subsidy				
2c_lulucf _sub, 1.5c_lulucf_sub		Tax				✓
		Subsidy				

Notes: a) Emission reductions from soil carbon sequestration are reflected in the LULUCF sector of countries' national inventories.
b) CO_2 emissions and carbon sequestration are from both above ground and below ground biomass sources in forestry and other land use sectors.

As mentioned in the note of Table 1, changes in soil carbon stocks are assigned to the LULUCF sector of national GHG inventories. However, since these actions occur on agricultural land and directly affect the production decisions of farmers, for policy purposes it makes sense to refer to policies targeting this abatement source as agricultural sector policies. Thus, for the remainder of the document, the policies targeting non-CO_2 emissions and soil carbon sequestration on agricultural land are designated as agricultural sector policies. All of the other policy options are designated as LULUCF sector policies.

There is an additional AFOLU-wide scenario, not shown in Table 1, which is the same as *2_afolu*, but which exempts least developed countries from paying taxes on emissions from either the agriculture or LULUCF sectors, called *2_afolu_wo_tax_ldc*.[6] While these countries are exempted from paying taxes the subsidies for non-CO_2 abatement, soil carbon sequestration and afforestation are all maintained. The exemption of least developed countries from taxes on AFOLU emissions is considered due to concerns about the impact of emission taxes on worsening food security and landholder incomes. This is a highly approximate attempt to consider the Common but Differentiated Responsibilities and Respective Capabilities (CBDR-RC) principle of the United Nations Framework Convention on Climate Change (UNFCCC), which acknowledges the differing capabilities and responsibilities of countries in tackling climate change.[7] Furthermore, poor producers in countries that are not classed as least developed, including in India and Latin America, are not exempt from paying emission taxes in the *2_afolu_wo_tax_ldc* scenario. Therefore, this scenario could still worsen food security among poor households in these countries.

For all of the global mitigation scenarios, bioenergy demand and carbon price trajectories consistent with the 2°C or 1.5°C climate stabilisation targets were implemented. In GLOBIOM, biomass demand for bioenergy can be satisfied from dedicated energy plantations, and forest biomass including forest industry residues. Energy plantations are represented through short rotation tree plantations of poplar, willow, or eucalyptus with rotation periods of up to 10 years. With respect to forests, biomass for bioenergy can be either sourced directly from managed forests (roundwood and fuelwood harvest including logging residues) or from forest industry by-products (sawdust, woodchips, bark, black liquor, and recycled wood). First generation biofuel demand sourced from annual crops (corn, wheat, sugarcane, rapeseed, soybean, sunflower, oil palm) is based on Lotze-Campen et al. (2014[12]) and kept constant across mitigation scenarios. In the baseline scenario, total biomass demand is projected to decline to around 28 EJ/yr in 2050 driven by the substitution of non-commercial biomass including fuelwood with other energy feedstocks. Bioenergy demand is projected to increase from around 55 EJ/yr in 2010 to 84 EJ/yr and 119 EJ/yr respectively in the 2°C and 1.5°C scenarios at global scale by 2050. In particular in Sub-Saharan Africa (24 EJ/yr and 25 EJ/yr by 2050) and Latin America (18 EJ/yr and 36 EJ/yr by 2050) significant growth in biomass production for bioenergy is anticipated through the establishment of dedicated energy plantations and increased forest harvest. Beyond 2050, ambitious climate stabilisation pathways show an even sharper increase in biomass demand (Lauri and Nordin, 2017[13]; Obersteiner et al., 2018[14]). The bioenergy demand and carbon prices were derived, prior to the modelling activity described in this study, in the MESSAGE-GLOBIOM framework and are consistent with achieving the above climate targets, cost-efficiently across all sectors (including AFOLU) over time. The implications of these changes in bioenergy demand on the final energy split on different fuel sources and on carbon capture and storage are not explicitly considered in this study, as only the land use sectors and GLOBIOM are within the scope of this study.

This carbon price trajectory from this framework reaches USD 70 and USD 240/tCO_2eq^{-1} for the 2°C and 1.5°C scenario respectively by 2050. These carbon prices are used for all the tax and subsidy policy instruments in the assessment. Both the carbon prices and demand for bioenergy enter the current GLOBIOM assessment as exogenous trends. Consequently, rather than starting with a GHG mitigation target for AFOLU, this study seeks to identify mitigation contributions from AFOLU that make sense, for carbon prices that are reflective of economy-wide global efforts to meet the temperature goals of the Paris Agreement.

Each of the nine policy schemes in Table 1 are repeated for both the 2°C and 1.5°C targets, for a total of 18 global policy scenarios. It should be noted that only the first policy scheme in this table will induce emission reductions from the AFOLU sector that are consistent with global sector-wide efforts for meeting these targets, because this scenario covers all of the sector’s emission and abatement sources, and regions. The implication for all of the other policy schemes, is that more mitigation would be required from other sectors, and at higher cost, to meet the shortfall from AFOLU.

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[6] This includes: all countries in sub-Saharan Africa except South Africa; all countries in South Asia except India; all countries in South East Asia, and all Pacific Island countries.

[7] The CBDR-RC principle is enshrined in the 1992 UNFCCC treaty, https://unfccc.int/resource/docs/convkp/conveng.pdf.

Additional stylised scenarios are constructed to assess the mitigation potential of from reducing the amount of livestock products in consumers' diets. Since livestock products account for most of the GHG emissions in consumers' basket of food products, these changes are expected to make an important contribution to emission reductions. However, these scenarios differ from those outlined in Table 1 as the changes in consumption are made directly in the model and do not occur in response to an explicit policy intervention to achieve the changes in consumption. In other words they are foresight scenarios, which reveal the technical rather than policy potential of changes to consumer diets. Consequently, the dietary change scenario descriptions and results are presented in Box 1 rather than in the main body of the report.

2.3. Sensitivity analysis

A number of additional scenarios are also conducted in relation to the central *2c_afolu* scenario to assess the impact of the following factors on mitigation outcomes:

- Change in the shared socioeconomic pathway from SSP2 to SSP1
- Climate change impact assumptions
- Technological progress for add-on technologies

Change in the shared socioeconomic pathway (SSP)

In this set of scenarios the impact of the *2c_afolu* mitigation policy was quantified for SSP1 – i.e. the underlying population and GDP growth assumptions, yields, and diets were changed to match those consistent with SSP1. Mitigation efforts (carbon price and bioenergy demand) were maintained at the SSP2 levels to enable comparison with the central *2c_afolu* scenario.

Climate change impact assumptions

The sensitivity of emissions and mitigation outcomes to different assumptions about climate change are also assessed. Specifically, the impact of different representative concentration pathways on the mitigation outcomes for the central *2c_afolu* policy package was also quantified. These included comparing the outcomes of RCP 6.0, RPC 8.5, and RCP 8.5 without CO_2 fertilisation, in comparison to the central RCP 2.6 assumption.

Technological progress for abatement technologies

For abatement technologies which target non-CO_2 emissions, the impacts of technological changes that improve their cost-effectiveness are assessed. In the standard scenarios emission saving coefficients and impacts on yields for the non-CO_2 technologies change proportionally to any yield increases assumed for crop- and livestock in SSP2. This assumption ensures that the percentage of emissions reduced by a particular technology is maintained over time.

For the sensitivity analysis additional technological progress assumptions are based on Harmsen et al. (2019[15]) who assumed that an additional 10% of non-mitigated residual emissions can be abated once all technologies have been adopted. We apply the same assumption for technologies with a negative emission coefficient and increase the efficiency (10% of residual emissions). For technologies with a positive emission factor (e.g. those that increase yields but result in some increases in emissions as well), we assume that emission increases are reduced by 10% in 2050. On top of the improvements in emission factors, we also assume a 28% decrease in costs by 2050.[8]

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[8] This is based on assumptions in the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) assessment, shown in Table 1 of Höglund-Isaksson (2018[51]).

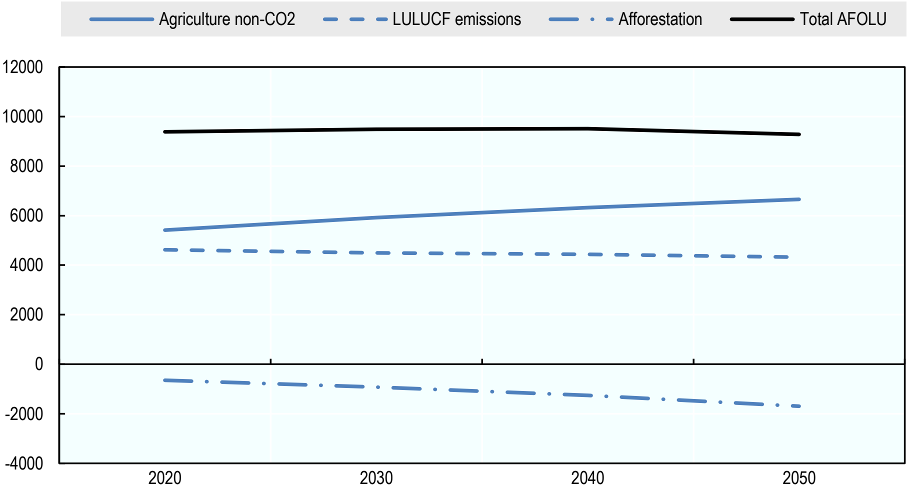
3. Policy scenario results relating to the 2°C target

In this section, results from the mitigation scenarios relating to the 2°C target, which form the backbone of the results section, are presented. This narrowing of focus serves the purpose of cutting down the number of scenario results that are discussed in detail, to focus on the more conservative end of an ambitious range of carbon prices. The results from the mitigation scenarios for the 1.5°C target are presented in a more summarised format in Section 4.

3.1. Global impacts of AFOLU-wide policies on GHG emissions and land use

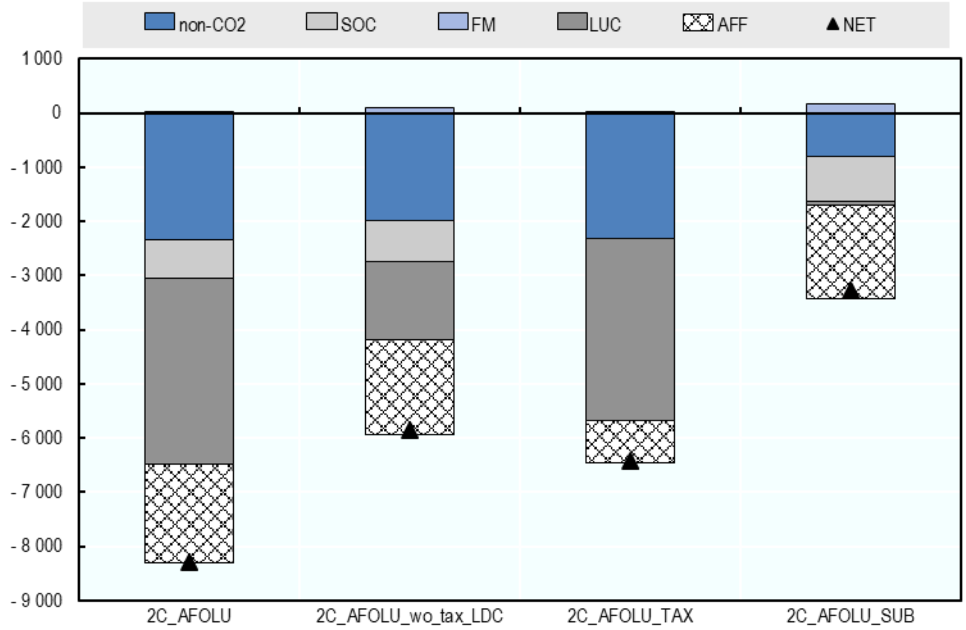
In the baseline scenario, which does not include any mitigation policies and is consistent with the SSP2 baseline, non-CO_2 emissions from agriculture increase from 5.4 $GtCO_2eq$ to 6.7 $GtCO_2eq$ between 2020 and 2050, but this increase is more than offset by net reductions in LULUCF CO_2 emissions (LULUCF emissions + removals from afforestation), causing total net AFOLU emissions to decline slightly from 9.4 $GtCO_2eq$ to 9.3 $GtCO_2eq$ over this period (Figure 1). With agricultural production and emissions growing over time, from 5.4 $GtCO_2eq$ to 6.7 $GtCO_2eq$ between 2020 and 2050, agriculture's share of net AFOLU emissions is projected to increase from 58% in 2020 to 72% in 2050. LULUCF emissions on the other hand are relatively more stable, declining from 4.6 $GtCO_2eq$ to 4.3 $GtCO_2eq$ over this period (4.4 $GtCO_2eq$ and 4.2 $GtCO_2eq$ of which are from the combination of deforestation and other land use changes).

Figure 1. Baseline trends in AFOLU emission sources (in $MtCO_2eq$)



In the scenario targeting all sources of mitigation in AFOLU, (*2c_afolu*) total net annual emissions from AFOLU fall by 8.3 $GtCO_2eq$, relative to the baseline in 2050 (Figure 2). This represents a substantial 89% reduction in net AFOLU emissions, in CO_2 equivalent terms. This equates to a 12% reduction of the 67 $GtCO_2eq$ baseline projection for total global anthropogenic emissions in 2050, and 18% of the 46 $GtCO_2eq$ projected total global mitigation in 2050, corresponding to the 2°C target calculated in McCollum et al. (2018[16]). Most of this mitigation is due to the emissions tax, which almost eliminates emissions from deforestation and other land use changes, accounting for a 3.4 Gt $GtCO_2eq$ reduction in emissions (42% of total mitigation from AFOLU). This represents an 82% reduction in the 4.2 $GtCO_2eq$ of emissions from deforestation and other land use changes in 2050. Consequently, the mitigation potential of the AFOLU sector is highly dependent on the assumed continuation of emissions from land clearing, include in the LULUCF emissions category in Figure 1 above. The subsidy component of this scenario incentivises most of the afforestation which, combined with afforestation from energy plantation growth, generates CO_2 removals of 1.8 $GtCO_2eq$. Subsidies for soil carbon sequestration on agricultural land promotes a further 0.7 $GtCO_2eq$ in removals. A combination of the carbon tax and the technology adoption subsidy are responsible for reducing most of the 2.3 $GtCO_2eq$ of non-CO_2 emissions from agriculture by 2050, representing a 35% reduction in annual agricultural emissions, relative to the baseline.

Figure 2. AFOLU emission changes ($MtCO_2eq$) for the AFOLU-wide policy scenarios relative to baseline in 2050, in relation to the 2°C target



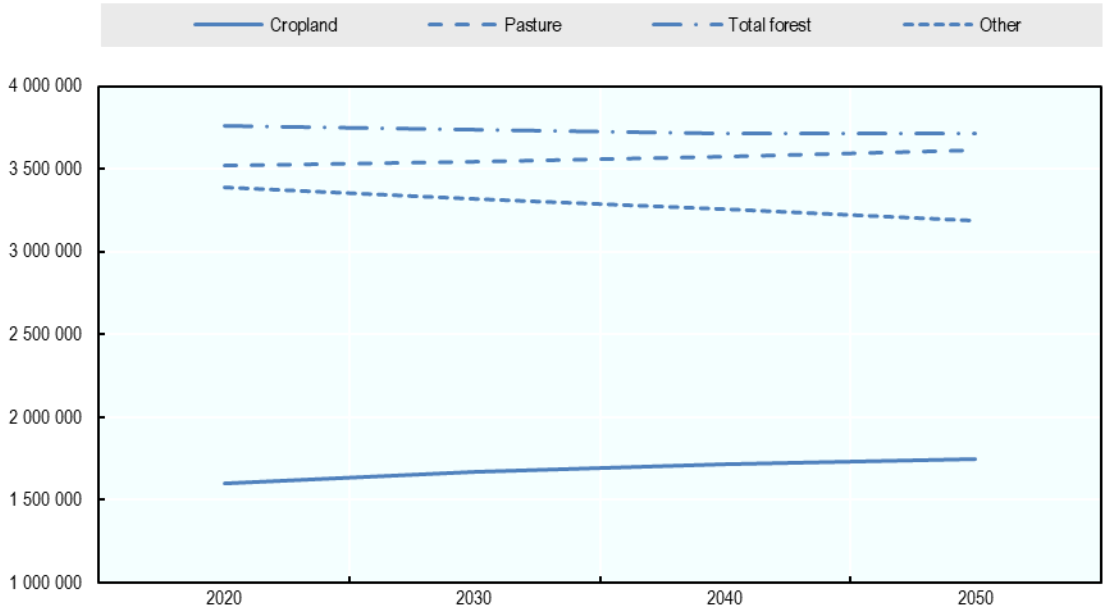
Note: The emission and mitigation sources shown in the figure include non-CO_2 emissions (methane and nitrous oxide emissions from agriculture), SOC (soil organic carbon sequestration), FM (CO_2 emission changes from forestry management), LUC (CO_2 emission changes from land use changes), AFF (CO_2 emission changes from afforestation), and NET (net GHG emission changes aggregated across all AFOLU sources).

As expected, the other AFOLU scenarios, which apply the tax and subsidy policies separately (*2c_afolu_tax*, *2c_afolu_sub*) are less effective at mitigating emissions, primarily because fewer emission and abatement sources are covered in these scenarios. Recall that the AFOLU tax scenarios only target non-CO_2 emissions from agriculture and CO_2 emissions from FOLU, whereas the AFOLU subsidies incentivise the adoption non-CO_2 abatement technologies and AFOLU-wide carbon sequestration (Table 1).

At the same time, taxing AFOLU emissions reduces emissions by more than subsidising mitigation. For example, in 2050, AFOLU emissions fall by 5.8 $GtCO_2eq$ in the *2c_afolu_tax* scenario, compared to only 3.3 $GtCO_2eq$ in the *2c_afolu_sub* scenario. The main reason for this difference is that the subsidy fails to halt emissions from land use changes, whereas the tax incentivises substantial emission reductions of 3.4 $GtCO_2eq\ yr^{-1}$ from this source. In addition, the tax drives larger reductions in non-CO_2 emissions from agriculture of 2 $GtCO_2eq\ yr^{-1}$ compared to 0.8 $GtCO_2eq\ yr^{-1}$ for the subsidy. This is because the tax induces substantial emission reductions from reallocating agricultural land use and production towards less emission intensive commodities, along with reductions in overall consumption due to increases in the prices of commodities. It also increases the concentration of production in regions with relatively lower emission intensities.

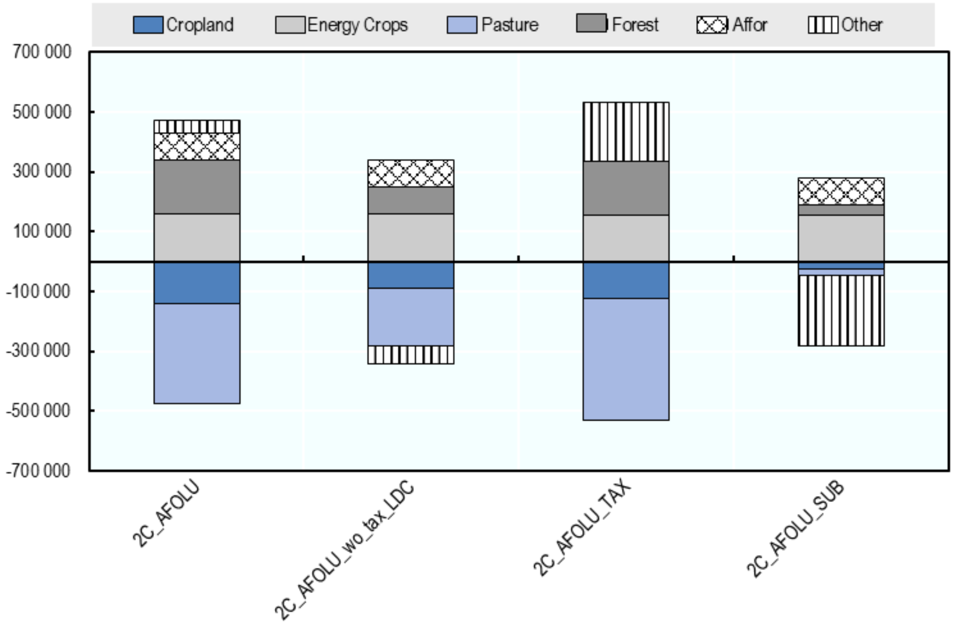
These varying impacts of the policy packages on emissions are also accompanied by differing impacts on land use. In the baseline, population and income growth underpin demand for agricultural products, causing cropland and pastureland to expand by 9% and 3% respectively, between 2020 and 2050. This increase in agricultural land occurs at the expense of total forest and other natural land which decline by 1% and 6% over this time frame. The changes in land use compared to the 2050 baseline, are shown in Figure 4 for a selection of policy packages.

Figure 3. Baseline trend in global land uses (1 000 ha) between 2020 and 2050



Note: Total forest is the combination of established forests (referred to as Forest in Figure 4) that can only decrease compared to their year 2000 levels and recent forest (referred to as Affor. in Figure 4). The category "Other", refers to other natural land.

Figure 4. Land use changes (1 000 ha) for AFOLU-wide policy scenarios relative to baseline in 2050, in relation to the 2°C target



Note: the Forest land cover refers to existing forests in the year 2000. Forests established after the year 2000 are represented by Affor. The category "Other", refers to other natural land. Regarding the correspondence between these land use categories and the emission sources and sinks reported in Figure 2, the LUC emissions represent emissions from the conversion of forest (old and new) and other natural land, whereas the carbon sink called AFF corresponds to an expansion in afforestation and the bioenergy plantations (included in Energy Crops), relative to the baseline.

The policies in taxing global AFOLU emissions (*2c_afolu* and *2c_afolu_tax)* cause conventional global agricultural land use (cropland and pastureland) to contract by 10%. This land reallocation effect plays out more broadly at the AFOLU level, with this land being replaced by other land uses with lower emissions and higher potential for carbon storage (Figure 4). The tax and subsidy policies also have contrasting impacts on the direction of changes in other natural land (Other). This reflects the differing impacts these policies have on the relative competitiveness of different land uses. The global emission taxes in *2c_afolu* and *2_afolu_tax* reduce competitiveness of conventional agricultural land, resulting in less conversion of other natural land and forest into conventional agricultural production relative to the baseline. This also allows energy crops, which expand in response to growing bioenergy demand in all of the mitigation scenarios, to displace land for conventional agricultural production. In contrast, when abatement is subsidised, the opportunity cost of displacing cropland and pastureland increases relative to other natural land. Thus in this case, other natural land is instead displaced by growing energy crops. The exemption of least developed countries from paying taxes in *2c_afolu_wo_tax_ldc* leads to the same dynamics in sub-Saharan Africa as well as fall in the forest cover in this region, resulting in a lower overall increase in global forest cover when compared to either *2c_afolu* or *2c_afolu_tax*.

Exempting least developed countries from paying emission taxes in the AFOLU-wide policy (*2c_afolu_wo_tax_ldc*) lowers global mitigation from AFOLU from 8.3 $GtCO_2eq$ to 5.7 $GtCO_2eq$, compared to the most comprehensive AFOLU-wide policy (*2c_afolu_tax*). This reduction is mainly due to a fall in the mitigation from avoided land use change in sub-Saharan Africa. Similar, but lower, global mitigation is achieved by applying a tax to all AFOLU emissions in all countries, but not a subsidy for sequestration (*2c_afolu_tax*).

In the *2c_afolu* scenario, agriculture contributes 37% (28% excluding soil carbon sequestration on agricultural land) of the AFOLU's 8.3 $GtCO_2eq$ emission reduction in 2050. Closer inspection of the mitigation contributions from agriculture shows that emission reductions from livestock (enteric CH_4 and manure CH_4 and N_2O) account for most of the non-CO_2 reductions across all scenarios, while most of the soil carbon sequestration occurs on cropland (Table 2).

Table 2. Percentage contribution of different agricultural sources to non-CO_2 emission reductions and soil organic carbon (SOC) sequestration relative to baseline for AFOLU-wide policy scenarios in 2050, in relation to the 2°C target

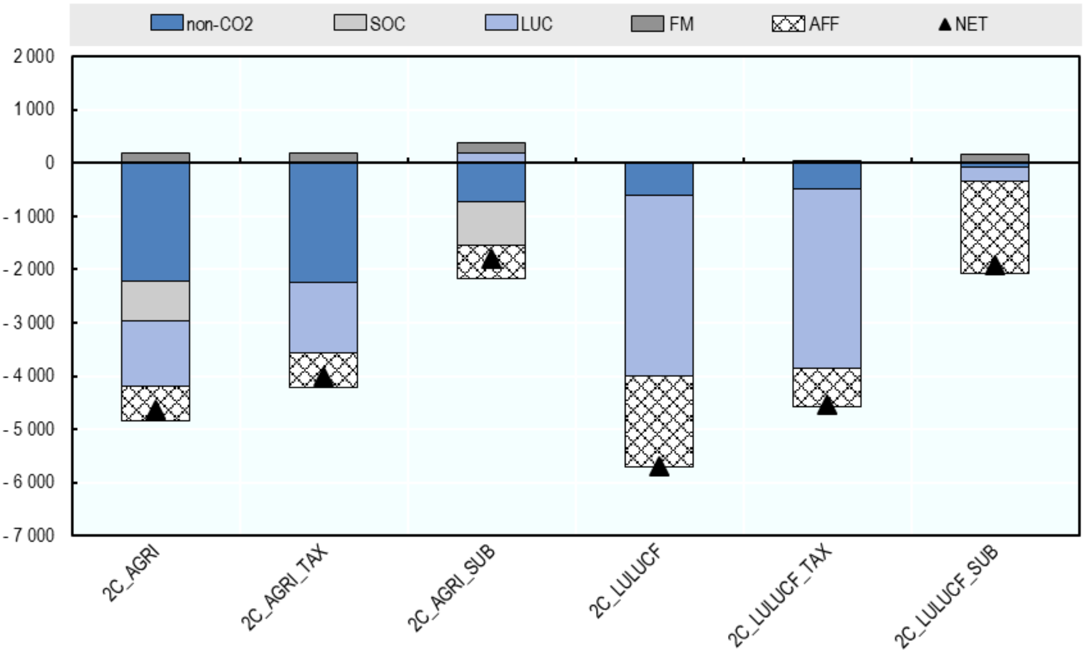
Policy scenario	Enteric CH_4	Manure CH_4 & N_2O	Rice CH_4	Crop N_2O	Pasture SOC	Cropland SOC	Total non-CO_2 & SOC ($MtCO_2eq$)
2c_afolu	37%	19%	10%	11%	8%	16%	-3 046
2c_afolu_wo_tax_ldc	19%	14%	15%	7%	16%	29%	-1 777
2c_ afolu _tax	49%	25%	13%	14%	0%	0%	-2 309
2c_ afolu _sub	17%	12%	16%	4%	18%	32%	-1 627

3.2. Global impacts of sector-specific policies on GHG emissions, land use and production

By exploring results for the policy scenarios which target agriculture and LULUCF sectors separately (Figure 5), it is possible to show the respective contributions from each component of the AFOLU-wide mitigation policy package more clearly. Moreover, comparing the results of the separate agriculture and LULUCF policies also reveals how mitigation policies in one sector can influence the other.

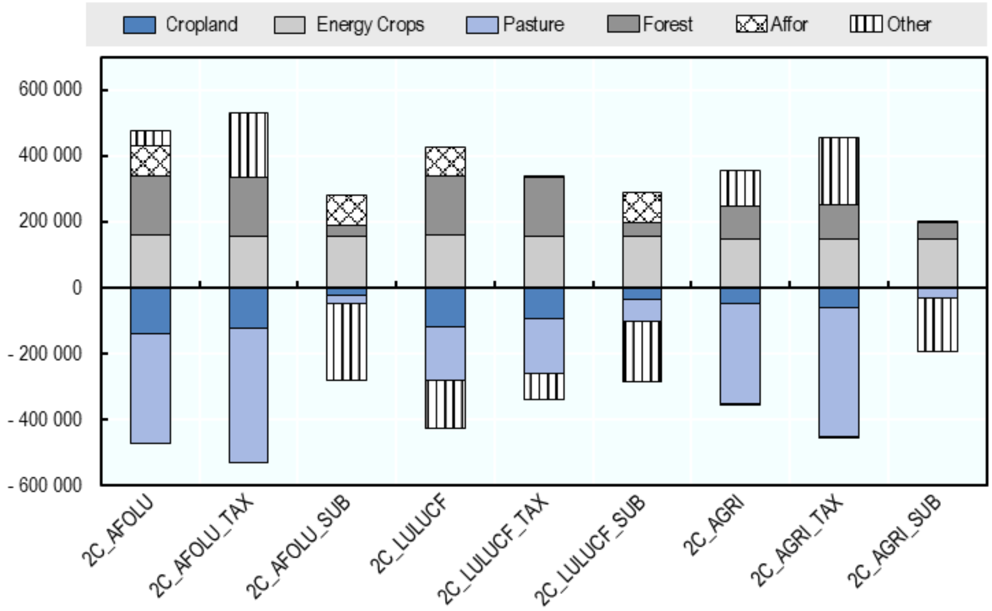
For example, with reference to the 2°C target, the tax on agricultural emissions generates near equal shares of mitigation from agriculture and LULUCF, despite only targeting agricultural emissions: 56% of the 4.0 $GtCO_2eq\ yr^{-1}$ of the emissions abated by *2c_agri_tax* are from agriculture, with the rest from avoided land use change (34%) and afforestation (16%). By reducing agricultural land rents, the tax causes some agricultural land to shift to forest and other land uses, increasing the land-based stock of carbon.

Figure 5. AFOLU emission changes (MtCO$_2$eq) relative to baseline for policies targeting agriculture and LULUCF sectors separately in 2050, in relation to the 2°C target



As shown in Figure 6, it is apparent that all of the scenarios that tax agricultural emissions (*2c_agri_tax*, *2c_afolu_tax*) induce the largest contraction of pastureland and crop land. There is a commensurately large increase in forest (from avoided deforestation rather than afforestation) other natural land, and energy crops.

Figure 6. Land use changes (1 000 ha) relative to baseline for all policies in 2050, in relation to the 2°C target



As with the AFOLU-wide scenarios, emission reductions from livestock (enteric CH_4 and manure CH_4 and N_2O) account for most of the non-CO_2 reductions across all scenarios, while most of the soil carbon sequestration occurs on cropland (Table 3). The total mitigation numbers presented in the final column of this table only include emission reductions in the agricultural sector and therefore differ from the net AFOLU mitigation quantities shown in Figure 5.

Table 3. Percentage contribution of different agricultural sources to non-CO_2 emission reductions and soil organic carbon (SOC) sequestration for the agriculture and LULUCF policy scenarios, relative to baseline in 2050, in relation to the 2°C target

	Enteric CH_4	Manure CH_4 and N_2O	Rice CH_4	Crop N_2O	Pasture SOC	Crop SOC	Total non-CO_2 & SOC ($MtCO_2eq$)
2c_agri	37%	19%	10%	8%	8%	18%	-2 978
2c_ agri _tax	50%	25%	14%	11%	0%	0%	-2 171
2c_ agri _sub	17%	12%	17%	-2%	20%	36%	-1 467
2c_lulucf	70%	30%	9%	-9%	0%	0%	-596
2c_ lulucf _tax	76%	31%	8%	-15%	0%	0%	-491
2c_ lulucf _sub	112%	58%	24%	-95%	0%	0%	-86

Note: for the emission sources with negative shares, emissions increased rather than decreased.

The addition of a subsidy for agriculture increases total mitigation from AFOLU from 4.0 $GtCO_2eq\ yr^{-1}$ to 4.6 $GtCO_2eq\ yr^{-1}$, by incentivising soil carbon sequestration and further non-CO_2 emission reductions (compare *2c_agri_tax* with *2c_agri* in Figure 6). In addition to the 0.83 $GtCO_2eq\ yr^{-1}$ of sequestration in agricultural soils and the 0.72 $GtCO_2eq\ yr^{-1}$ in non-CO_2 emission reductions from applying the abatement subsidy to agriculture alone (*2c_agri_sub*), there is also a similar increase in the quantity of CO_2 removals through afforestation. This is not induced by the abatement subsidy in agriculture, but is instead a consequence of the exogenous increase in biomass demand from energy sector, present in all of the mitigation policy scenarios.

As shown in Figure 6, the increase in energy crops is consistently large across all of the policy scenarios (150-166 Mha.by 2050). Despite the significant growth, the impact on agricultural areas differs across the mitigation policy scenarios. While the increase in energy crops causes a net agricultural area expansion (if energy crops are included along with conventional cropland and pasture) beyond baseline levels, the other mitigation scenarios induce a decline in total agricultural area.

Just as mitigation policies directed at agriculture have large indirect impacts on lowering LULUCF emissions, the reverse is also true. The LULUCF policies all help to lower non-CO_2 emissions from agriculture, particularly those that tax LULUCF emissions. For example, the *2c_lulucf-tax* and *2c_lulucf* policies help to reduce agricultural non-CO_2 emissions by 0.5-0.6 $GtCO_2eq$, in addition to directly mitigating 4-5 $GtCO_2eq$ from LULUCF sources in 2050. The non-CO_2 reductions are smaller but still similar in magnitude to the reduction achieved by directly subsidising non-CO_2 abatement in agriculture.

These impacts are reflected in the land use changes associated with these policies – with *2c_lulucf-tax* causing large reductions in cropland and particularly pastureland (and other natural land), with commensurate increases in forest area and area devoted to energy plantations. The main mechanism for this is the impact of the LULUCF tax on preventing deforestation relative to the baseline, which increases the opportunity costs of agriculture relative to other land uses.

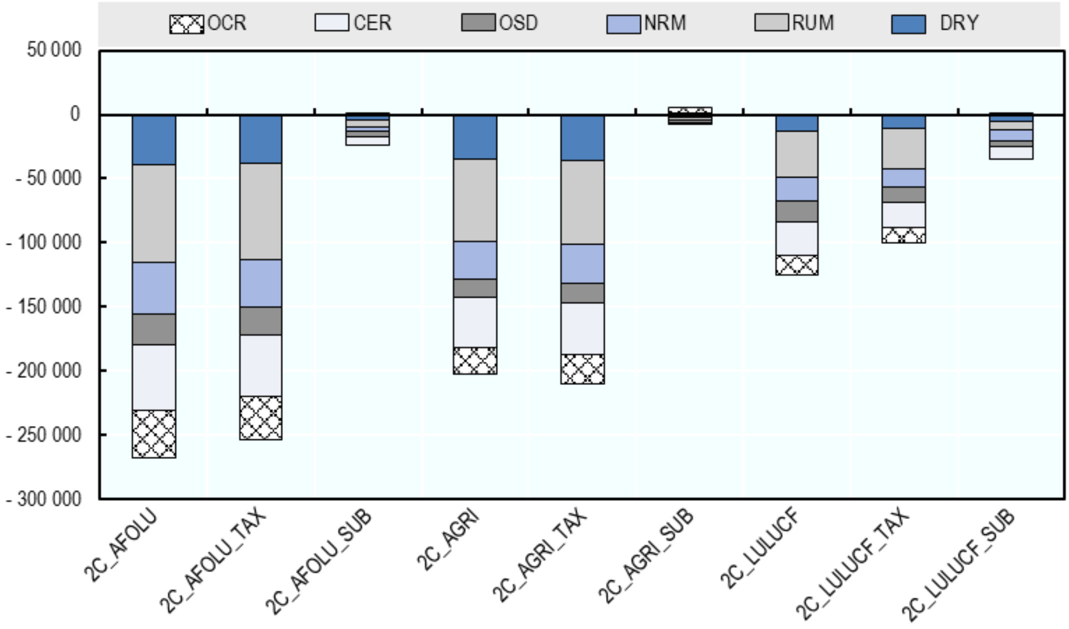
The policies targeting LULUCF are more effective at lower net emissions than those that are limited to agriculture. For example, the LULUCF policy scenario that applies both a tax on emissions and subsidy for increasing carbon stocks (*2c_lulucf*) achieves 69% of the emission reductions from the most comprehensive AFOLU-wide policy package for the 2°C target (*2c_afolu*), whereas the agriculture-only version (*2c_agric*) achieves 56% of reductions by this package. The main reason for this higher effectiveness is that the emission tax applied to LULUCF significantly lowers land use change emissions. The LULUCF subsidy also generates substantial mitigation via afforestation.

As a consequence of these spill-over effects, the mitigation policies separately targeting agriculture and LULUCF are non-additive. That is, the sum of the mitigation quantities from the separately applied policies exceeds the mitigation quantity from the corresponding policies applied simultaneously to all AFOLU sources. For example, the sum of the *2c_agric* and *2c_lulucf* policies generates a 10.3 $GtCO_2eq$ reduction, exceeding the 8.3 $GtCO_2eq$ from *2c_afolu* in 2050. This lack of additivity extends to all sources of mitigation across AFOLU.

Global production of all agricultural commodities falls in all of the scenarios, with the exception of the subsidy for mitigation in agriculture which causes near-zero changes (between -0.6% and 0.6% in percentage terms) in agricultural production (see *2c_agric_sub* in Figure 7). As with land use changes, there is a large disparity in the impacts of the tax and subsidy policies, with taxes, particularly on agricultural emissions, driving more substantial declines in production across both crop and livestock commodities. The production impacts are minimised for all of the scenarios involving the use of a subsidy alone (see *2c_afolu_sub*, *2c_agric_sub*, *2c_lulucf_sub*).

The largest falls in output occur for ruminant and dairy products which are the most emission intensive, compared to non-ruminant products. For example, the *2c_afolu* policy causes an 18% decline in ruminant meat output and an 11% decline in dairy products, compared to a 5% decline in non-ruminant meat output, relative to the baseline in 2050. Much of the fall in cereal products can also be attributed to a reduction in demand for cereal feeds by livestock.

Figure 7. Production changes (million USD) relative to baseline for all policies in 2050, in relation to 2°C target



Note: The different agricultural outputs were valued at constant baseline world prices (valued in 2000 USD) so that they could be aggregated. As they are based on constant world prices, the changes can be considered as approximate changes in the volume of production.
The components of the aggregate product categories are listed in parentheses as follows: OCR (Other crops), CER (cereals including wheat, coarse grain crops and rice), OSD (oilseed crops including as soy beans and rapeseed crops), NRM (non-ruminant products including meat and eggs), RUM (ruminant meat), DRY (dairy products).

As discussed in Section 2.2, a number of additional stylised scenarios are constructed to assess the mitigation potential of reducing the amount of livestock products in consumers' diets. The motivation behind these scenarios, the approach used to construct them and their impacts on global GHG emissions are summarised below in Box 1. The strongest dietary shift, involving a 50% reduction in the consumption of livestock products by 2050, reduces net emissions in AFOLU by 1.7 $GtCO_2eq$ in 2050. As mentioned in

Section 2, these diet change scenarios are not linked to any policy levers and can therefore only be considerd as indicative scenarios that are secondary to the main assessment of the report. The policy potential for mitigating GHG emissions via changes in consumer diets is likely to be lower than indicated in the results of these scenarios. The economic impacts of the changes are not reported here; however, as shown in OECD (2019[2]), such dietary shifts can cause significant loss of income to livestock producers.

Box 1. The potential for changes in consumer diets to mitigate AFOLU emissions

Livestock products account for the main share of emissions from agriculture and they are the most emission intensive of all agricultural products. For instance, in 2020 and 2050, livestock products are projected to account for 74% and 73% baseline share of total non-CO_2 emissions from agriculture.

In light of this dominant contribution, four stylised scenarios are constructed to assess the mitigation potential of changes to consumers' dietary choices. These involve the following reductions in the volume or share of livestock products as a whole, or ruminant products (e.g. red meat and dairy), in consumer diets by 2050 (excluding least developed countries and India):

- 50% reduction in the consumption of all livestock products (*diet50lsp*)
- 50% reduction in the consumption of ruminant products (*diet50rum*)
- Reduction in the share of all livestock products in regions with above average (per capita) baseline consumption of these products, to match the global average (per capita) level of consumption of these products by 2050 (*dietavlsp*)
- Reduction in the share of ruminant products in regions with above average (per capita) baseline consumption of ruminant products, to match the global average (per capita) level of consumption of these products by 2050 (*dietavrum*).

These scenarios were constructed by recalculating baseline demand projections for the consumption of livestock products with compensatory increases in the amount of non-livestock products consumed in each region. Thus, these diet change scenarios differ from the mitigation scenarios outlined in the previous section in that they are imposed exogenously without consideration of any policy interventions to motivate the changes. They are therefore foresight scenarios, which reveal the technical rather than policy potential of changes to consumer diets.

Since these practices target emissions from agriculture, they are most comparable to the policy packages that are also confined to the agricultural sector (*2c_agri_tax* and *2_agric_sub*).

The changes in the total per capita intake of food products from animal and non-animal sources, as consequence of the above scenarios are shown in Table 4. These details are useful for understanding why the effectiveness of the different dietary change scenarios vary. It shows, for instance, that the scenario which caps per capita consumption at the average global level, *dietavlsp*, generates about two-thirds of the reductions in livestock consumption as the *diet50lsp* scenario. The main reason that the changes in the consumption of calories from livestock and ruminant products do not equate to 50% in the diet50lsp and diet50rum is due to the exclusion of least developed countries and India from the consumer diet change scenarios. There are also some very minor rebound effects that also cause a slight deviation in the final reduction of livestock calorie intake in regions where the full percentage reduction is applied (e.g. the final reduction of livestock products in North America is 48%).

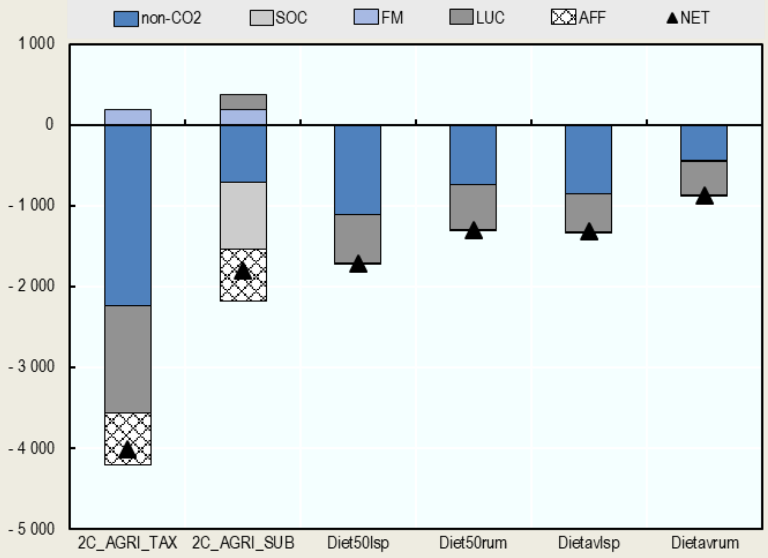
The impacts of these scenarios on AFOLU emissions are summarised in Figure 8. The largest dietary shift, *diet50lsp*, lowers net AFOLU emissions by 1.7 $GtCO_2eq$ in 2050, with about two-thirds of this (1.1 $GtCO_2eq$) coming directly from a reduction in non-CO_2 emissions and the rest from avoided emissions from land use change. An equivalent reduction in the consumption ruminant products alone (*diet50lsp*) leads to lower reduction in net AFOLU emissions of 1.3 $GtCO_2eq$. The corresponding scenarios based on lowering above average per capita consumption of animal products to the global average generate comparable, but lower, emission reductions of 1.3 and 0.9 $GtCO_2eq$ for *diet5avlsp* and *diet5avrum*, respectively.

However, even the strongest dietary change only delivers half the reductions in non-CO_2 or land use change emissions achieved a by applying a USD 70/tCO2eq^{-1} tax to agricultural emissions. This clearly demonstrates the additional impact that can be generated from incentivising the uptake of abatement technologies and the reallocation of production away from emission intensive commodities and practices.

Table 4. Percentage changes in total per capita calorie intake for food products, relative to the baseline in 2050

	Livestock	Ruminant	All food excluding livestock products	All food excluding ruminant products	All food
2c_agri_tax	-8%	-18%	-1%	-2%	-3%
2c_agri_sub	0%	0%	0%	0%	0%
Diet50lsp	-32%	-31%	11%	2%	1%
Diet50rum	-14%	-32%	5%	2%	0%
Dietavlsp	-24%	-24%	8%	2%	0%
Dietavrum	-9%	-22%	3%	1%	0%

Figure 8. AFOLU emission changes (MtCO$_2$eq) relative to baseline for the consumer diet scenarios and the tax and policy mitigation scenarios for agriculture in 2050



Note: The emission and mitigation sources shown in the figure include non-CO_2 emissions (methane and nitrous oxide emissions from agriculture), SOC (soil organic carbon sequestration), FM (CO_2 emission changes from forestry management), LUC (CO_2 emission changes from land use changes), AFF (CO_2 emission changes from afforestation), and NET (net GHG emission changes aggregated across all AFOLU sources).

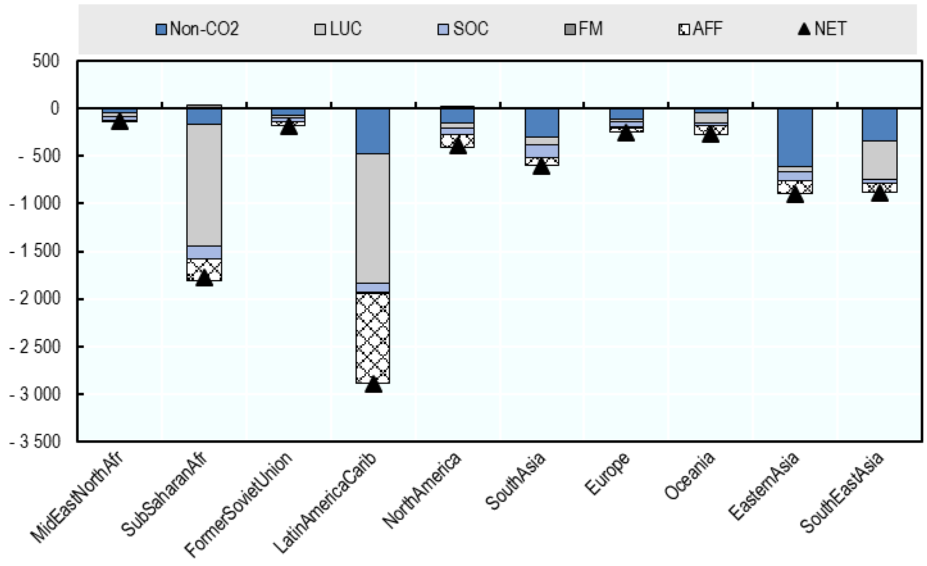
3.3. Regional policy impacts on emissions, production and land use

The contribution of different regions to global emission reductions varies considerably across each of the policy scenarios. The emission reductions, from the combined tax and subsidy policy package corresponding to the 2°C target, are broken down by source for ten different global regions in Figure 9. The countries comprising each of these regions is shown in Table A A.1 of the Annex. It is clear from these results that the large contribution of the LULUCF sector to global mitigation is overwhelmingly due to the avoided clearing of forest (and other natural land) in Latin America, sub-Saharan Africa and, to a lesser extent, Southeast Asia. In fact, this mitigation source from these three regions accounts for 37% of global emission reductions from AFOLU. This result is, however, strongly dependent on the assumption of large scale deforestation in the baseline scenario. The mitigation contribution from LULUCF measures in these regions increases to 52% when afforestation in these regions, which are particularly large in Latin America, is included. In terms of non-CO_2 emission reductions, East Asia (the People's Republic of China (hereafter "China"), Japan, Korea, and the Democratic People's Republic of Korea) is the largest contributor.

As shown earlier, exempting least developed countries from paying taxes on AFOLU emissions in either the agriculture or LULUCF sectors (*2c_afolu_wo_tax_ldc*) lowers global mitigation by 2.4 $GtCO_2eq$ from 8.3 $GtCO_2eq$, under the most comprehensive AFOLU-wide policy package, to 5.9 $GtCO_2eq$ (Figure 9). Comparing Figure 9 and Figure 10 reveals that this is mainly due to a reduction in the avoided LUC emissions in sub-Saharan Africa, but also in Southeast Asia. These changes cause net mitigation in these regions to fall from 1.8 $GtCO_2eq$ and 0.9 $GtCO_2eq$, respective, to 0.1 $GtCO_2eq$ for both regions. The fall in avoided emissions from land use change in these two regions accounts for 75% of the 2.4 $GtCO_2eq$ reduction in mitigation that comes from exempting least developed countries from paying taxes on AFOLU emissions.

Nevertheless, net emissions decline for all regions, including sub-Saharan Africa and Southeast Asia, under the *2c_afolu_wo_tax_ldc* scenario (Figure 10).[9] In other words the exemptions did not cause net AFOLU emissions to "leak" from the taxed regions to the untaxed regions. Emissions decline among all AFOLU sources in the exempted regions, except for land use change and forestry management emissions. An important reason why net emission in the exempted regions do not increase is because the subsidies for non-CO_2 abatement, soil carbon sequestration and afforestation are still maintained in the *2c_afolu_wo_tax_ldc* scenario, which offsets the increases in land use changes emissions that occur as agricultural land use expands slightly in least developed countries (Figure 14).

Figure 9. Regional emission changes ($MtCO_2eq$) for the combined AFOLU-wide tax and subsidy policy relative to the baseline in 2050, in relation to the 2°C target (*2c_afolu*)



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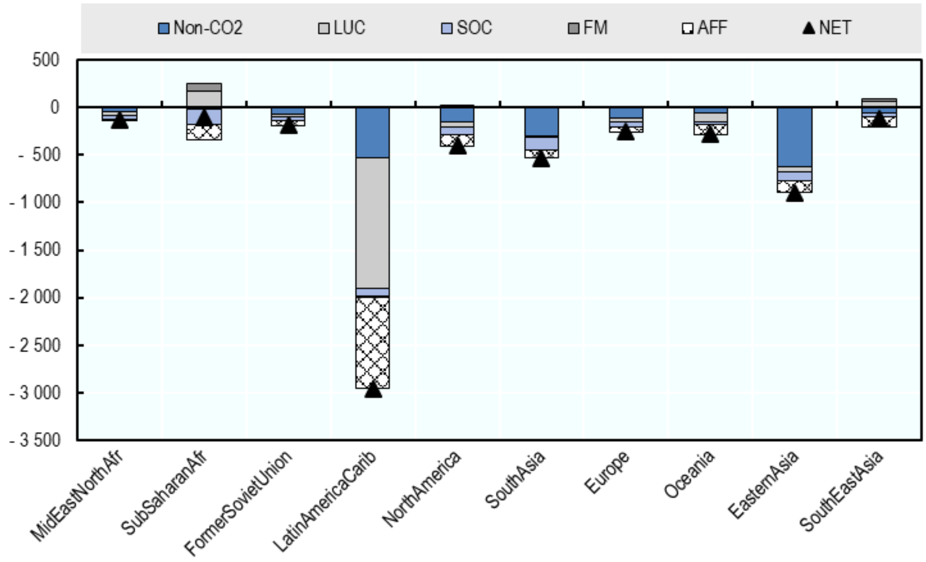
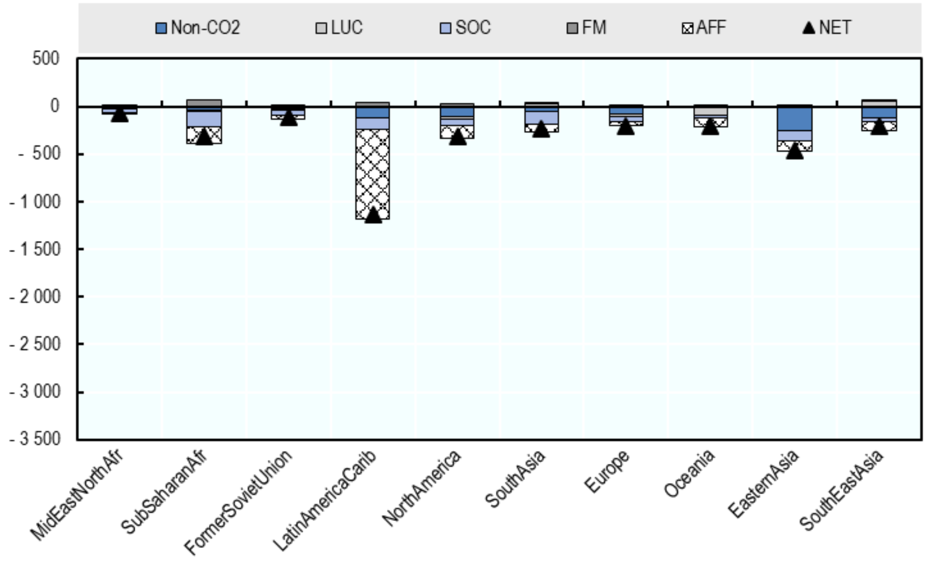
[9] The following regional aggregates contain a mixture of least developed and other countries: sub-Saharan Africa (all countries are considered to be least developed countries apart from South Africa); South Asia (all countries are considered to be least developed except for India); Oceania (Pacific Island countries are considered to be least developed countries, but the rest are not).

Figure 10. Regional emission changes (MtCO$_2$eq) for the combined AFOLU-wide tax and subsidy policy, exempting LDCs from emission taxes, relative to the baseline in 2050, in relation to the 2°C target (*2c_afolu_wo_tax_ldc*)



For the AFOLU-wide subsidy scenario (*2c_afolu_sub*), Latin America remains the most important source of global mitigation, but the relative importance of sub-Saharan Africa, in particular declines, with higher contributions from both East Asia and North America (Figure 11).

Figure 11. Regional emission changes (MtCO$_2$eq) for the AFOLU-wide subsidy policy relative to the baseline in 2050, in relation to the 2°C target (*2c_afolu_sub*)



The regional changes in emissions induced by the policy packages are reflected changes in land use shown in Figure 13 and Figure 14, and can be compared to the regional baseline levels of land use in 2050. As expected, the large mitigation contribution of Latin America, sub-Saharan Africa and, to a lesser extent, Southeast Asia, in the *2c_afolu* scenario is accompanied by large falls in pastureland and cropland, and the commensurately large increases in forest cover, energy crops and other natural land (Figure 13).

The increase in emissions in sub-Saharan Africa when the AFOLU emission taxes are removed from least developed countries, is accompanied by an increase in the production of most agricultural commodities (Figure 16), compared when all global emissions are taxed (Figure 15). The exemption causes a greater number of commodities to expand in Southeast Asia, but this more than offset by a decline in sugar cane and oil seed production (Figure 15). Despite the expansionary impacts of the tax exemption on agriculture, particularly in sub-Saharan Africa, the abatement subsidy causes non-CO_2 emissions to fall, and the sequestration subsidy maintains the increase in soil carbon stocks relative to the central *2c_afolu* policy (Figure 10).

The increase in emissions from land use change and forestry management in least developed countries, when they are exempted from the AFOLU emission taxes (Figure 10), is mirrored by a reduction in forest and other land in in these regions (Figure 14). In sub-Saharan Africa this is also accompanied by an increase in agricultural land use, whereas agricultural land use falls slightly only with forest and other land in Southeast Asia, relative to the baseline in Southeast Asia, when the exemption is in place. In this region the expanding use of land for energy crops displaces a broader range of land uses than in sub-Saharan Africa.

Figure 12. Baseline regional land uses (1 000 ha) in 2050

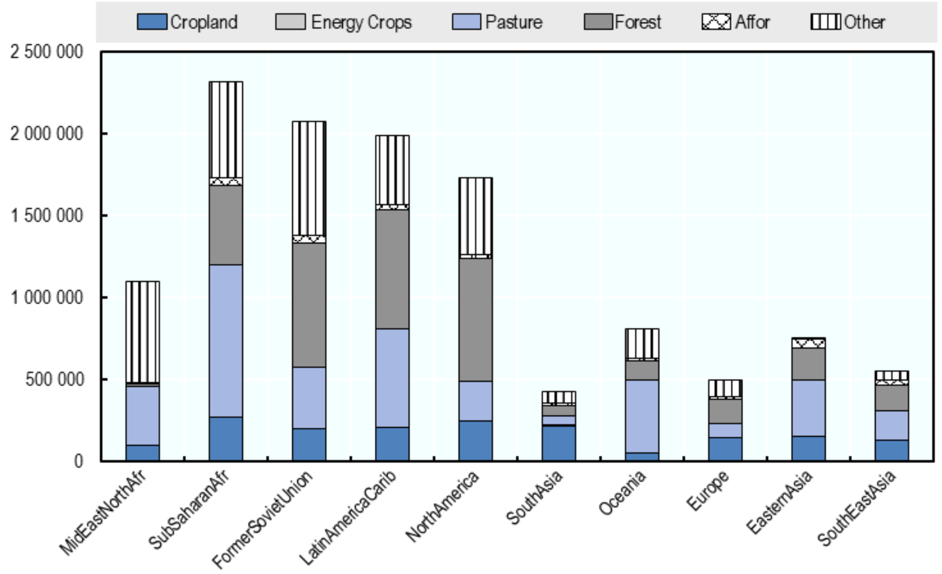


Figure 13. Regional land use changes (1 000 ha) for the combined AFOLU-wide tax and subsidy policy relative to the baseline in 2050, in relation to the 2°C target (*2c_afolu*)

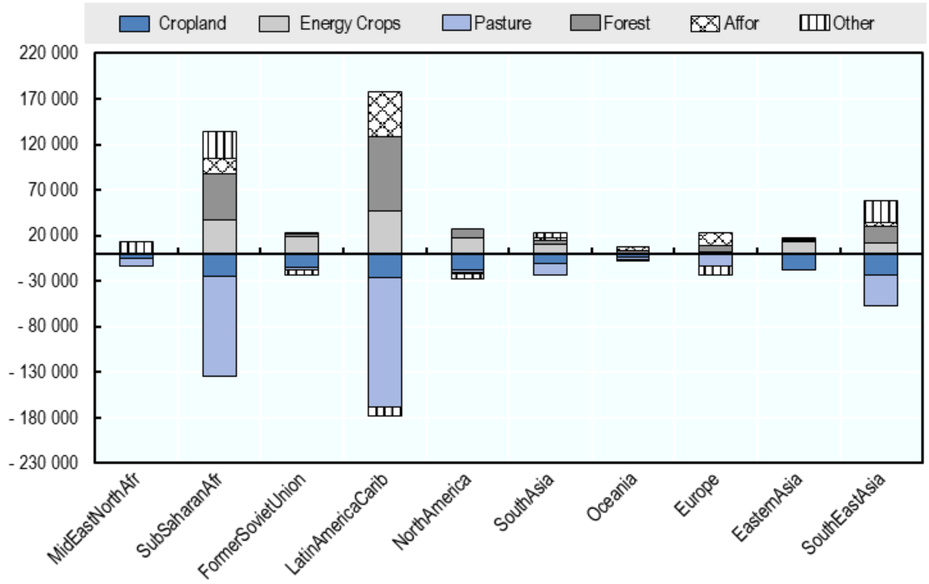


Figure 14. Regional land use changes (1 000 ha) for the combined AFOLU-wide tax and subsidy policy, exempting LDCs from emission taxes, relative to the baseline in 2050, in relation to the 2°C target (*2c_afolu*)

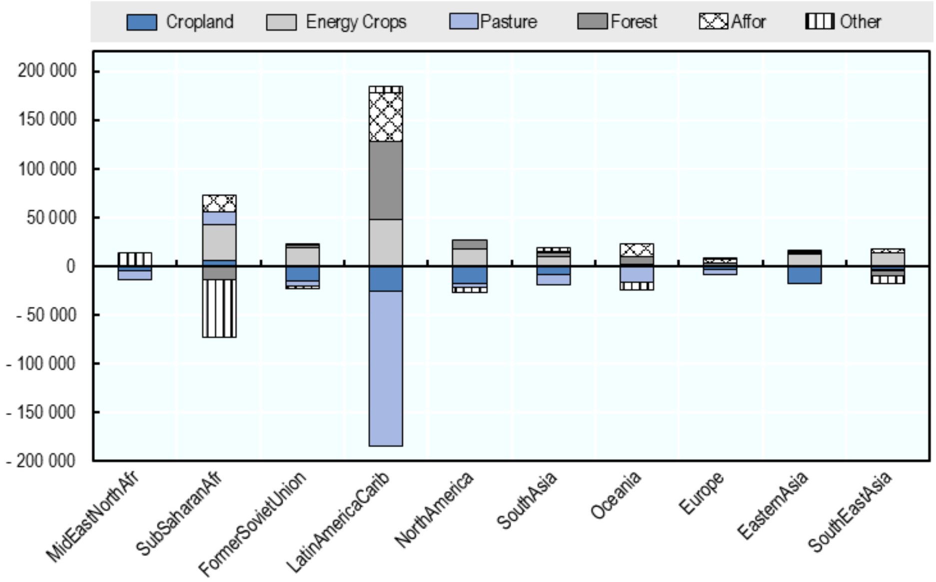
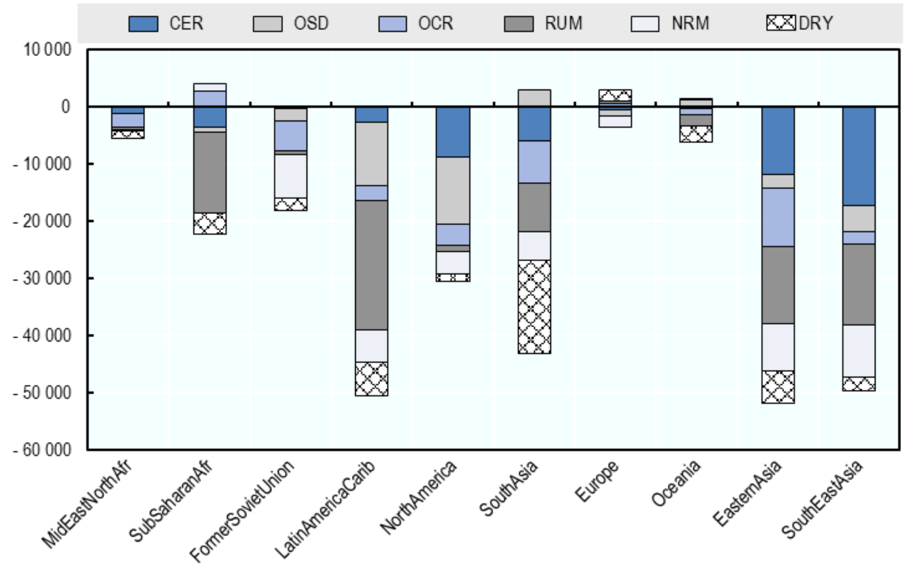
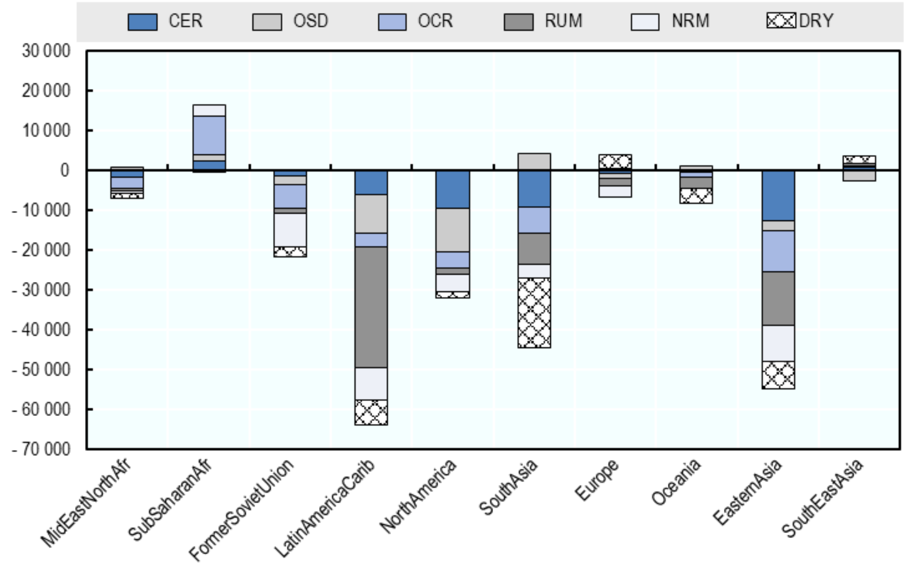


Figure 15. Regional production changes (million USD) for the combined AFOLU-wide tax and subsidy policy relative to the baseline, in 2050, in relation to the 2°C target (*2c_afolu_sub*)



Note: The different agricultural outputs were valued at constant baseline world prices (valued in 2000 USD) so that they could be aggregated. As they are based on constant world prices, the changes can be considered as approximate changes in the volume of production. The components of the aggregate product categories are listed in parentheses as follows: OCR (Other crops), CER (cereals including wheat, coarse grain crops and rice), OSD (oilseed crops including as soy beans and rapeseed crops), NRM (non-ruminant products including meat and eggs), RUM (ruminant meat), DRY (dairy products).

Figure 16. Regional production changes (million USD) the combined AFOLU-wide tax and subsidy policy, exempting LDCs from emission taxes, relative to the baseline, in 2050, in relation to the 2°C target (*2c_afolu_wo_tax_ldc*)



Note: The different agricultural outputs were valued at constant baseline world prices (valued in 2000 USD) so that they could be aggregated. As they are based on constant world prices, the changes can be considered as approximate changes in the volume of production. The components of the aggregate product categories are listed in parentheses as follows: OCR (Other crops), CER (cereals including wheat, coarse grain crops and rice), OSD (oilseed crops including as soy beans and rapeseed crops), NRM (non-ruminant products including meat and eggs), RUM (ruminant meat), DRY (dairy products).

3.4. Economic impacts of mitigation: Exploring the trade-offs

As reflected by the land use change results presented in the previous sections, all of the assessed mitigation policy scenarios generate trade-offs between consumers, producers, government and the environment. In addition to the large disparity in the impacts of the tax and subsidy policies on production, all of the policy scenarios including carbon taxes cause per capita consumption to fall, but by less than falls in production (Table 5). At the same time, these policies generate the largest emission reductions, substantially larger, in percentage terms, than the reductions in either agricultural production or per capita consumption of food. In contrast, the policy scenarios that only subsidise mitigation have negligible or zero (in the case of *2c_agri_sub*) impact on agricultural production and food consumption, but are typically around half as effective at reducing emissions as the policies that only tax emissions.

Unsurprisingly, the changes in wood production move in the opposite direction to agricultural production, and increase relative to the baseline in all of the policy scenarios, because agricultural land use shrinks and forest land increases in all of the policy scenarios. Wood production increases by less in the scenarios that tax emissions from forest management, because this tax penalises more emission intensive forms of forest production that also tend to be more productive.

The exemption of LDCs from paying taxes in the AFOLU-wide policy combining taxes and subsidies, *2c_afolu_wo_tax_ldc*, alleviates but does not eliminate declines in per capita consumption in sub-Saharan Africa, Southeast Asia and South Asia, relative to the central *2c_afolu* policy package (Table 5). The reason that per capita consumption still declines in the presence of the tax exemption is partly because the LULUCF subsidy that is still in place in *2c_afolu_wo_tax_ldc* puts downward pressure on agricultural supply.

Table 5. Changes in consumption, production and emissions, relative to the baseline in 2050, in relation to the 2˚C target

Policy scenario		Per capita consumption (kcal/cap/d)			Global production value (billion USD at year 2000 constant world prices)				Net AFOLU emissions ($GtCO_2eq$)
	Global	Sub-Saharan Africa	Southeast Asia	South Asia	Agriculture	Crops	Livestock	Wood	Global
Baseline level	2 735	2 373	2 502	2 583	3 536	1 859	1 677	183	9.3
2c_afolu	-4%	-3%	-9%	-5%	-8%	-6%	-9%	8%	-89%
2c_afolu_wo_tax_ldc	-3%	-1%	-3%	-3%	-6%	-4%	-8%	8%	-63%
2c_afolu _tax	-4%	-3%	-8%	-4%	-7%	-6%	-9%	8%	-69%
2c_afolu _sub	-1%	0%	-2%	-1%	-1%	-1%	-1%	13%	-35%
2c_agri	-3%	-1%	-6%	-4%	-6%	-4%	-8%	15%	-50%
2c_ agri _tax	-3%	-1%	-7%	-4%	-6%	-4%	-8%	15%	-43%
2c_ agri _sub	0%	0%	-1%	0%	0%	0%	0%	15%	-19%
2c_lulucf	-2%	-3%	-5%	-2%	-4%	-3%	-4%	7%	-61%
2c_ lulucf _tax	-2%	-2%	-4%	-1%	-3%	-2%	-3%	9%	-49%
2c_ lulucf _sub	-1%	0%	-2%	-1%	-1%	-1%	-1%	13%	-21%

These factors are reflected in the aggregate food price changes shown in Table 6 All the scenarios inflate aggregate global food prices with the exception of the subsidy for abatement in agriculture *2c_agri_sub*. The policies with the broadest coverage of taxes on AFOLU emissions, *2c_afolu* and *2c_afolu_tax*, are the most inflationary, with the taxes on agricultural emissions causing the most upward pressure on prices with additional increases from the tax on LULUCF emissions (see 2c_ *agri _tax* and *2c_ lulucf _tax* in Table 5). The exemption of least developed countries from paying emission taxes in *2c_afolu_wo_tax_ldc* lowers the impact of price increases relative to *2c_afolu*, particularly for sub-Saharan Africa and Southeast Asia. The impact is more muted in South Asia because India, the dominant country in this region, is not considered to be a least developed country and is therefore not exempted from paying taxes in *2c_afolu_wo_tax_ldc* policy package.

Table 6. Percentage changes in food prices, relative to the baseline in 2050, in relation to the 2˚C target

Policy scenario	World	Sub-Saharan Africa	Southeast Asia	South Asia
2c_afolu	29%	23%	50%	27%
2c_afolu_wo_tax_ldc	22%	10%	6%	21%
2c_afolu _tax	30%	22%	51%	26%
2c_afolu _sub	6%	1%	3%	1%
2c_agri	23%	14%	34%	22%
2c_ agri _tax	24%	14%	35%	22%
2c_ agri _sub	0%	0%	2%	1%
2c_lulucf	11%	12%	25%	8%
2c_ lulucf _tax	10%	10%	22%	6%
2c_ lulucf _sub	3%	2%	4%	2%

The various policy packages also have vastly different impacts on government budgets (Table 7). Here it can be seen that the taxes on agricultural emissions provide the main source revenue across the AFOLU sector, for the policy packages that include emission taxes, generating between USD 231 billion and USD 324 billion in revenue in 2050. These tax revenues dwarf the costs of providing subsidies in agriculture for either reducing non-CO_2 emissions or for promoting soil carbon sequestration. With respect to non-CO_2 emissions, this asymmetry stems from the fact that taxes are applied the full stream of emissions, whereas the subsidy is only applied to the subset of emissions that landholders find profitable to reduce. It should be noted that since this assessment is based on a partial equilibrium model, it was only possible to track the government budget implications of the policies. It was not possible explore the economic and fiscal implications of the changes in government budgets (e.g. the impacts of raising taxes to pay for net losses in government revenue or vice versa).

Table 7. Changes in costs and revenues for government budgets (billion USD), and changes in net GHG emissions ($GtCO_2eq$) directly associated with each policy package, relative to the baseline in 2050, in relation to the 2˚C target

	Agriculture (including SOC)				LULUCF (excluding SOC)			AFOLU	AFOLU
	Tax revenue (non-CO2)	Subsidy cost (non-CO2)	Subsidy cost (SOC)	Net revenue	Tax revenue	Subsidy cost	Net revenue	Net revenue	Net emission change
2c_afolu	315	-48	-52	215	75	-265	-190	25	-8.3
2c_afolu_wo_tax_ldc	231	-50	-55	126	13	-261	-247	-121	-5.9
2c_afolu _tax	317	0	0	317	73	0	73	390	-6.4
2c_afolu _sub	0	-58	-59	-118	0	-256	-256	-374	-3.3
2c_agri	324	-49	-55	221	0	0	0	221	-4.6
2c_ agri _tax	322	0	0	322	0	0	0	322	-4.0
2c_ agri _sub	0	-58	-60	-119	0	0	0	-119	-1.8
2c_lulucf	0	0	0	0	76	-255	-180	-180	-5.7
2c_ lulucf _tax	0	0	0	0	74	0	74	74	-4.5
2c_ lulucf _sub	0	0	0	0	0	-258	-258	-258	-1.9

The pattern of policy costs and revenues in the LULUCF sector is reversed, with the cost of subsidising afforestation being significantly higher than the revenues from emission taxes in the sector. The LULUCF tax revenues are much lower than the agricultural emission tax revenues partly because LULUCF emissions are lower than from agriculture (4.2 GtCO2eq compared to 6.7 GtCO2eq in the baseline in 2050), but mainly because the carbon tax is much more effective at lowering emissions LULUCF emissions (e.g. all tax policies covering LULUCF lower its baseline emissions to just 0.8 GtCO2eq, whereas taxes covering agriculture lower its baseline emissions to 4 GtCO2eq).

For the packages in agriculture that subsidise abatement, the costs of subsidising non-CO_2 emission reductions and SOC emissions are very similar. However, there are significant uncertainties about these costs, especially with regard to SOC sequestration.

The net revenues at the total AFOLU level are positive for all policies including a tax with global regional coverage, with the exception of *2c_lulucf*, for which the cost of subsidising afforestation significantly offsets the modest tax revenue from the sector. The net revenues from the central AFOLU-wide policy, *2c_afolu*, switches from being modestly positive to strongly negative following the exemption of least developed countries from paying taxes in *2c_afolu_wo_tax_ldc*.

Comparing the final two columns in Table 7 provides an approximate sense the budgetary effectiveness of the different policy packages. The packages containing taxes tend to provide the double dividend of stronger mitigation and a net increase to government budgets at the global level. For a more complete understanding of the trade-offs these budgetary changes need to be compared with the policy impacts on production and food consumption. With these in mind it is apparent that the budgetary benefits of the emission taxes come with more detrimental impacts on production and food consumption.

It should however be cautioned that these budgetary effects are highly approximate, particularly because the partial equilibrium setting of the model assessment ignores the feedback effects on other taxes collected from household and producer incomes expenditures, which will be affected by the policies. These missing general equilibrium effects would have also caused some reallocation of government expenditures, with further flow on effects for governments and other economic participants.

4. Policy scenario results relating to the 1.5°C target

All of the nine policy schemes outlined in Table 1 for the 2°C target were also simulated using the carbon price trajectory that is relevant for the 1.5°C target. In this section, the findings for the 1.5°C target are summarised, for which carbon prices reaching USD 240 tCO_2eq^{-1} by 2050, consistent this target are used. These are substantially higher than the carbon prices used for the 2°C target, which only reach USD 70 tCO_2eq^{-1} by 2050.

The most ambitious policy scenario, *1.5c_afolu*, targeting all AFOLU mitigation sources, generates substantial net emission reductions of 12 $GtCO_2eq$, in 2050, with agriculture contributing nearly identical shares to the total mitigation as with *2c_afolu*. The main difference being the much larger contribution that afforestation (inclusive of energy plantations) makes for the more stringent target.

The 12 $GtCO_2eq$ of net emission reductions from AFOLU represents a 129% reduction of the sector's baseline net emissions, causing it to become a net sink of -2.7 $GtCO_2eq$ under the 1.5°C target, in 2050. When compared to the 57 $GtCO_2eq$ of total global mitigation projected for 2050, under the 1.5°C target calculated by McCollum et al. (2018[16]) the 12 $GtCO_2eq$ net reduction from AFOLU calculated here corresponds to a 21% contribution to this total.

Interestingly, the net emission reductions from the 2°C AFOLU subsidy scenario are 23% larger than the 1.5°C AFOLU subsidy scenario (Figure 17). This is because demand for energy crops is significantly higher under the 1.5°C target, causing these crops to displace forest and other natural land, and substantially drive up emissions from land use change, and these emissions are not fully compensated by the increases in the afforestation and soil carbon sinks (Figure 18). In general, the changes in land use are larger under the 1.5°C scenarios compared to the 2°C scenarios (Figure 16). Similar patterns of change are observed for most land uses except that afforested land increases and other land use falls under all of the 1.5°C scenario.

Although not presented here, the pattern of production impacts for the 1.5°C scenarios are similar to the one that emerged from the corresponding 2°C scenarios, but the magnitude of impacts from the more stringent target are larger, as was the case with the emission and land use changes.

Figure 17. AFOLU emission changes (MtCO2eq) for the AFOLU-wide policy scenarios relative to baseline in 2050, in relation to the 1.5˚C and 2˚C

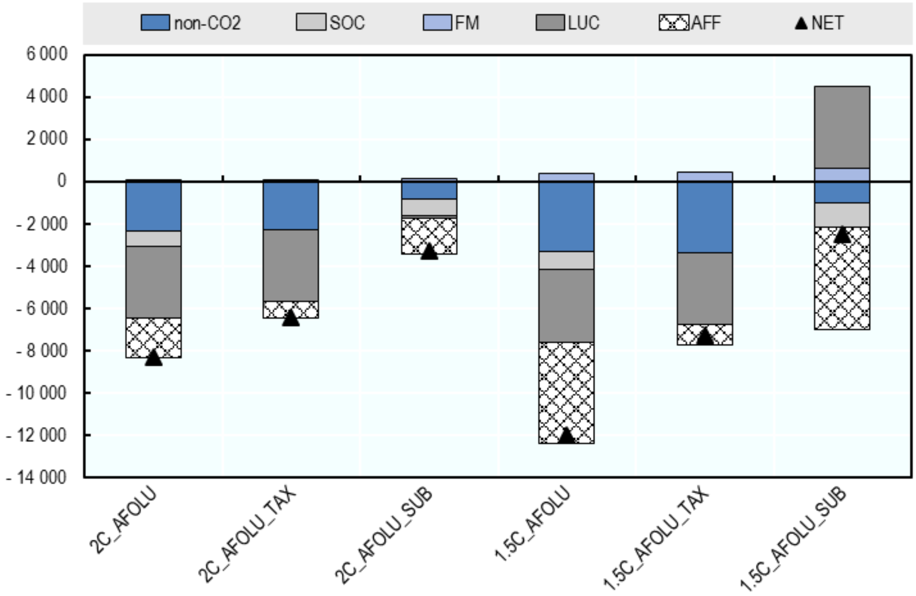
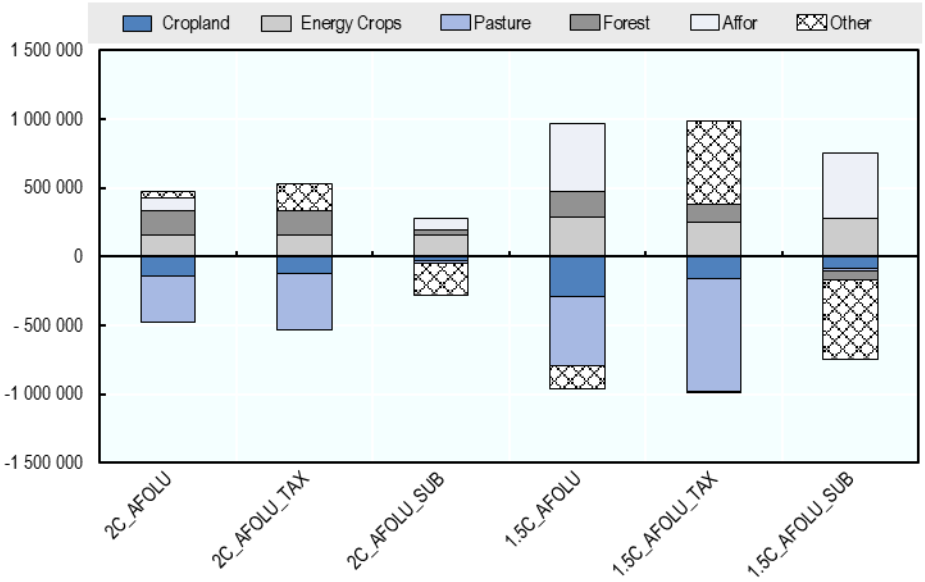


Figure 18. Land use changes (1 000 ha) for the AFOLU-wide policy scenarios relative to baseline in 2050, in relation to the 1.5°C and 2°C targets



5. Sensitivity analysis

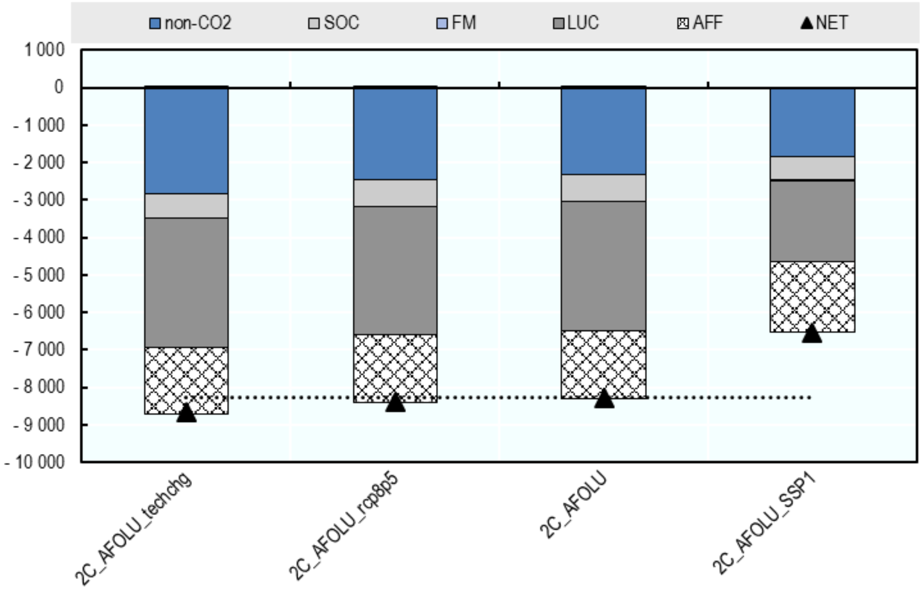
In this section, the sensitivity main global results to changes in assumptions about climate change, the effectiveness of non-CO_2 abatement technology, macro-economic trends (i.e. SSP assumptions), are reported.

The impacts of changes to all of these assumptions are shown in Figure 19, with the dotted line referencing the total net mitigation of the central *2c_afolu* scenario for comparison. Each of these scenarios uses the same combination of taxes and subsidies as applied in the central scenario.

Altering the climate change pathway from RCP 2.6 as assumed in the central scenario to the strong climate impact pathway if RCP 8.5, only marginally changes net mitigation from AFOLU (Figure 19 and Table 8).[10] The assumed efficiency gains in non-CO_2 abatement technologies (*2_afolu_techchg*) generate a significant 22% increase in the amount of non-CO_2 emissions mitigated, relative to the central *2_afolu* scenario, however, this translates to a more modest 5% increase in net AFOLU emission reductions relative to *2_afolu*. This is because non-CO_2 emission reductions only represent a share of total mitigation (e.g. 28% of in *2c_afolu* and 34% in *2c_afolu_techchg*).

In contrast, changing the socio-economic pathway from SSP2 to SSP1 causes a 21% decline the mitigation of net AFOLU emissions. This is mainly because baseline net emissions are 30% lower under the SSP1 pathway (6.6 $GtCO_2eq$) compared to the SSP2 pathway (9.3 $GtCO_2eq$). In fact, on the basis of the percentage of baseline net emissions reduced, the AFOLU-wide policy package is more effective under SSP1 (*2c_afolu_ssp1*), reducing 100% of baseline net emissions pathway compared to 89% of net emissions for the same package under the SSP2 pathway (*2c_afolu*).

Figure 19. Mitigation ($GtCO_2eq$) from the AFOLU-wide policy to assumptions about climate, technology, global coverage and socio-economic pathway, relative to the baseline in 2050, in relation to the 2°C target



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[10] However, since the climate change impacts are modelled as average yield changes and do not consider the impacts of extreme events (e.g. droughts and floods) on either production or the carbon sinks, the overall impacts of climate change are underestimated.

Table 8. Percentage changes in mitigation of AFOLU-wide policy to assumptions for climate, technology, global coverage and socio-economic pathway, relative to the central 2c_afolu scenario in 2050, in relation to the 2°C target

	non-CO2	SOC	FM	LUC	AFF	NET
2C_AFOLU_techchg	22%	-9%	59%	0%	-4%	5%
2C_AFOLU_rcp6	12%	2%	10%	-1%	-3%	3%
2C_AFOLU_rcp8p5	6%	2%	6%	-1%	-1%	1%
2C_AFOLU_SSP1	-21%	-13%	-219%	-37%	2%	-21%

6. Comparison, and complementarities with other work, and limitations of the study

The mitigation estimates from some, but not all parts of AFOLU, in this study can be compared to those from other global modelling assessments. For example, IPCC (2019[1]) and Wollenberg et al. (2016[17]) show that annual non-CO_2 emissions from agriculture could fall by between 14% and 23% as part of economy-wide policy efforts to limit global temperature increases to 2°C. While this study focuses on AFOLU-wide net emission changes, results from this assessment show that non-CO_2 emissions fall by 17% as part of sector-wide scenario consistent with limiting global temperature increases to 2°C. This fits within the range of projected non-CO_2 reductions reported in the related studies mentioned above.

As mentioned, this study adds value to previous global assessments by OECD (2019[2]) and others, by broadening the coverage of mitigation policies from agriculture to also target sources of mitigation within the LULUCF sector. Both OECD (2019[2]) and the present study calculated similar differences in the relative effectiveness of an emission tax and abatement subsidy with respect to non-CO_2 emissions. Both studies also reveal similar differences in these policies in terms of their impacts on producers and consumers. However, by considering LULUCF mitigation policies, the present study revealed that the LULUCF sector delivered around double the emission reductions of the agricultural sector, when mitigation policies were applied AFOLU-wide.

The effect of taxes on agricultural non-CO_2 emissions on leveraging additional emission reductions from the LULUCF sector was also calculated with similar magnitude in the computable general equilibrium assessment in OECD (2019[2]). By also assessing mitigation policies in the LULUCF sector, the present study showed that this leveraging effect also works in the other direction, with the land competition impacts of these policies causing agricultural emissions to fall.

As with all modelling assessments, there are limitations in scope and simplifications of real-world complexities that are relevant to the policy making process. Some of these are addressed in the sensitivity analysis, while others beyond the scope of the model. For example, the practical policy implementation challenges that need to be overcome to reach the levels of policy adoption and impact calculated in this assessment are not considered. These challenges include the measurement of emissions and removals, the setting of baselines, contracting, and capacity building. Some of these issues are being explored in other OECD projects. Another important policy issue beyond the scope of this assessment is the impact of the mitigation policies on biodiversity and other environmental goods and services. These impacts can be caused by policy-induced changes in land use (e.g. increased forest cover) and farming practices (e.g. reduced fertiliser use). The interaction between mitigation and other environmental policies could also be a useful future extension to this assessment. The sensitivity analysis provides some assurance about the robustness of the model results, although better data availability for some of the key inputs driving the model would further improve the accuracy of the results. For example, as shown in Annex A (Table A A.2), SSP1 and SSP2 entail quite different assumptions about the evolution of agricultural productivity. However, these are based on different rates of improvement in crop yields and animal feed conversion efficiencies over time, while pasture yields remain static over time. Thus, the accuracy of the model could be improved in future if global datasets on projected changes in pasture yields become available and are incorporated. Finally, the effectiveness and costs of the various policies is dependent on the emission reduction potentials embodied in the MACs used in the assessment, which are aggregate approximations of the potentials that may exist in practice. Thus, the construction of more detailed MAC estimates would also add significant value to future mitigation policy assessments.

Annex A. Model details, data and scenario drivers

GLOBIOM: Model overview

The Global Biosphere Management Model (GLOBIOM) (Havlík et al., 2014[18]) is a partial equilibrium model that covers the global agricultural and forestry sectors, including the bioenergy sector. Commodity markets and international trade are represented at the level of 37 economic regions. Commodity prices are endogenously determined at the regional level to establish market equilibrium by reconciling demand, domestic supply, and international trade. The spatial resolution of the supply side relies on the concept of simulation units, which are aggregates of 5 to 30 arcmin pixels belonging to the same altitude, slope, and soil class, and also the same country (Skalský et al., 2008[19]) that are usually aggregated to 2 degrees (about 200 x 200 km at the equator).

For crops, livestock, and forest products, spatially explicit Leontief production functions covering alternative production systems are parameterised using biophysical models like EPIC (Environmental Policy Integrated Model) (Williams, 1995[20]), G4M (Global Forest Model) (Kindermann et al., 2008[21]; Gusti, 2010[22]), or the RUMINANT model (Herrero et al., 2013[23]). The forest sector is modelled based on Lauri et al. (2014[24]) and represents seven final products (chemical pulp, mechanical pulp, sawnwood, plywood, fiberboard, other industrial roundwood, and household fuelwood) where the demand for the various final products is modelled using regional level constant elasticity demand functions. Forest industrial products (chemical pulp, mechanical pulp, sawnwood, plywood and fiberboard) are produced by production technologies, with input-output coefficients based on the engineering literature, e.g. FAO (2010[25]). By-products of these technologies (bark, black liquor, sawdust, and sawchips) can be used for energy production or as raw material for pulp and fiberboard. Initial production capacities for forest industry final products are based on production quantities from FAOSTAT (2012). After the base year the capacities evolve according to investment dynamics, which depend on depreciation rate and investment costs.

The model includes six land cover types: cropland, grassland, short rotation plantations, managed forests, unmanaged forests, and other natural vegetation land. Depending on the relative profitability of primary, by-, and final products production activities, the model can switch from one land cover type to another. Spatially explicit land conversion over the simulation period is endogenously determined within the available land resources and conversion costs that is taken into account in the producer optimisation behaviour. Land conversion possibilities are further restricted through biophysical land suitability and production potentials, and through a matrix of potential land cover transitions. Land and other resources are allocated to the different production and processing activities to maximise a social welfare function which consists of the sum of producer and consumer surplus. The model is calibrated to 2000 and solved recursively dynamic up to 2100 in ten-year steps.

AFOLU GHG emissions and mitigation

GLOBIOM covers major GHG emissions from agriculture, forestry, and other land use (AFOLU) including CO_2 emissions from above- and belowground biomass changes following land use changes (including afforestation/deforestation), N_2O from the application of synthetic fertiliser and manure to soils, N_2O from manure dropped on pastures, CH_4 from rice cultivation, N_2O and CH_4 from manure management, and CH_4 from enteric fermentation. The model explicitly covers different mitigation options for the agriculture and forestry sectors: technical mitigation options for agriculture such as anaerobic digesters, livestock feed supplements, nitrogen inhibitors etc. are based on USEPA (2013[7]) and Beach et al. (2015[8]), and soil carbon sequestration is based on Smith et al. (2008[26]), whereas structural adjustments are represented through a comprehensive set of crop- and livestock management systems, i.e. transition in management systems, reallocation of production within and across regions through international trade (Havlík et al., 2014[18]), consumers' response to market signals (Valin et al., 2014[27]), and land use changes such as afforestation, establishment of dedicated energy plantations, or avoided deforestation. Detailed information on the parameterisation of the different mitigation options for the agricultural sector are presented in Frank et al. (2018[9]) and Frank et al. (2017[28]). For more information on the general model structure see Havlík et al. (2011[29]) and Havlík et al. (2014[18]). Summaries of the approaches for incorporating marginal costs of abating non-CO_2 emissions from agriculture and for carbon sequestration in agricultural soils, are also provided below.

Marginal costs of abating non-CO_2 emissions from agriculture

GLOBIOM represents a comprehensive set of technical non-CO_2 mitigation options for the agricultural sector (crop including rice and livestock) as presented in Frank et al. (2018[9]). Emission reduction coefficients, economic cost, and impact on productivities for each technical mitigation option are based on the US EPA database (Beach et al., 2015[8]; USEPA, 2013[7]) and implemented explicitly in GLOBIOM. A quadratic cost function is assumed, where marginal costs double from initial costs at the adoption maximum of a technology to mimic adoption behaviour. With respect to adoption rates of different options mutually exclusive mitigation option bundles for the crop- and livestock sectors are defined. For non-rice crops it is assumed that only one option can be applied per ha (full competition between the options). However rice options are defined as a combination of different water, residue, and fertiliser management practices. For the livestock sector two separate bundles are differentiated: enteric fermentation options and manure management options, where options from both bundles can be implemented at the same time. Mitigation options get adopted if the carbon price exceeds the cost of the practice. The measures for reducing enteric fermentation 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, 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 (Beach et al., 2015[8]). All of the mitigation measures listed above are currently available except for anti-methanogens for reducing enteric fermentation, which is still under development.

Marginal costs of sequestering carbon in agricultural soils

The marginal abatement costs implemented for soil organic carbon (SOC) sequestration in agriculture are based on Smith et al. (2008[26]) for a carbon price of USD 20, USD 50 and USD 100/tCO_2. These three points related to improved cropland and grazing management are implemented in GLOBIOM as additive “mitigation technologies” with different carbon sequestration coefficients reflecting the implementation rates and costs from Smith et al. (2008[26]). SOC sequestration options are only applied once on each field and may get adopted from 2020 onwards once expected revenues (i.e. through the carbon price scheme) exceed costs. Average sequestration rates are assumed constant until 2050, which seems reasonable since other studies estimate that additional SOC sequestration of these options may be realised over a limited time span of around 20-40 years (Paustian et al., 2016[30]; Minasny et al., 2017[31]). Yield increases for the cropland SOC sequestration options can be can be considered based on Lal (2006[32]). Annual yield increases of crop aggregates can reach 1.5%, 1.2% and 0.7% in Africa, Latin America and Asia, respectively, and 0.9% at world average, per tCO_2/ha sequestered annually.

Improved representation of afforestation/deforestation

Within the project, the representation of forest related CO_2 emissions/removals will be improved by developing an approach that is able to endogenously represent afforestation and additional drivers for deforestation outside agriculture in the model. Previously, these emission accounts/activities were quantified through the link with the Global Forest Model (G4M). Regional afforestation and deforestation as estimated by G4M consistent with certain climate mitigation pathways will be used to calibrate the afforestation/deforestation patterns in GLOBIOM. The model will be calibrated to match the average afforestation and deforestation rates over the historical period on the regional scale.

Regional aggregation scheme

The countries and territories comprising each of the ten global regions used in the GLOBIOM assessment are shown below in Table A A.1.

Table A 0.1. Mapping between the regions and countries and territories in the GLOBIOM assessment

Region	Country
Middle East North Africa	Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestinian Authority, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen, Algeria, Egypt, Libya, Morocco, Tunisia, Western Sahara, Turkey
Sub-Saharan Africa	Cameroon , Central African Republic, Democratic Republic of Congo, Equatorial Guinea, Gabon, South Africa, Burundi, Ethiopia, Kenya, Rwanda, Tanzania, Uganda, Angola, Botswana, Comores, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Réunion, Eswatini, Zambia, Zimbabwe, Benin, Burkina Faso, Cabo Verde, Chad, Côte d'Ivoire, Djibouti, Eritrea, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Senegal, Sierra Leone, Somalia, Sudan, Togo
Latin America and the Caribbean	Argentina, Brazil, Mexico, Bahamas, Belize, Costa Rica, Cuba, Dominican Republic, El Salvador, Guadeloupe, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Trinidad and Tobago, Bolivia, Chile, Colombia, Ecuador, Falkland Islands (Malvinas), French Guiana,, Paraguay, Peru, Suriname, Uruguay, Venezuela
Russian Federation	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Tajikistan, Turkmenistan, Uzbekistan, Russian Federation, Ukraine
South Asia	India, Bangladesh, Bhutan, Nepal, Pakistan, Sri Lanka
Europe	Estonia, Latvia, Lithuania, Bulgaria, Croatia, Czech Republic, Hungary, Poland, Romania, Slovak Republic, Slovenia, Austria, Belgium, France, Germany, Luxembourg, Netherlands, Denmark, Finland, Ireland, Sweden, United Kingdom, Cyprus[1], Greece, Italy, Malta, Portugal, Spain, Albania, Bosnia and Herzegovina, Republic of North Macedonia, Serbia, Montenegro, Greenland, Iceland, Norway, Switzerland
North America	Canada, Puerto Rico, United States
Oceania	Australia, New Zealand, Fiji Islands, French Polynesia, New Caledonia, Papua New Guinea, Samoa, Solomon Islands, Vanuatu
Eastern Asia	China (People's Republic of), Japan, Korea, Democratic People's Republic of Korea
Southeast Asia	Indonesia, Malaysia, Brunei Darussalam, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, Cambodia, Lao People's Democratic Republic, Mongolia, Viet Nam

1. Note by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus" issue.
Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

Previous assessments of existing mitigation policies and commitments for AFOLU in GLOBIOM studies

Existing IAMs based assessments of the NDCs have focused mainly on the energy sector (Rogelj et al., 2016[33]; Hof et al., 2017[34]; Rogelj et al., 2017[35]; den Elzen et al., 2019[36]; Harmsen et al., 2019[15]). For the land use sector, some studies investigated the impact on net AFOLU emissions using the projections and data provided in the NDCs (Forsell et al., 2016[37]; Grassi et al., 2017[38]; Richards, Wollenberg and van Vuuren, 2018[39]), however no detailed AFOLU modelling studies have been published so far at global scale.

The consideration of NDCs in sectors outside AFOLU in MESSAGE slightly impacted carbon prices and biomass demand related to energy specific mitigation targets. GLOBIOM-G4M was used to quantify the AFOLU pathways where a very limited number of most important NDCs (including current policies) were implemented as aspirational target in G4M for the forest sector in particular related to afforestation and reduced deforestation in Latin America and East and Southeast Asia:

- Brazil: Afforestation/reforestation of 12 Mha by 2030 and zero deforestation by 2030 (aspirational)
- China: Afforestation of 221 Mha by 2020 (aspirational)
- India: Afforestation of 5 Mha by 2030
- Indonesia: Decrease in deforestation by 50 Mm3 by 2025 compared to 2015.

NDC policies for agriculture were not considered in the analysis. However, MESSAGE provided GHG specific (CO_2, CH_4, and N_2O) residual emission caps for AFOLU when distributing overall NDC emission reduction targets across sectors that were then used to constrain net AFOLU emissions in GLOBIOM-G4M.

A similar approach could be used in this project, by complementing the database developed during the CD-LINKS project[11] and Forsell et al. (2016[37])with information about the most important NDC and policy targets in the agricultural sector, and implementing in GLOBIOM. However, such targets are very uncommon in the agricultural sector with the exception of some developing countries which had committed to targets that are conditional on external finance and a couple of OECD countries with modest binding targets. A more feasible approach given time and resource constraints will be to make an ex-post comparison of the mitigation scenario results in the project with the few NDC and national policy targets that do exist, and assess their convergence. This was the approach used by Richards et al. (2018[39])for African countries that have submitted AFOLU mitigation targets in their NDCs.

Baseline scenario drivers

The scenarios quantified by the IAMs used by the Intergovernmental Panel on Climate Change (IPCC) in their most recent assessment reports (AR5, Global Warming of 1.5 C, and Climate Change and Land) distinguish between two dimensions: the Representative Concentration Pathways (RCPs) (Moss et al., 2010[40]) and the Shared Socio-economic Pathways(SSPs) (Kriegler et al., 2012[41]). The Shared Socio-economic Pathway 2 (SSP2) (O'Neill et al., 2014[42]; Fricko et al., 2017[10])is chosen as the baseline scenario in GLOBIOM, and the approach for specifying this pathway in existing GLOBIOM studies (Fricko et al., 2017[10]; Rogelj et al., 2018[43]) is described below.

Using population and GDP projections directly taken from the SSP database, this scenario depicts a "Middle of the Road" scenario with moderate challenges to mitigation and adaptation. Under these assumptions, the global population increases by 35% from 6.83 billion to 9.24 billion, and GDP per capita increased by 72%, from USD 6 841 per person to USD 11 783 per person (in 2005 USD). Growth for demand for animal protein is relatively high, due to this comparatively strong income and population growth. For food demand projections, income elasticities are calibrated to mimic FAO projections of diets (Alexandratos, 2012[44]). Moderate reductions in food waste and losses over time add to the availability of agricultural products. Technological change for crops is based on 18 crop specific yield responses function to GDP per capita growth estimated for different income groups using a fixed effects model. The response to GDP per capita was differentiated over four income groups oriented at World Bank's income classification system (<1.500, 1.500-4.000, 4.000-10.000, >10.000 USD GDP per capita). Country level yield data was provided from FAOSTAT while GDP per capita was based on World Bank data. Fertiliser use and costs of agricultural production increase in proportion with yields. Productivity changes through technological change in the livestock sector follow Bouwman et al. (2005[45]). Transition towards more efficient livestock production systems takes place at a moderately fast pace. Livestock productivity, measured as kg of animal protein per tonne of dry matter (DM) feed increase by 8% from 12.0 to 12.9 kg per t of DM between 2010 and 2050, while total crop productivity increases by 42% from 3.1 to 4.4 t DM

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[11] This is a multi-partner project that combines several streams of research, including the use of models and scenarios to analyse interactions between climate mitigation and development, from global and national perspectives to help inform the design of climate-development policies (https://www.cd-links.org).

per ha over this period. More specifically, Table A A.2 shows the baseline productivity changes for specific crops and livestock under SSP2 (used for the core of the analysis) and SSP1 between 2020 and 2050.

Table A 0.2. Assumed productivity changes under the baseline scenarios for different agricultural activities, 2010-50

Crop/ feedstock	2010 values	2050 values	2050 values	2050 values	Annual average productivity change 2010-2050 without climate change	
		SSP2	SSP1	SSP2 with climate change (RCP)	SSP2	SSP1
Crops	(t DM / ha)					
Coarse grains	2.97	4.57	4.94	4.50	1.35%	1.66%
Oilseeds	2.24	3.10	3.29	3.06	0.95%	1.18%
Rice	3.93	5.57	5.99	5.67	1.04%	1.31%
Sugarcrops	17.16	19.27	20.57	20.13	0.31%	0.50%
Wheat	2.76	3.99	4.22	3.86	1.12%	1.33%
All crops	3.13	4.45	4.77	4.43	1.05%	1.31%
Livestock	(kg protein / t DM feed)					
Dairy	19.08	20.66	21.02	20.66	0.21%	0.25%
Ruminants	4.08	4.95	5.15	4.95	0.53%	0.66%
Non ruminants	24.30	24.84	24.96	24.84	0.06%	0.07%
All livestock	11.97	12.93	13.15	12.93	0.20%	0.25%

Source: GLOBIOM input database.

Besides SSP2, SSP1 will be included in in the assessment. SSP1 is characterised by relatively high levels of GDP growth, lower levels of population growth, fast technological growth, and convergence between developed and developing countries. In addition, future diets are considered to be more sustainable than in the FAO baseline and animal protein demand is assumed to be reduced in overconsuming regions. The detailed translation of SSPs into GLOBIOM, is presented in Fricko et al. (2017[10]).

Global climate targets

Two climate stabilisation scenarios (1.5°C and 2°C) are quantified using IIASA's IAM framework (MESSAGE-GLOBIOM) (Fricko et al., 2017[10]; Rogelj et al., 2018[43]). IAMs are used to develop climate stabilisation pathways across all economic sectors and underpin the different IPCC reports. IAMs have consistent perception on the net emission profile and energy portfolio required to achieve ambitious climate stabilisation cost-efficiently (van Vuuren et al., 2016[46]; Rogelj et al., 2018[43]), which has direct implications for the required AFOLU mitigation efforts through supply of biomass for bioenergy to decarbonise the energy system and reduction of land use related GHGs and enhancement of carbon sinks. IAMs anticipate an up to fivefold increase in total primary biomass demand for energy by 2050 in the Shared Socio-economic Pathway (SSP)2 to stay on track with the 1.5°C target (Rogelj et al., 2018[43]). To achieve the respective global climate target, GLOBIOM includes climate target specific trajectories for solid biomass demand for bioenergy production and AFOLU sector carbon prices (implemented as additional cost/subsidy per tCO_2eq emitted/sequestered on the supply side) that were derived based on the MESSAGE-GLOBIOM iterations.

A two dimensional emulator of the GLOBIOM model is created containing the land-use implications for scenarios combining different bioenergy price pathways and carbon price pathways. The resulting two dimensional scenario matrix covers an extensive space of land-use developments conditional on biomass and carbon prices. This GLOBIOM emulator is integrated into MESSAGE. During its energy-system optimisation, MESSAGE can hence select and combine emulated land-use pathways for each of its geographical regions based on the modelled bioenergy demands, taking into account estimated GHG emissions and bio-energy prices related to the chosen land-use pathways. Once an equilibrium has been determined in MESSAGE, specific outputs (bioenergy demand, carbon prices) fed-back to GLOBIOM where the final scenarios are quantified, and land use related results are reported. This process ensures that a given RCP emission trajectory and carbon and biomass prices for the land use sector are fully consistent between the two models.

Climate change impacts

Four representative concentration pathways have been developed for the climate modelling community as a basis for long-term and near-term modelling experiments (van Vuuren et al., 2014[47]). The four RCPs span from 2.6 to 8.5W/m2 radiative forcing values until 2100 ranging thereby from a <2 degree warming scenario up to a 4 degree scenario. For implementation of climate change impacts on crop- and grasslands in GLOBIOM, average yield shifters per crop, management system and region from the crop models for the different climate scenarios were calculated. The shifters were applied to shift future yields and costs in the different climate scenarios. RCP 8.5, RCP 6.0, and RCP 2.6 quantified by HadGEM2-ES and EPIC crop model with CO_2 fertilisation effect next to a scenario with current climate conditions were chosen.

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