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National Land-based Climate Mitigation Scenarios Dataset

DATA DESCRIPTOR

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Given the need to reduce greenhouse gases emissions to meet the 2°C or 1.5°C target of the Paris Agreement, over 150 countries currently have net-zero targets. National inventories and projections of land-based emissions and mitigation strategies have not been well developed and remain limited compared to energy sectors. Here, we provide worldwide national land-based emission and mitigation scenario data with a detailed portfolio of mitigation options. This information contributes to filling the gap between integrated assessment model estimates and national greenhouse gas inventories for land-based emissions through estimation of carbon sequestration in managed forests. Second, these data can be used as a benchmark for countries developing national targets or strategies for agriculture, forestry, and other land use sectors as well as for reviewing national contributions in global assessments in a manner consistent with integrated assessment model estimates.

Background & Summary

The Paris Agreement adopted in 2015 sets a long-term goal of “keeping the global average temperature increase well below 2°C above pre-industrial levels and pursuing efforts to limit it to 1.5°C”. To meet this long-term goal, global CO₂ emissions must decrease rapidly and deeply, reaching net zero CO₂ emissions by the middle of this century, while non-CO₂ emissions are also to be sharply reduced¹. Agriculture, forestry, other land use (AFOLU) sectors account for one-fourth of global total greenhouse gas (GHG) emissions². In particular, agriculture is a major source of non-CO₂ emissions. Compared to technologies for CO₂ removal, those for removing non-CO₂ gases from the atmosphere are less well developed, such that non-CO₂ emissions remain a major source of residual emissions. Reducing emissions from agriculture will be key to achieving net zero status and stabilising the global temperature at a low level of warming.

In response to this global goal, a growing number of parties to the Paris Agreement are adopting net-zero emissions targets. Currently, more than 150 countries have set the goal of achieving net zero status³. The Nationally Determined Contributions (NDCs)⁴ for GHG reductions after 2020 require each country to introduce domestic measures to achieve its GHG reduction targets. National inventories for AFOLU sectors have been developed for some countries (e.g., Brazil, Ethiopia, European countries, India, Indonesia, Kenya and the United States), but have not yet been developed for most developing countries. National-level emissions projections and mitigation strategies for AFOLU sectors remain less developed than similar data for energy sectors⁵. Advanced research communities such as the Food, Agriculture, Biodiversity, Land-Use, and Energy Consortium⁶ and the Institute for Sustainable Development and International Relations⁷ have addressed the integration of national and global scales for some countries (20 and 6 countries, respectively) to support national decision-making toward sustainable decarbonisation. The number of countries that have not yet set their own targets is smaller than the number of countries that have such targets. Therefore, developing country-specific reduction scenarios for a wide range of countries and a detailed portfolio of specific reduction options or technologies would be useful steps toward achieving net zero emissions.

Integrated assessment models (IAMs) have been mainly used for assessing global emissions pathways associated with a wide range of sectors and components in a consistent manner at global and regional levels. However, given the growing need for national- and local-scale assessments to support national decision-making toward a

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decarbonised or sustainable world, three potential improvements can be made. Firstly, most global IAM results employ regional aggregation and do not provide country-level estimates with individual measures worldwide, as this was not their original purpose. IAM estimates of national-level mitigation pathways could strongly improve the robustness of country-level mitigation estimates and their consistency with global-scale analyses, e.g., by reflecting future macroeconomic effects and supply-and-demand and price changes in the market. Global models consider interlinkages between sectors and regions and can thus account for interactions driven by international trade and conflict that affect the usage of land and other resources.

Secondly, a limited portfolio of land-based mitigation measures has been reported in IAMs. A large gap exists between bottom-up sectoral approaches and IAMs⁸ for estimation of land-based mitigation potential. This gap arises from the limited portfolio of land-based mitigation measures included in IAMs. Most IAMs consider only afforestation, reforestation, and bioenergy with carbon capture and storage. Implementing a wider range of land-based mitigation measures in IAMs could contribute to filling this gap, providing projections for a wide range of land-based emission reduction options to countries and clarifying the roles of global land sectors in achieving long-term targets.

Thirdly, National Greenhouse Gas Inventory (NGHGI) and IAM global model assessments follow different accounting approaches, resulting in a large gap in estimates of present land-based emissions and sinks due to differences in the definitions of terms (e.g., the definition of anthropogenic) and coverage of sinks⁹. Some of that gap derives from whether the carbon sink of managed forest can be defined as anthropogenic or natural. IAMs do not include the carbon sink of managed forests, assuming it is natural, while NGHGIs include this sink as caused by humans. For scientific assessment, IAM estimates of carbon sink in managed forests could allow for direct comparison with NGHGI estimates. Such comparison would be important for IAMs, providing national-level benchmark pathways to countries considering the development of national targets or strategies as well as for reviewing national contributions via global stock assessment in a manner consistent with NGHGIs. Previous studies have developed translation approaches to allow for comparison of these estimates. For example, Grassi *et al.*⁹ proposed adding the estimated CO₂ sink in managed forests obtained from dynamic global vegetation models (DGVMs) to the estimates from IAMs to fill the gap. Based on the same idea, Gidden *et al.*¹⁰ developed a tool based on the simple Ocean Surface Current Analysis Real-time (OSCAR) climate model, adding estimates from DGVMs, adjustment to include emissions from managed land and translation of the results of IAMs to estimates compatible with NGHGIs. These approaches would be very useful for comparisons among disparate data sources, while IAM estimates of indirect emissions would allow for more direct comparison using the same accounting approaches.

Based on the background presented above, this dataset aimed to address outstanding data needs by providing:

- 1) National-level land-based emission pathways with detailed composition of carbon emissions including direct emissions from land conversion and indirect emissions from managed land.
- 2) Country-level GHG emission reduction potential and cost-effective countermeasure technologies in alignment with the long-term climate target.
- 3) Comparison of emissions estimates between IAMs, the Emissions Database for Global Atmospheric Research (EDGAR), the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT), and the NGHGI, and evaluation of the uncertainty range.

Methods

Overview of the dataset generation framework. The overall model framework is shown in Fig. 1. In this dataset, simulations were conducted in an integrated assessment modelling framework containing the Asia–Pacific Integrated Model (AIM) combined with a global economic model (AIM-Hub)¹¹, the AIM Platform for Land-Use and environmental Modeling (AIM-PLUM)¹², which is used for global spatial land use allocation, and the agriculture, forestry, other land use changes, and bioenergy (AFOLUB) model, which is used for land mitigation technology selection¹³. AIM-Hub first estimates future supply and demand for commodities in the agricultural and forest sectors, land use changes, prices of agricultural goods and energy, wages, land rent and the price of carbon at the regional level under assumptions of future population, gross domestic product (GDP), consumption preferences, technology developments such as agricultural land productivity (crop yields) and emissions constraints toward achieving the long-term climate target.

Then, the AIM-PLUM model downscales this regional aggregated land use data into a spatial grid at the half-degree scale and calculates land-based carbon emissions and sequestration into biomass and soil carbon associated with afforestation and reforestation, soil carbon management and managed land. The calculation is based on spatial biophysical conditions for land productivity of afforestation and reforestation, crops, and soil carbon sequestration, which strongly affect carbon sink potential.

Finally, the AFOLUB model calculates GHG emissions, as well as potential reductions and abatement costs by country, given future human activity levels such as agricultural production and land use changes estimated by AIM-Hub. AFOLUB estimates emissions reductions using a detailed portfolio of individual mitigation technologies. These models have been applied to Asian countries for mitigation analysis^{13–16} and are applied to countries around the world in the present dataset. The results are reported at the country level and for five aggregated regions: Organisation for Economic Co-operation and Development (OECD) and European Union (EU) member countries; Asia; Latin America; the Middle East and Africa; and countries surrounding the former Soviet Union. This analysis covers the period 2005–2100 at 10-year intervals.

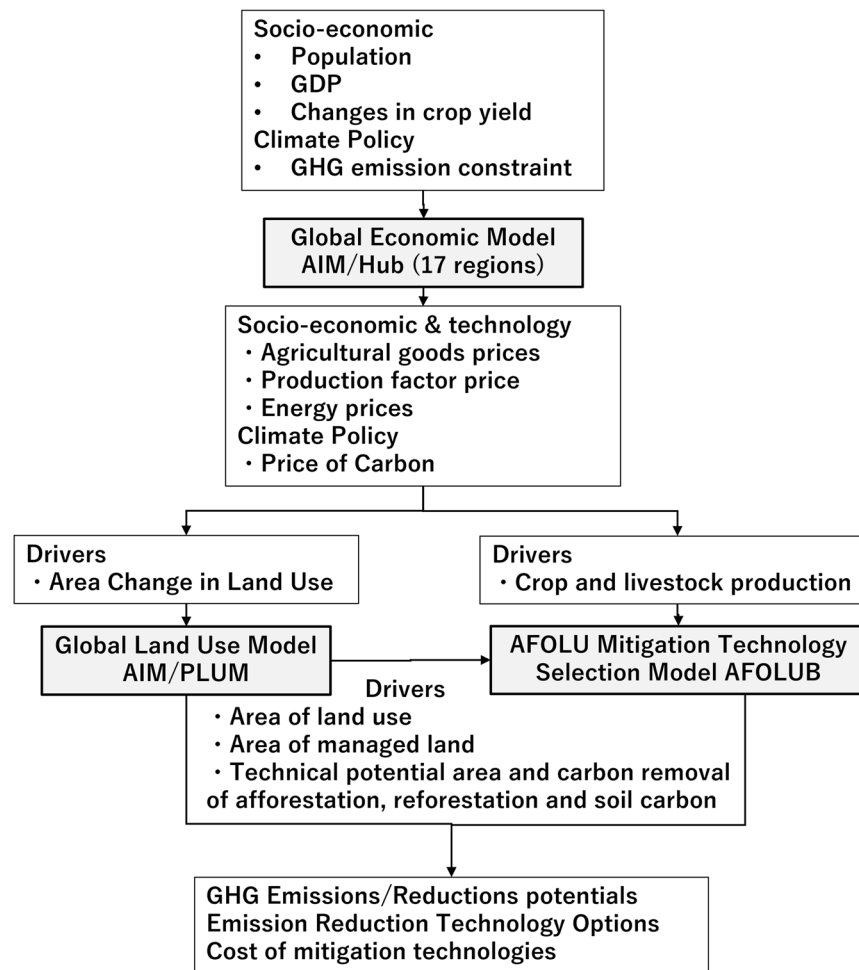


Fig. 1 Model framework used to generate the National Land-based Climate Mitigation Scenarios Dataset.

Global economic model AIM-Hub. AIM-Hub was developed by Fujimori *et al.* in 2012¹¹ and 2014¹⁷ and has been widely used for global^{18–22} and national^{23,24} studies of climate change. In AIM-Hub, supply, demand, trade, and investment are described as individual behavioural functions that respond to changes in the prices of production factors and commodities, in addition to changes in technology. The functions also respond to preference parameters based on the assumed population, GDP, and consumer preferences. The model contains 17 regions and 42 industrial classifications including ten agricultural sectors. Production functions are formulated as multi-nested constant elasticity substitution functions wherein land is a production factor for agricultural and forest commodities. Allocation of land into sectors is formulated as a multinomial logit function to reflect differences in substitutability among land categories with land rent¹⁷. The model estimates future agricultural activity, crop yields, land use, food goods, energy prices, wages, and carbon prices based on inputs of total factor productivity, population, GDP, crop yield estimates, consumption propensities, and global GHG emission pathways. The results of AIM-Hub are input into the AFOLUB model.

Global land use model AIM-PLUM. AIM-PLUM, a global land use allocation model, disaggregates regional land use data from AIM-Hub into half-degree grid cells¹². Regional aggregated land use projections from AIM-Hub (17 regions) were fed into the land use allocation model and downscaled into grid cells ($0.5^\circ \times 0.5^\circ$). Half-degree information was aggregated to ISO national-scale data when the data were input to the AFOLUB model. The cropland and afforestation areas were allocated based on profit maximisation wherein a fraction of land use categories are determined to obtain the greatest profit under given biophysical land productivity conditions (based on a DGVM²⁵ for afforestation, the LPJmL model²⁶, for seven non-energy crops with or without irrigation, and the H08 global hydrological model²⁷ for bioenergy crops), an irrigation map²⁸, land use map for the base year (Monfreda *et al.*, 2008^{29,30} for cropland and CMIP6 for other land categories), costs of land conversion and carbon prices. As sufficient data are not available for estimating the future distribution of potential profit from livestock products, pastureland was allocated near the base-year distribution to meet the regional aggregated pasture area based on minimising land transition costs. Livestock management systems were not explicitly considered. Protected areas were designated based on the protected area map developed by Wu *et al.*³¹. Cropland and afforestation were allocated to unprotected areas, and land covered by natural vegetation was allocated in protected areas. Some protected areas presently include pastureland, as shown by the partial overlap

between the protected land map and the current pasture distribution. Pasturelands were allowed to expand only into unprotected areas over time. Land covered by natural vegetation was divided into forests and other land use types according to carbon stock density, which is tracked over time in each grid cell. A carbon stock density threshold between forest and grassland was determined such that the forest area was equal to that reported by the Food and Agriculture Organization of the United Nations (FAO). Forested areas were divided into afforestation/reforestation and other forests, including managed and unmanaged forests. Carbon stock changes were estimated assuming native forest types for afforestation/reforestation and natural forest for other naturally regenerating forests on abandoned lands, using forest growth curves parameterised based on growth rates from the Vegetation Integrative Simulator for Trace gases (VISIT) model and International Panel on Climate Change (IPCC) 2006 guidelines³², respectively³³. Allocation was conducted in 10-year steps. The model is described in detail elsewhere¹².

Estimates of spatial land-based mitigation potential. To avoid duplication, different land-based options are implemented in different land category areas; specifically, afforestation is implemented in natural land that is not used for cropland and pasture in the future and has biophysical potential to be forest, while soil carbon sequestration is implemented in fallow cropland or unused natural land with the potential to be grassland (non-forest). Forest management is implemented in managed forests.

Afforestation and reforestation. Afforestation and reforestation implementation was based on a previously developed approach³³. Afforestation carbon sequestration was calculated as the annual forest growth rate (t C/ha/year) (dependent on the planting year) multiplied by the afforested land area (million ha). The annual forest growth rate was obtained from a timber yield function (Eq. 1) describing the change in forest carbon over time, originally developed by Sohngen *et al.*³⁴ and parameterised with the net primary production (NPP) estimate from VISIT²⁵. Parameters B and δ of the function were set to 30 and 1, respectively; parameter A was estimated for each forest type so that the forest growth rate when tree age = 20 was equal to the NPP calculated with VISIT. The maximum carbon stock amount was set to 140 Mg C/ha (~300 t dry matter/ha)³⁵. Forest age was calculated as years since the forest was planted. Thus,

$$V = \delta \times \exp[A - B/\text{Age}], \quad (1)$$

where V (Mg C/ha) is the amount of C stored in trees, Age is the tree age (years), and δ , A, and B are coefficients.

To calculate NPP for all land grid cells, an ideal afforestation experiment was performed using VISIT: all vegetation was removed from the land in 2010 and afforested simultaneously with a native forest type. The change in annual per-unit-area NPP in all grid cells was calculated from 2010 onward. In calculations of future carbon sequestration through afforestation, Representative Concentration Pathway 4.5³⁶ was used as the future climate condition. This climate condition may not be consistent with the mitigation scenario, but any inconsistency would not alter the overall results for this dataset. The risk of natural disturbance through fire is considered, while other natural disturbances (e.g., strong winds, pests, and landslides) and emissions associated with the operations required for afforestation (e.g., land preparation) are excluded.

Soil carbon sequestration. Two types of soil carbon sinks were estimated. The first type is the planting of cover crops during the part of the year when the land is unused for growth of the main crop, to increase soil carbon sequestration (based on the definition by Griscom *et al.*³⁷). This strategy was applied to unused cropland (crop fallow) and land abandoned and returned to grassland (non-forest), assuming a maximum of 50% of the total area.

The other sink type is soil management and a shift from tillage to no-till or reduced tillage methods on cropland, to increase soil carbon sequestration. As reducing tillage may reduce the productivity of crops and thus affect food supply, this option is not applied to normal cropland, but only to cropland with degraded soils. This strategy is based on the idea that improved soil management on land with degraded soil increases soil carbon sequestration while potentially maintaining the level of land productivity. To estimate the carbon sink, we assumed that 50% of the total carbon stock is in the top 30 cm of soil depth. This option increased the soil carbon stock by 0.4%³⁸. We used the soil carbon stock estimate from VISIT²⁵. The fraction of soil area that is degraded was based on the case study described in Wu *et al.*³¹.

Carbon sinks in managed forests. To make managed forest compatible with NGHGI and FAOSTAT, we set a wide definition of management using high-resolution (100 m) forest management data³⁹. For this data, management is defined as including naturally regenerating forests with signs of forest management activities (e.g., logging, clear cuts), planted forests (rotation > 15 years), plantation forests (rotation \leq 15 years) and short-rotation plantations for timber. This definition is broader than the current IAM definition (e.g., land use changes, timber production, and afforestation/reforestation) and closer to that used by NGHGI⁹. From the spatial land management data, we calculated the fraction of managed forest area at 0.5-degree resolution and calculated the fractions of managed and unmanaged forest by multiplying the fraction of managed forest area by the fraction of forest area. Globally, managed forest (1830 Mha) occupied 47% of total forest land area in the base year. The difference from the original dataset is due to our adjustment of forest area to align with FAO estimates as well as the exclusion of agroforestry and perennial crops from forests in this dataset. We considered carbon sinks in terms of naturally regenerating forest on managed land. The natural forest growth curve was parameterised using the natural forest growth rate shown in the IPCC 2006 guidelines³². We differentiated managed and unmanaged forests on a land area basis but did not assume specific forest management practices.

Land-based mitigation technology model (AFOLUB). AFOLUB is a bottom-up model that calculates GHG emissions and reductions in AFOLU sectors based on specific information about mitigation measures at the national and regional levels^{13–16}. The model estimates GHG emissions and reductions in AFOLU sectors based on detailed information about mitigation technologies given future activity levels such as crop and livestock production levels, land use changes and carbon price. Activity data at the ISO national level were prepared for the base year from FAOSTAT statistics and estimated for future decades according to a change rate derived from AIM-Hub regional estimates. The model selects emission reduction options (technologies) for farmers and landowners based on economic rationality (maximisation of profit in each period). The emission estimation methodology is based on the IPCC 2006 guidelines³². When calculating GHGs, we considered current livestock management systems, water management, and fertiliser input at the national or regional level, and assumed that these systems would remain in place throughout future decades. The model covers non-CO₂ greenhouse gases emissions from agriculture, CO₂ emissions from land conversion, CO₂ emissions and sinks of remaining land, and emissions from forest fires. To construct the land conversion matrix required as an input, which illustrates the conversion of land from one category to another, we assumed that the increase in a specific land category is converted proportionally from all land categories that show decreases based on their share of the total area decrease within a given region and time step. This method inherently represents only net land use conversion, not allowing gains and losses in the same year within a given region. For forest fires, the share of area affected by forest fire to total forest area was calculated from FRA 2010⁴⁰ and used to estimate the future area of forest fires.

GHG emission abatement technology data. Data for land-based GHG emission reduction options were based on previous studies^{13–16,41} and updated for this dataset through the addition of biochar and agroforestry as follows. For biochar, a cost per unit area of 510US\$/ha was set in this dataset, derived from the biochar production costs of 51US\$/t biochar from yard waste⁴² and 10 t biochar/ha/year that we estimated from carbon abatement of 0.42–0.78 t CO₂eq/t char (average: 0.60 t CO₂eq/t char) and carbon abatement per area of 7 t CO₂/ha/year. The time period of this measure is 1 year. An application curve was used to apply the total application area to a technological potential area for biochar⁸ by 2100 and calculate the annual change rate associated with introducing biochar, which was set as the maximum pace of introduction. For agroforestry, the cost of a plantation of fast-growing species was set at 100 US\$/ha¹³, and a lifetime of 10 years was assumed. An application curve was used to achieve a total application area equal to 10% of the current total of cropland and pasture area. The same maximum pace of introduction was used as for biochar.

Scenario assumptions. We ran three scenarios to quantify the effects of GHG emission reductions on the producer side of the agriculture and land sectors, as well as the effects of a consumer side measure (dietary change). These three scenarios include a no-climate-policy scenario, a climate policy scenario in which mitigation measures are implemented on the producer side of the agriculture and land sectors, and a climate policy scenario in which mitigation measures are implemented on both the producer and consumer sides.

The climate policy scenario assumes emissions constraints corresponding to the 2 °C and 1.5 °C climate goals. Mitigation measures were introduced in a cost-effective manner using an endogenously set carbon price. The following carbon budgets were applied with reference to cumulative CO₂ emission budgets from 2018 onwards: 600 and 1,100 Gt CO₂ for 1.5 °C and 2.0 °C, respectively. To capture country-specific changes in diet, we first calculated future caloric consumption per capita for each country and commodity and then converted it into the income elasticity by country and commodity. Given the income elasticity of food consumption, AIM-Hub calculates changes in supply, demand, international trade and prices of agricultural goods in response to changes in food consumption. As a demand-side mitigation measure, dietary changes and livestock product reductions were represented by assuming income elasticity for crops that was less sensitive to changes in income growth than that for livestock products in AIM-Hub and reducing the future consumption of livestock products. All scenarios assumed the socioeconomic conditions of “Middle of the road (SSP2)”⁴³ for future socioeconomic factors including population and GDP.

Data Records

The dataset⁴⁴ is available for download at Zenodo, where it is assigned a reference number and a DOI. The comma-separated (.csv) file contains two data sheets. The reference data sheet provides the numerical scenario results as time series data for each region and scenario. The columns are labelled Model, Scenario, Region, Variable, Unit, Year, and Values. The variable definitions data sheet provides definitions. The columns are labelled Variable and Definition.

Technical Validation

The whole model framework consists of three models (Fig. 1); AIM-Hub calibration and AIM-PLUM validation results were described in detail in earlier studies^{11,45}. AIM-Hub was calibrated at an aggregated regional level but not at the national level considered in this dataset. As AIM-Hub was used to provide future projections for aggregated regions, these data match historical data at the regional scale. For AIM-PLUM, base-year spatial land use data were reconciled and generated from multiple historical land use spatial datasets. AIM-PLUM was also validated at the half-degree level by comparing GHG emission and sink estimates from land use–land use change data with historical data from the period; the results showed good reproducibility¹². Here, we present validation data for AFOLUB, which was validated at the national level by comparing its estimates with other reported values for the base year.

Current emissions and comparability. Although greenhouse gas emissions from AFOLU sectors are not directly monitored, several institutes provide emission estimates based on international statistics and IPCC methodology.

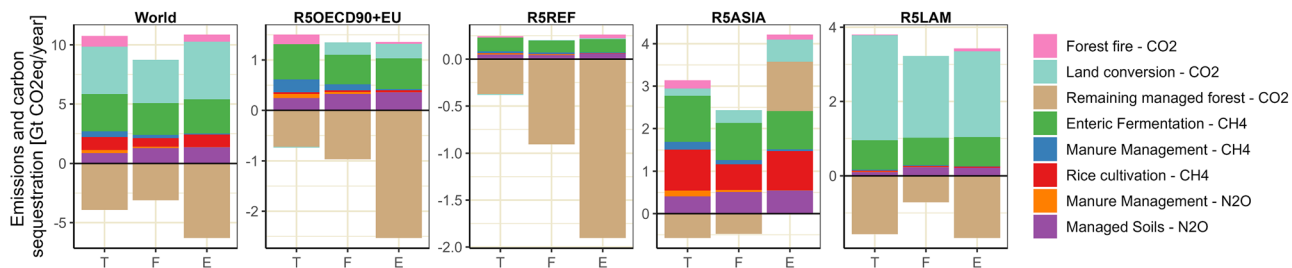


Fig. 2 Comparison of agriculture, forestry, and other land use (AFOLU) base-year greenhouse gas (GHG) emissions data with sub-emission categories in the present dataset (T) with data from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT, F) and Emissions Database for Global Atmospheric Research (EDGAR, E) at the global scale and for five continents. National Greenhouse Gas Inventory (NGHGI) global emissions are not shown because data are lacking for some countries. EDGAR does not provide land sector emissions data for individual countries. Wildfire emissions data are reported in T, E, and F.

To validate the results for this dataset, we compared AFOLU emissions estimates obtained using the present dataset with AFOLU emissions data from FAOSTAT⁴⁶, EDGAR⁴⁷, and NGHGI⁴⁶ at three levels: global, aggregated (five regions), and national (top 100 countries). Figure 2 and Table 2 compare GHG emissions from agriculture, land conversion, and remaining managed land at the global scale and for five aggregated regions. Figure 3 and Tables 3, 4 show the national-level results. At the global level, the discrepancies with EDGAR and FAO reported values were 440–750 Mt CO₂/year (8–15%) for agricultural emissions, –880 to 330 Mt CO₂/year (–18 to 9%) for direct emissions from land conversion, and –820 to 2,370 Mt CO₂/year (–27 to 38%) for indirect emissions from remaining managed land. These discrepancies in direct and indirect emissions are driven by differences in land area accounting (i.e., gross or net changes in land use) and carbon flux values, respectively.

In the five regions, the discrepancies were –130 to 640 Mt CO₂/year (–19 to 30%) for agricultural emissions, –13 to 630 Mt CO₂/year (–290 to 30%) for direct emissions from land conversion, and –650 to 1,530 Mt CO₂/year for indirect emissions from remaining managed land at the global level. The emissions from the land conversion category are from managed forests, including those associated with deforestation and excluding those from wildfire. The percentage difference for indirect emissions from remaining managed land was increased dramatically (>1,000%) by a small absolute value (–44 Mt CO₂/year) in the FAOSTAT data.

At the national scale, our results showed distributions similar to EDGAR and FAOSTAT estimates for agriculture across many countries, but with a larger discrepancy from the EDGAR, FAOSTAT, and NGHGI land use estimates (Figs. 3, 4). The discrepancy in agricultural emissions was –50 to 310 Mt CO₂/year. The emissions from agriculture in this dataset were within 30% of the FAOSTAT and EDGAR estimates for most countries, within 50% for about 20 countries, and in excess of 50% for the remaining countries. These large differences were mainly caused by low values (<10 Mt CO₂/year) reported for low-emission countries, particularly in Africa and Europe.

The discrepancies from the reported values ranged from –170 to 870 Mt CO₂/year for land conversion emissions and –520 to 380 Mt CO₂/year for managed forests. Emissions from converted land and managed forests in this dataset were within 50% of the FAOSTAT and NGHGI estimates for most countries, and exceeded 50% for the remaining countries, partly due to the low values (<10 Mt CO₂/year) reported for low-emission countries. As we used FAOSTAT forest area data, another reason for the differences in emissions from managed forests were mainly due to the per-area carbon fluxes used in this study rather than forest area. These per-area carbon fluxes for managed forests used here were based on the carbon sink due to forest growth estimated by VISIT, and carbon emissions were calculated by dividing the amount of wood harvested (obtained from FAOSTAT) by the managed forest area. For countries with large carbon sinks in the present dataset (e.g. Colombia and Peru), per-area carbon emissions were lower than FAOSTAT levels. The other reason for the observed discrepancy is that FAOSTAT accounts for the deforested area, whereas the present dataset captures only net land conversion without accounting for deforestation. In the present dataset, net land conversion was used to create the land use conversion matrix required as an input. This method provides only net land use conversion and cannot account for simultaneous gains and losses. See the Methods section for further details.

The managed forests carbon sink of 4 Gt CO₂/year estimated for the base year in this dataset is compatible with estimates (around 5 Gt CO₂/year) provided by DGVM and bookkeeping models⁹. Notably, the sink in managed land, which is considered in the NGHGI but not IAMs, is a major potential source of the discrepancy between the two land use emissions estimates. The indirect sink in managed forests estimated in this dataset was 4 Gt CO₂/year in 2005. This amount of indirect emissions is compatible with the difference between NGHGI and FAOSTAT data of 5.5 Gt CO₂/year⁹ and with State of Carbon Dioxide Removal data⁴⁸ and a recent report¹⁰. The carbon removal estimate in this dataset is also compatible with estimates obtained by bookkeeping models used for global carbon budgeting (4–4.5 Gt CO₂/year⁴⁹). This indirect emissions estimate reported by AIM (an IAM) would contribute to filling the gap in land-based emissions between the NGHGI and IAMs.

Future baseline emission trends. The baseline scenario lacks both climate policy and mitigation strategy but is an important benchmark for the development of national mitigation strategies. In the baseline scenario (Fig. 5a), total gross emissions from AFOLU sectors steadily increase from 10.7 Gt CO₂ in 2005 to 13.8 Gt CO₂eq

Options/Sources	Cumulative emissions 2010 onward [GtCO ₂ eq]	Annualized emissions [GtCO ₂ eq/year]	Options/Sources	Cumulative reduction [GtCO ₂ eq]	Reduction ratio [%]	Annualized reduction [GtCO ₂ eq/year]
Agriculture						
Enteric fermentation	395	4.4	Enteric fermentation	89	22	0.98
Manure management	80	0.9	Manure management	32	40	0.35
Rice cultivation	89	1.0	Rice cultivation	49	55	0.54
Managed soil	103	1.1	Managed soil	55	54	0.6
		0.0	Dietary change	121	na	1.3
a) Total non-CO ₂ emissions in agriculture	666	7.4	Total non-CO ₂ reduction in agriculture	377	57	4.2
Land						
Emissions from land conversion	295	3.3	Afforestation and reforestation	139	40	1.5
Emissions from remaining managed forest	−279	−3.1	Agroforestry	1	0.3	0.0
Indirect emissions from fire	49	0.5	Biochar	37	11	0.4
			Soil Carbon sequestration	26	7	0.3
			Enhanced natural regeneration	2	1	0.0
			Forest management (e.g. reduced irrigal logging)	1	0	0.01
			Forest protection excl. avoided deforestation (e.g. prevention of fire)	4	1	0.04
b) Gross CO ₂ emissions in Land	344	3.8	Total CO ₂ reduction in LULUCF	209	61	2.3
c) Gross CO ₂ sink in Land	−279	−3				
Net CO ₂ emissions in Land = b) + c)	65	1				
Total GHG emissions in AFOLU = a) + b)	1010	11	Total GHG reduction in AFOLU	586	58	6.5

Table 1. Global land-based business-as-usual emissions and reductions under the mitigation scenario by source and option.

[MtCO ₂ /year]	Emissions - Agriculture			Gross emissions from land conversion			Gross removals in managed forest		
	This study	EDGAR	FAO	This study	EDGAR	FAO	This study	EDGAR	FAO
World	5834	5393	5079	4002	4878	3668	−3932	−6304	−3108
Difference [%]		8	15		−18	9		38	−27
OECD and EU	1315	1035	1103	−16	285	246	−720	−2533	−968
Difference [%]		27	19		−106	−107		72	26
Reforming economies	230	213	198	−9	10	5	−373	−1905	−904
Difference [%]		8	16		−193	−292		80	59
Asia	2776	2412	2132	166	522	303	−577	1165	−480
Difference [%]		15	30		−68	−45		−150	−20
Middle East and Africa	563	696	624	1027	1749	912	−691	−1352	−44
Difference [%]		−19	−10		−41	13		49	−1481
Latin America	951	1037	1022	2835	2312	2203	−1571	−1678	−712
Difference [%]		−8	−7		23	29		6	−121

Table 2. Emissions comparison at the global scale and in five aggregated regions for 2005. Percentage differences are expressed relative to the previously reported level.

in 2100 (1.3 times the base-year level). Emissions from agriculture are 5.8 Gt CO₂ (54%) of total AFOLU emissions in 2005, increasing to 11 Gt CO₂ in 2100. The largest share of agricultural emissions is from enteric fermentation of livestock animals (67% of total agricultural emissions). The remaining emissions originate from land use changes (46% of total AFOLU emissions in 2005), with this share decreasing throughout the century due to saturation of such changes. This reduction trend is apparent in many countries with high land-based emissions, such as Brazil and India (Fig. 7).

More than 80% of total emissions come from Latin America (35%), Asia (30%) and Africa and the Middle East (20%) (Fig. 6). Livestock is a major source in Africa and the Middle East as well as Latin America, while rice cultivation is a major source in Asia. The amount and regional contributions to the carbon sink are stable throughout this century, varying from 3.9 Gt CO₂/year in 2005 to 2.6 Gt CO₂/year in 2100.

GHG emissions reduction potentials. Under the assessed climate policy, emissions begin decreasing before 2030 and do not achieve AFOLU net-zero status in which CO₂, CH₄ and N₂O emissions and sink in the AFOLU sector are equal by the end of this century (Fig. 5a). Notably, the AFOLU net-zero status used in this

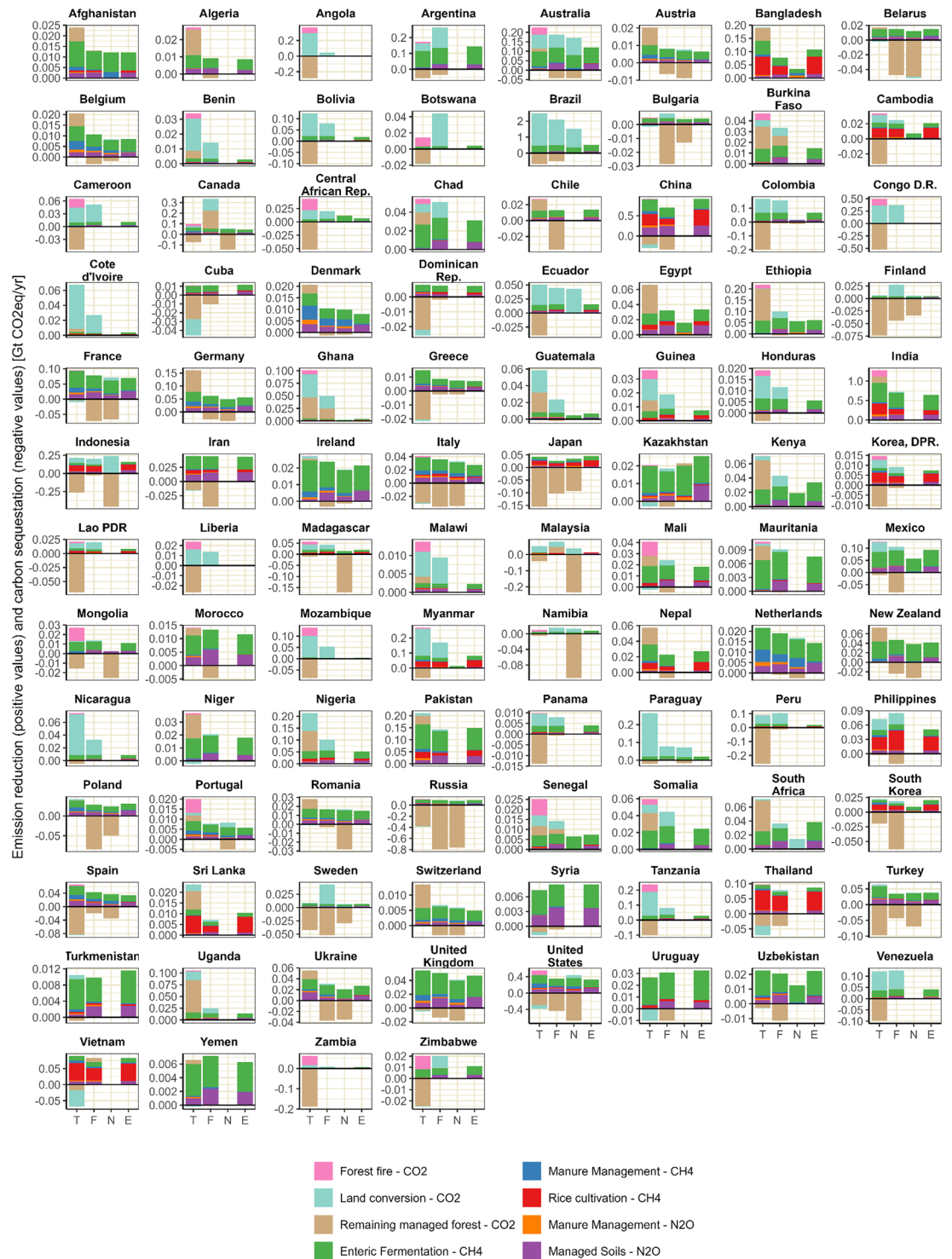


Fig. 3 Comparison of AFOLU base-year GHG emissions with sub-emission categories in the present dataset (T) with data from FAOSTAT (F), NGHGI (N), and EDGAR (E) for the top 100 countries by emissions. NGHGI data are lacking for some countries. EDGAR land sector emissions data are lacking for some countries. Wildfire emissions data are reported in T, E, and F, but not in NGHGI.

dataset and the concept of net zero discussed in the IPCC Sixth Assessment Report (AR6) differ in the gas types included, as the AFOLU net zero includes both CO₂ and non-CO₂ emissions from AFOLU, whereas the IPCC AR6 net zero includes only CO₂ emissions.

In terms of the regional distribution, a total reduction potential of 3 Gt CO₂eq (43%) is projected in Asia in 2050, followed by 1.3 Gt CO₂eq (18%) in the Middle East and Africa, and 1.1 Gt CO₂eq in Latin American countries. Toward achieving net zero, 20% of Asia's emission reduction is associated with rice cultivation (570

[MtCO ₂ /year]	Emissions - Agriculture				Emissions from land conversion			Emissions in managed forest		
	This study	EDGAR	FAO	NGHGI	This study	FAO	NGHGI	This study	FAO	NGHGI
Afghanistan	17	12	13	12	na	na	na	7	0	na
Algeria	11	9	9	na	0	na	na	15	-2	na
Angola	7	8	7	na	289	35	na	-282	na	na
Argentina	115	143	135	na	49	128	na	-56	-36	na
Australia	100	119	119	79	74	68	92	16	-42	-42
Austria	10	7	8	7	na	0	1	10	-6	-9
Bangladesh	141	108	78	34	2	1	na	48	na	na
Belarus	15	15	15	12	-2	na	-2	2	-47	-50
Belgium	15	8	11	8	0	0	0	6	-3	-2
Benin	4	3	3	na	22	11	na	5	-0.1	na
Bolivia	22	18	22	na	102	57	na	-101	-0.4	na
Botswana	3	4	4	na	0	41	na	-18	na	na
Brazil	460	512	496	354	2033	1605	1164	-670	-504	na
Bulgaria	4	4	5	4	-1	4	0	0	-28	-13
Burkina Faso	14	15	17	na	6	7	na	20	9	na
Cambodia	22	21	20	7	10	5	na	-33	-1	na
Cameroon	10	11	11	na	35	41	na	-54	-1	na
Canada	64	46	53	52	12	111	5	-74	171	-144
Central African Republic	5	6	6	12	17	14	na	-52	na	na
Chad	27	31	34	na	9	17	na	13	na	na
Chile	12	14	13	na	0	na	na	14	-37	na
China	901	914	701	na	-95	na	na	-202	-334	na
Colombia	67	67	67	14	100	89	na	-199	-9	-15
Congo, Dem. Rep.	5	4	3	na	358	367	na	-524	-0.1	na
Cote d'Ivoire	4	4	3	na	59	24	na	5	na	na
Cuba	11	12	11	na	-18	na	na	-27	-10	na
Denmark	17	8	11	10	0	na	0	4	-1	-1
Dominican Republic	8	7	8	na	-4	na	na	-22	-2	na
Ecuador	14	16	16	na	36	29	43	-40	-1	na
Egypt, Arab Rep.	28	34	32	16	-1	na	na	38	-0.2	na
Ethiopia	59	62	71	57	1	30	na	142	-6	na
Finland	5	5	5	4	2	23	2	-73	-45	-34
France	93	70	79	62	-6	na	9	-4	-72	-67
Germany	78	56	62	49	0	na	2	82	-28	-35
Ghana	5	4	4	3	46	25	na	41	21	na
Greece	15	7	9	7	-1	na	na	-20	-3	-2
Guatemala	8	7	8	5	27	16	na	24	-2	na
Guinea	7	7	9	na	15	10	na	8	0	na
Honduras	7	6	6	na	10	5	na	-4	na	na
India	955	647	699	na	-23	23	na	168	-25	na
Indonesia	143	156	126	na	74	75	239	-262	-27	-457
Iran, Islamic Rep.	45	44	44	na	-1	na	na	-15	-44	na
Ireland	25	22	24	19	2	na	0	1	-3	-1
Italy	39	27	36	31	-2	na	2	-30	-36	-35
Japan	43	45	26	34	0	1	2	-155	-103	-93
Kazakhstan	20	26	17	20	-2	2	na	-1	-3	1
Kenya	24	34	28	19	6	15	na	40	na	na
Korea, Dem. People Rep.	9	7	6	na	4	3	na	-11	-1	na
Korea, Rep.	20	21	15	9	2	4	na	-20	-64	na
Lao PDR	9	8	8	na	9	13	na	-69	0	na

Table 3. Emissions comparison for the top 100 countries by agriculture, forestry, other land use (AFOLU) emissions for 2005. Percentage differences are expressed relative to the previously reported level.

[MtCO ₂ /year]	Emissions - Agriculture				Emissions from land conversion			Emissions in managed forest		
	This study	EDGAR	FAO	NGHGI	This study	FAO	NGHGI	This study	FAO	NGHGI
Liberia	0.4	0.2	0.3	na	16	14	na	-27	0	na
Madagascar	19	20	22	14	25	22	na	-12	-5	-172
Malawi	3	2	2	na	7	7	na	2	na	na
Malaysia	13	14	11	2	39	33	36	-42	36	-234
Mali	19	18	19	na	-2	5	na	9	-5	na
Mauritania	7	8	9	na	1	1	na	3	0	na
Mexico	85	94	91	57	40	15	na	-11	-82	na
Mongolia	12	11	13	3	1	1	na	-16	na	-26
Morocco	11	12	13	na	na	0.1	na	3	-5	na
Mozambique	5	5	4	na	95	49	na	-86	0	na
Myanmar	82	81	68	16	181	104	na	-66	na	na
Namibia	5	7	6	4	na	11	9	-5	na	-113
Nepal	36	27	23	na	-1	na	na	22	-7	na
Netherlands	22	14	19	16	0	na	1	0	-1	-2
New Zealand	43	42	47	38	na	0	0	30	-24	-33
Nicaragua	9	9	9	na	64	24	na	-5	0	na
Niger	17	18	19	na	-2	1	na	18	0	na
Nigeria	53	52	55	na	76	46	na	85	na	na
Pakistan	165	149	137	na	11	7	na	35	na	na
Panama	4	4	4	na	6	4	na	-14	-1	na
Paraguay	20	20	22	18	245	57	54	-20	0	-16
Peru	29	20	26	na	62	78	na	-260	-13	na
Philippines	50	51	61	na	23	23	na	-3	-21	na
Poland	39	31	28	24	3	na	0	1	-85	-50
Portugal	9	6	7	6	1	0	2	3	0	-5
Romania	17	15	17	16	-1	na	1	11	-3	-28
Russia	97	89	88	73	-5	na	7	-382	-797	-761
Senegal	7	7	8	7	5	4	na	5	2	na
Somalia	22	25	27	na	10	17	na	21	na	na
South Africa	25	39	30	na	2	7	14	44	-1	na
Spain	62	34	43	37	-2	na	1	-82	-20	-35
Sri Lanka	12	10	6	na	3	1	na	9	na	na
Sweden	8	7	7	5	1	37	1	-43	-52	-29
Switzerland	6	5	6	6	0	1	0	8	-3	-3
Syrian Arab Republic	7	9	9	na	-1	na	na	-1	-1	na
Tanzania	31	30	35	na	158	47	na	-101	na	na
Thailand	96	88	73	na	-31	6	na	-40	-40	na
Turkey	58	38	35	37	5	na	1	-97	-43	-70
Turkmenistan	10	12	10	na	1	na	na	-1	0	na
Uganda	16	14	14	na	19	11	na	69	-2	na
Ukraine	39	27	28	21	0	2	0	16	-37	-35
United Kingdom	55	47	51	40	-2	na	1	-4	-14	-19
United States	443	335	358	362	-96	na	78	-293	-442	-680
Uruguay	26	33	31	na	-10	na	na	0	-10	na
Uzbekistan	23	22	20	13	0	na	na	-3	-12	na
Venezuela, RB	37	41	41	na	85	84	na	-99	2	na
Vietnam	89	84	70	na	-51	na	na	-17	13	na
Yemen, Rep.	6	6	7	na	0	na	na	1	na	na
Zambia	4	8	5	na	13	4	na	-188	na	na
Zimbabwe	8	11	9	na	0	11	na	-25	0	na

Table 4. Emissions comparison for the top 100 countries by agriculture, forestry, other land use (AFOLU) emissions for 2005. Percentage differences are expressed relative to the previously reported level (Continued).

Mt CO₂eq/year in 2050), while the OECD and EU countries obtain 22% of its emission reduction through afforestation (0.25 Gt CO₂/year in 2050).

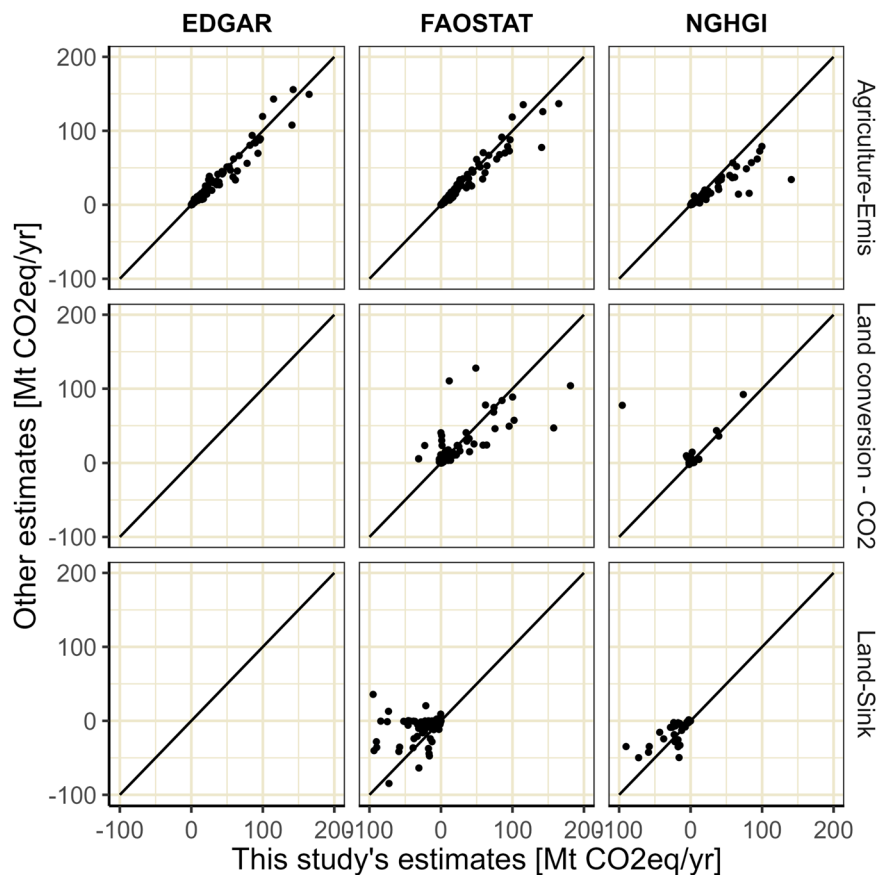


Fig. 4 Comparison of AFOLU base-year GHG and sink data from the present dataset with data from EDGAR, FAOSTAT, and NGHGI (N) across all countries. NGHGI data are lacking for some countries. EDGAR land sector emissions data are lacking for some countries. Wildfire emissions data are excluded from this comparison.

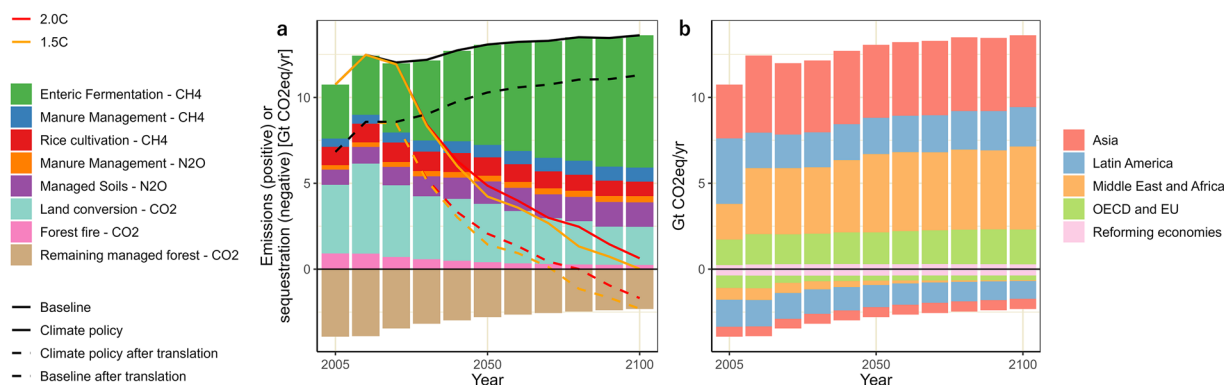


Fig. 5 Global land-based baseline emissions pathways for AFOLU sectors: (a) business-as-usual emission pathways with breakdowns by emissions source and sink and (b) region. Red and orange lines indicate net emission pathways under climate policy scenarios aiming at the 2.0°C and 1.5°C global targets with and without considering indirect emissions from managed land, respectively.

Table 1 compares global land-based business-as-usual emissions and reductions under the mitigation scenario by source and option. For the land use sector, carbon reductions of 2.7 Gt CO₂ in 2050 and 4.3 Gt CO₂ in 2100 were obtained (2.3 Gt CO₂/year average). 60% of CO₂ emissions from the land use, land use change, and forestry (LULUCF) sector can be offset by land-based carbon removal technologies throughout this century. The largest reduction potential option is afforestation/reforestation (1.5 Gt CO₂/year average). In contrast, biochar, soil carbon sequestration and agroforestry show limited potential due to low efficacy of carbon sequestration.

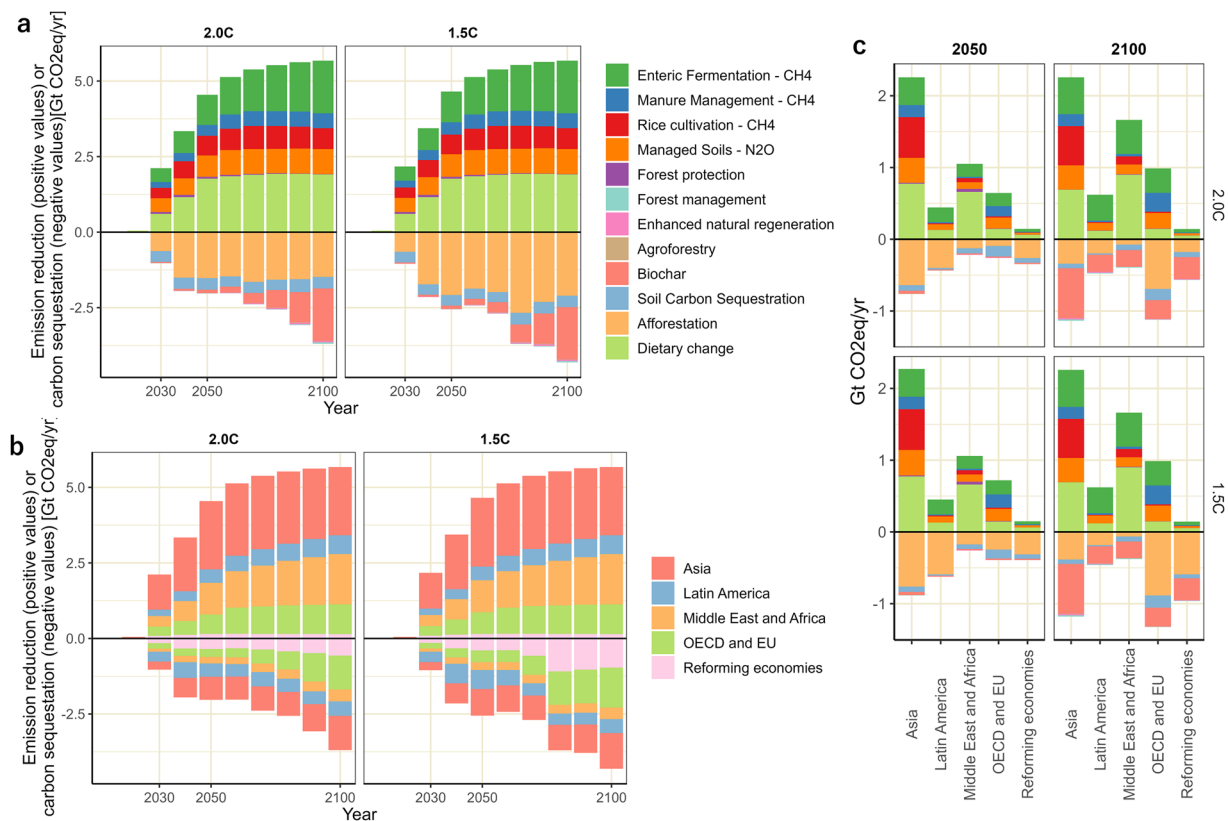


Fig. 6 Global land-based mitigation pathways for AFOLU sectors with breakdown by (a,c) emissions source and sink and (b,c) region for climate policy scenarios aiming at the 2.0°C and 1.5°C global target scenarios.

Cumulative emissions of non-CO₂ greenhouse gases from the agricultural sector decrease by 57% over this century compared to the no-climate-policy projection. The total annual non-CO₂ emissions reduction is 4.5 Gt CO₂/year in 2050 and 5.7 Gt CO₂/year in 2100 (4.2 Gt CO₂/year average). The largest potential source for reduction is dietary change (1.3 Gt CO₂ average), followed by enteric fermentation by livestock (1.0 Gt CO₂/year average). Emissions from livestock enteric fermentation decrease by 22% compared to the no-climate-policy scenario. This low reduction rate is mainly due to the relatively high costs and low reduction efficacy (around 40%) of mitigation options for livestock enteric fermentation (e.g., improved feed management and replacement of roughage with concentrated feed), leading to low cost-efficiency and low implementation, especially in developing regions with high livestock emissions. CH₄ from rice cultivation and N₂O from managed soil are projected to decrease by half due to being relatively cost-efficient, but these reduction effects are limited at the global level because the share of total agricultural emissions associated with these sources is less than half.

Future emission pathways of the top 100 countries by emissions. Figures 7, 8 show land-based baseline emissions and mitigation pathways for the top 100 countries by emissions, as calculated for this dataset. Consistent with the global trend, agricultural emissions increase by 2100 while emissions from the LULUCF sector decrease and the sink of managed land is relatively stable. Baseline emissions in many countries are not currently on track to meet long-term climate targets by mid-century. Notable examples where emissions are expected to increase over the next few decades include Argentina, Australia, Canada, Ethiopia, India, Pakistan, Mexico and Tanzania. In China, Brazil and the US, emissions from AFOLU have been relatively stable or decreasing, but are not on track to meet 2050 targets. Increased agricultural emissions are driven by population and economic growth, which increase the production of food, particularly livestock products. In response to food demand, agricultural land expands, but this expansion is saturated by 2030 or 2050. This expansion leads to a slight decrease in forest land and thus the sink in managed forest land. LULUCF emissions from land conversion decrease with the saturation of farmland expansion.

The mitigation option portfolio reflects agricultural and land use conditions in each country. For example, in countries with high livestock production and agricultural emissions, the potential of agricultural mitigation is also high. In countries with high livestock production such as Argentina, Australia, Brazil and India, high mitigation potentials are associated with livestock-derived gases, while Asian countries showed high mitigation potential related to methane from rice cultivation. In addition, countries with relatively large areas of agricultural land showed high potential for land-based carbon dioxide removal (CDR).

Future emission reductions and compatibility. We compared our results with land use emission estimates from IAMs in the IPCC AR6 database⁵⁰ (Fig. 9). For comparison with IAM estimates, indirect emissions were

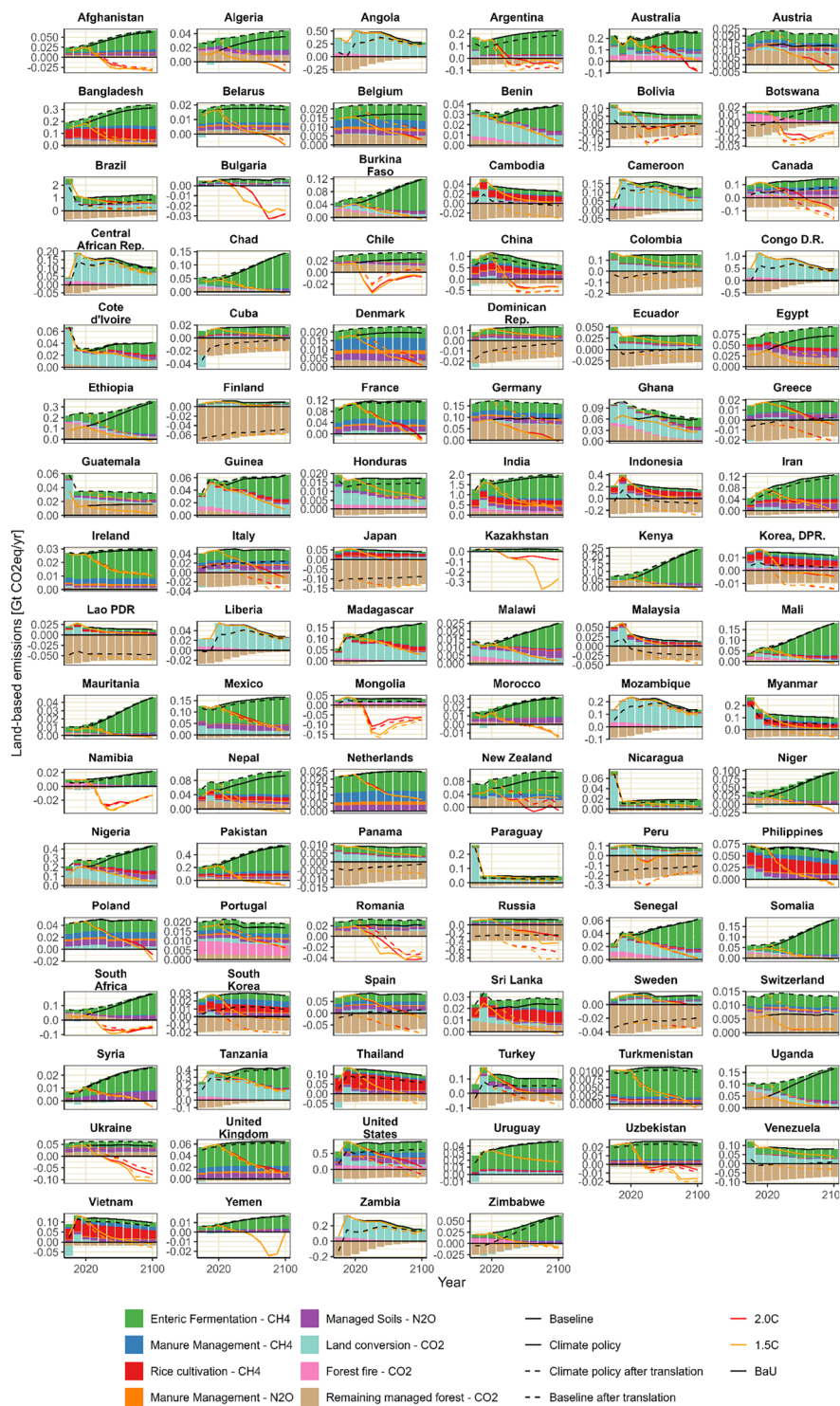


Fig. 7 Land-based emissions pathways for AFOLU sectors in selected top-emitting countries: business-as-usual emission pathways with breakdowns of emission source categories (bar charts). Red and orange lines indicate emissions pathways under climate policy scenarios aiming at the 2.0 °C and 1.5 °C global targets with (dashed line) and without (solid line) considering indirect emissions from managed land.

excluded, as IAMs do not report indirect emissions. We found that our estimates of land-based emissions aligned with IAM estimates. The total land-based net emissions and carbon sink associated with afforestation calculated in the present dataset matched IAM estimates (Fig. 9a,c). The carbon sink from land use in this dataset is relatively large due to the inclusion of more land-based CDR methods (i.e., soil carbon sequestration, biochar, agroforestry, forest management) compared to earlier IAMs, which reported only afforestation as CDR for the AFOLU sector. This discrepancy explains the net negative emissions obtained at the end of this century in the present dataset.

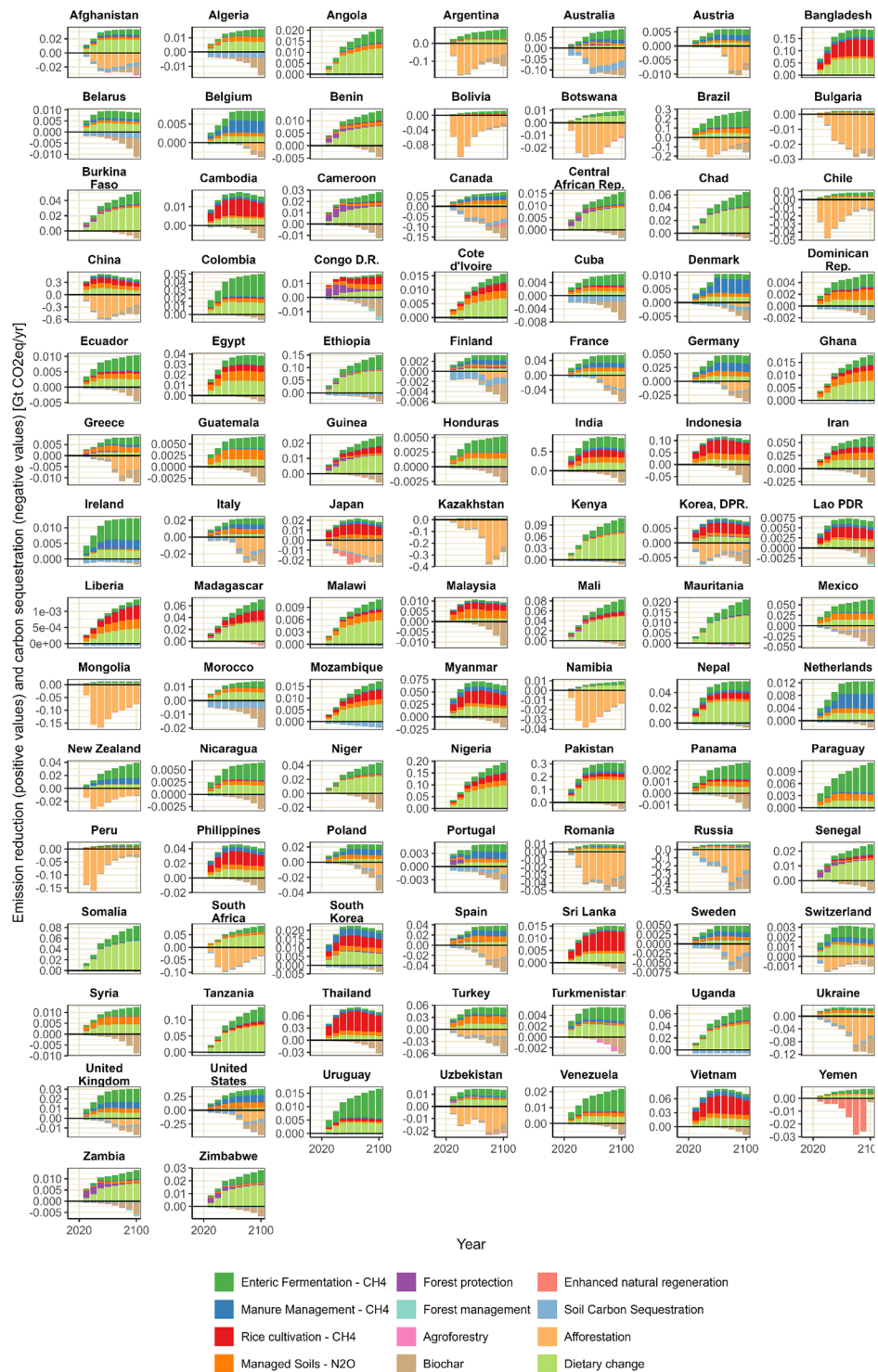


Fig. 8 Mitigation potential in selected top emitting countries with breakdown by mitigation source or option for the 1.5 °C scenario.

Usage Notes

The data are available at the following data repository: <https://doi.org/10.5281/zenodo.13907052>.

We provide some notes and limitations related to this dataset that could constrain its application and use as a reference for national emissions strategies, as follows.

- First, we used a one-way approach for AIM-Hub runs, providing regional agricultural production, land use area and carbon price data to AFOLUB and AIM-PLUM for estimation of emissions reductions. In this approach, the reduction potentials of AFOLU sectors in AIM-Hub, AFOLUB and AIM-PLUM are not

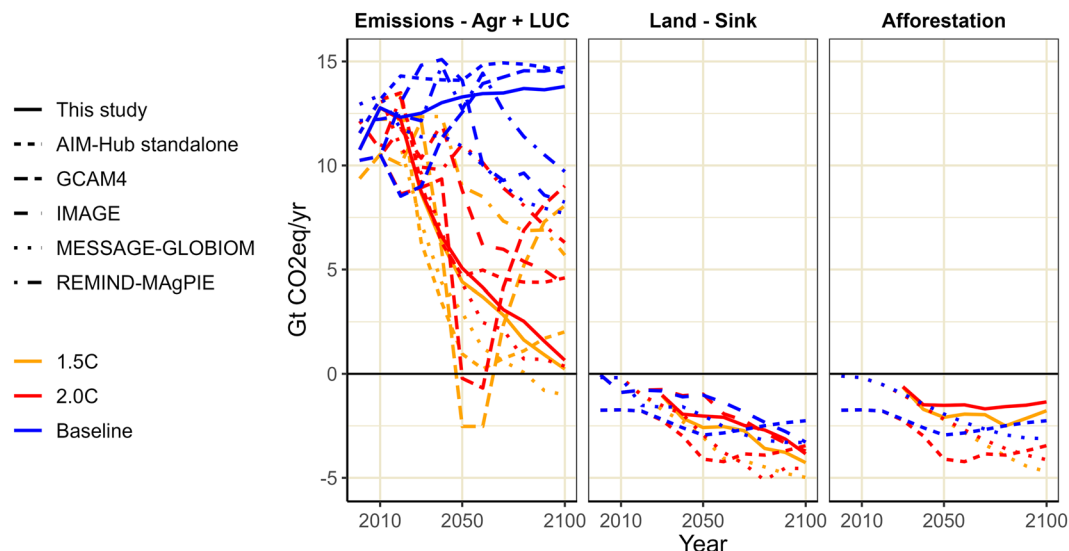


Fig. 9 Comparison of global AFOLU greenhouse gas emission pathways in the present dataset with International Panel on Climate Change 6th Assessment Report global integrated assessment model scenarios. The right column represents carbon removal through afforestation alone, and the middle column represents negative emissions through land-based options including afforestation and other forest management strategies. The available options differ among models.

identical. Feedback between mitigation potential and cost estimates from AFOLUB and AIM-PLUM provided to AIM-Hub and re-running of AIM-Hub for the whole economy using AFOLU mitigation information estimated with the two models would lead to more consistent results across models.

- Second, we assume hypothetical conditions of a uniform global carbon price, to achieve long-term climate goals in a cost-effective manner. In reality, other means of achieving long-term climate goals are possible, such as end-point regulation and behavioural changes, in addition to carbon pricing¹. The carbon price and implementation of other measures may vary. Although we present only one case of cost-effective pathways, it would be useful for national policymaking and related activities to set national targets and develop specific measures that consider all assumed activities, technology types, and estimation methods.
- Third, a feedback loop among models was not used, and the models are not fully coupled in the current framework. This limitation could represent a challenge in generating a similar dataset. Notably, substantial feedback from mitigation potentials estimated by AFOLUB into AIM-Hub could be sufficient to alter the results. However, as the current estimates show a good match with the estimates of the standalone AIM-Hub model at the global and continental levels (Fig. 9), we speculate that feedback would not greatly affect the results.
- Fourth, climate impacts were not considered in this dataset, which is intended to support the development of national climate mitigation strategies. Under scenarios aligned with long-term global climate goals, climate impacts are expected to be relatively small. However, accounting for climate impacts could alter both emissions and mitigation potential. For example, economic losses from climate change could reduce baseline emissions, crop yield losses could lead to cropland expansion and increased land use emissions, and accelerated forest growth could enhance carbon sinks. Incorporating climate impacts in future datasets would enable the development of more realistic national climate mitigation and adaptation strategies.

Code availability

We have compiled our calculations as open-source R packages that are available at zenodo⁵¹: <https://doi.org/10.5281/zenodo.15361799>.

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Author contributions

T.H. and S.F. designed the research; T.H. ran the economic, land use and technology selection models. K.T. ran the food demand module; A.I. prepared data of the dynamic global vegetation model. T.H. analysed the model results, created figures and drafted the paper; and all authors provided feedback and contributed to the writing of the entire manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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