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# Historical and Future Development of Greenhouse Gas Emission and Removal from the Land Use Sector from the View of Countries

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**Abstract**: Evaluating the progress towards global and national net-zero emissions goals requires a thorough assessment of historical emission levels and future targets. However, little attention has been paid to the actual reporting by the parties themselves. In this analysis, we examine parties reporting historical emissions and removals for Agriculture, Forestry, and Other Land Use (AFOLU) sector, as well as their commitments outlined in the Nationally Determined Contributions (NDCs) and the Long-term Low Emission Development Strategies (LT-LEDS). Our analysis reveals a worldwide decrease in historical net AFOLU emissions, spanning from 1990 to 2020. This decline primarily relates to increased removals in the LULUCF sector in non-Annex I countries. In 1990, global AFOLU emissions were recorded at 4,400 $MtCO_2eq$, but by 2020, they had been reduced to approximately 2,200 $MtCO_2eq$. Looking ahead, countries have committed to further reduce global net AFOLU emissions by 600–1,700 $MtCO_2eq$ by 2030 compared to 2020 levels. Moreover, fulfilment of the LT-LEDS commitment can provide an additional reduction of 2,300–3,400 $MtCO_2eq$. By integrating these datasets, the study provides insights into the progress towards achieving climate goals, highlighting the importance of land-based mitigation strategies. The findings reveal disparities between Annex I countries and Non-Annex I countries, particularly in the ambition of the commitments and objectives. As countries begin to submit their biennial transparency reports to the United Nations Framework Convention on Climate Change (UNFCCC), our recommendation is for countries to enhance transparency in reporting and communicating their progress of implementation.

**Keywords**: agriculture, forestry, and other land use (AFOLU), long-term low emission development strategies (LT-LEDS), nationally determined contribution (NDC), greenhouse gas emission inventories, mitigation options

## 1. Introduction

Developing and implementing mitigation and adaptation measures to meet the commitments established in the Paris Agreement is one of the biggest challenges facing governments today. As part of it, the parties should aim to keep the average global temperature rise at "well below 2°C above pre-industrial levels and pursue efforts to limit the increase to 1.5°C" (UNFCCC, 2015) (Article 2.1(a)). Achieving this goal will require both reducing greenhouse gas emissions (GHGs) and increasing carbon sinks.

To facilitate the progress towards the global climate goal, parties to the Paris Agreement are invited to document and submit their pledged contributions in the form of Nationally Determined Contributions (NDCs) (Article 4.2) and the Long-term Low Emission Development Strategies (LT-LEDS) (Article 4.9). Countries are obligated to regularly submit NDCs outlining their short-term ambitions, with the next round of commitments extending to 2035. Conversely, LT-LEDS are optional and do not have specific reporting obligations. Under Decision 1/CP.21, paragraph 35, it is noted that LT-LEDS should be considered up to the mid-century and are encouraged to be submitted to the UNFCCC Secretariat by 2020. The interrelation between NDCs and LT-LEDS is evident, as the comprehensive long-term planning outlined in LT-LEDS can provide valuable insights for the development of NDCs, including the identification of potential obstacles to near-term climate action. The implementation of LT-LEDS could potentially serve as a vital solution for balancing the long-term objectives of achieving net zero with the more immediate priorities of NDCs and policy cycles (Waisman et al., 2019). By April 2024, 195 parties had submitted their NDCs, and 71 parties had provided their LT-LEDS.

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Land-based mitigation (Griscom et al., 2017) is a key strategy to achieve the Paris Agreement's goal of balancing anthropogenic emissions and removals (Fuglestvedt et al., 2018). To mitigate global climate change, it is crucial to prioritize the avoidance of forest conversion, restoration of degraded and deforested landscapes, and the enhancement of forest management practices. These and other land-based mitigation activities within the Agriculture, Forestry, and Other Land Use (AFOLU) sector have the potential to achieve one-third of the cost-effective mitigation needed to limit warming to 1.5°C (Roe et al., 2021). Aligned with emission pathways for 2°C or 1.5°C targets, the AFOLU sector is expected to reduce emissions by 8,300–9,100 million metric tons of $CO_2$ equivalent ($MtCO_2eq$) in 2050 (Roe et al., 2019). Individual countries have also put forward climate change mitigation strategies that strongly feature land-based abatement options. In their NDCs, over 100 countries, accounting for at least 90% of global forest cover, have explicitly incorporated forest abatement activities (Fyson and Jeffery, 2019). Furthermore, land-sector mitigation is expected to contribute 10-30% of the global emissions reductions planned for 2030 (Forsell et al., 2016; Grassi et al., 2017). It has also been determined that most countries anticipate improving or sustaining the removal capacity of the Land Use, Land Use Change and Forestry (LULUCF) sector to meet the LT-LEDS targets (Buck et al., 2023). Additionally, strategies that receive the most support for enhancing forest and soil carbon sinks are essential (Smith et al., 2022). Overall, these studies highlight the central role of the AFOLU sector in ambitious climate change mitigation efforts.

To evaluate the progress being made in the implementation of measures and predict the projected emissions based on countries' existing commitments, it is crucial to analyze the historical data recorded in each nation's greenhouse gas inventories (NGHGI) (Grassi et al., 2022). Similarly, to track the progress in implementing mitigation measures, it is vital to gather and consolidate the latest information as put forward by the countries in their NDCs and LT-LEDS. With this goal in mind, this study documents the historical AFOLU greenhouse gas (GHG) emissions by countries, as documented in their NGHGI, and the targets as set out for the AFOLU sector in the countries' NDCs and LT-LEDS. In contrast to previous research, we have taken a systematic and comprehensive approach to jointly evaluate these three crucial datasets, recognizing their strong interdependence. Furthermore, our analysis encompasses a wider range of sectors compared to previous assessments, which have predominantly concentrated on either the Agriculture or the LULUCF sector. By combining these three essential sources of data, we can assess both historical progress and the intended mitigation efforts for the entire AFOLU sector.

## 2. Methods

In this section, we describe how the three key datasets (GHGI, NDC, and LT-LEDS) used in this paper were collected and the underlying assumptions taken when carrying out this task. For each of these datasets, we collect emissions and removals for the Agriculture and LULUCF sectors, which jointly correspond to the AFOLU category. This directly follows the IPCC 2006 guidelines (IPCC, 2006) as to how economy-wide emissions can be reported in terms of subcategories.

### 2.1 GHGI data

All countries that are part of the United Nations Framework Convention on Climate Change (UNFCCC), are required, according to Article 4, to develop, periodically update, publish, and make available national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases. This should be carried out considering their common but differentiated responsibilities and their specific national and regional development priorities, objectives, and circumstances. Furthermore, all countries should be using comparable methodologies (UNFCCC, 2014).

Inventories must adhere to IPCC principles of transparency, accuracy, completeness, consistency, and comparability (TACCC). GHG inventories must be developed following IPCC guidelines, there are three different methodological guidelines and directives from the IPCC as to how countries should develop their inventories: the Revised 1996 Guidelines for National GHG Inventories, the Good Practice Guidance for Land-Use, Land-Use Change, and Forestry (2003), and the Guidelines for National GHG Inventories (2006) (and its 2013 supplements and 2019 refinement). IPCC 2006 guidelines include four sectors Energy Industrial Processes and Product Use (IPPU), Agriculture, Forestry and Other Land Uses (AFOLU) and Waste. The AFOLU category includes emissions

from Agriculture and LULUCF activities (as a sum of the emissions in an aggregated category). The previous methodologies (IPCC, 1996; IPCC, 2003) have a different sector aggregation having five sectors Energy, IPPU, Agriculture, LULUCF and Waste. Table 1 displays the correspondence between the subcategories of the different IPCC methodologies and the reporting categories used in this database. Based on the IPCC principles, if countries follow the IPCC guidelines and the GHG emissions are reported in $CO_2$eq, the emissions estimates are comparable between countries, if they are aggregated according to the correspondence categories.

Table 1. Correspondence table between IPCC reporting categories and LULUCF and Agriculture. Source: Own elaboration.

| | LULUCF | Agriculture |
|---|---|---|
| 1996 Guidelines | · Changes in woody biomass stocks<br>· Forest and grassland conversion<br>· Abandonment of managed lands<br>· Changes in Soil Carbon<br>· Harvest Wood Products | · Agricultural Soils<br>· Prescribed Burning of Savannas<br>· Burning of Agricultural Residues<br>· Enteric Fermentation<br>· Manure Management<br>· Rice Cultivation<br>· Other |
| LULUCF GPG 2003 | · Forest land<br>· Grassland<br>· Cropland<br>· Settlements<br>· Wetlands<br>· Other Land<br>· Harvest Wood Products | Not Applicable |
| AFOLU 2006 IPCC Guidelines | · 3B Land<br>· 3D Other Harvest Wood Products | · 3A Agriculture<br>· 3C Aggregate Sources and Non-$CO_2$ Emissions Sources on Land |
| Aggregated country reporting | · AFOLU absorptions | · AFOLU emissions |

Under the Convention framework countries are divided into Annex I and Non-Annex I with differentiated responsibilities, including commitments related to the submission of GHG inventories. Annex I countries had stricter commitments under the UNFCCC and must submit their GHG emissions inventory every year. Furthermore, only Annex I countries must use the IPCC 2006 guidelines, while non-Annex I countries should utilize them. Under the Enhanced Transparency Framework and the Modalities, Procedures, and Guidelines, all Parties must use the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and enhance them to use the most recent guidelines, such as the 2019 Refinement to the 2006 IPCC Guidelines for developing their GHG inventories.

The GHG historical dataset as provided by the countries includes the AFOLU category or their correspondent Agriculture and LULUCF depending on the reporting methodologies selected by the country. If countries use the IPCC 2006, the data collected from subcategories 3B Land and 3D Other Harvest Wood Products were summed and reported as the LULUCF category, while subcategories 3A Livestock and 3C Aggregated and non-CO2 land-based emission sources are consolidated and reported as Agriculture.

The data sets include all UNFCCC countries except the Holy See and thus encompass a total of 195 countries GHG inventory estimates and 1 regional GHG inventory (European Union). The GHGI dataset was always collected from the most recent GHG inventories submitted to the UNFCCC. These inventories are part of the National Communications, Biennial Update Report, Biennial Report (for Annex I Countries), or submitted as a single document. GHG inventories from the NDC, the Biennial Transparency Reports, or the REDD+ Annex were not considered to maintain consistency between the data collected. The exact source used for collecting the data for each country is presented in Supplementary Table 2.

For Annex I countries, the GHGI database was built upon the GHG inventories submitted by countries in their Fifth Biennial Report in 2023. The data was collected from the Common Tabular Format (CTF) tables and is thus fully consistent in terms of reporting between countries. The reporting timeframe is from 1990 to 2021 and mainly follows the IPCC 2006 Guidelines for National Greenhouse Gas Inventories.

Historical GHG data from Non-Annex I is not reported in a specific set of tables as the Annex-I countries, making the data collection slightly more challenging. As established in the Convention, the reporting depends on the country's capabilities and international assistance, affecting the reporting

year. The oldest GHGI reported by a Non-Annex I country is from 2009, but the latest is from 2023. Regarding the methodology used by countries for their reporting, these vary among the different IPCC methodologies, the recommended methodology is IPCC 1996; however, as encouraged some countries have moved to the most recent methodologies such as the 2003 Good Practice Guidance for LULUCF or 2006 IPCC Guidelines. Based on the correspondence from Table 1 the categories reported by the countries were integrated into the GHGI dataset.

All Annex I countries provide a complete full-time series from 1990 to 2020, however, for some Non-Annex I countries the data set needed to be completed using interpolation. For Non-Annex I countries, the timeframe of reported years in the inventories varies, having a time series of four to six years in some countries and a full-time series with 30-year reporting in others. To have a full-time series of historical data for all Non-Annex I countries, three different approaches were used: (i) if the country's first reporting year is not 1990, the years before the first reporting year will use the same value as the first reporting year (e.g., if the first reporting year was 1992, in 1991 and 1990 the same value was repeated); (ii) if information gaps occurred in intermediate years, a linear interpolation was estimated for those years, and (iii) if gaps occurred in the last years, a projection was estimated based on the historical series of the previous years. This selection of approach for this interpolation is not expected to have a strong impact on our findings as this has been previously shown by Grassi et al. (2022).

### 2.2 NDC data

NDCs represent a vital instrument under the Paris Agreement, mandating parties to undertake domestic mitigation measures to fulfil their commitments (UNFCCC, 2015). The NDCs define country mitigation objectives for 2030 and they contain information on targets and measures for reducing national emissions, adapting to climate change impacts, and the need for, or the provision of, finance, technologies, and capacity building for these actions.

When reviewing the NDCs and developing our database, we primarily focused on two key reporting categories: LULUCF and Agriculture. However, in cases where countries exclusively provide aggregated emission values for the AFOLU sector, we duly incorporated these. In terms of sectorial targets, we meticulously gathered sectorial targets, quantified in $MtCO_2eq$, as stipulated by the respective countries' submissions. We documented the information concerning the business-as-usual (BAU), unconditional, and conditional targets where available (see Supplementary Table 3).

Following the methodology for documenting the NDC targets as set out by Forsell et al., (2016), only quantitative information about the AFOLU, Agriculture and LULUCF sectors, was gathered from the NDCs. This implies that if a country specifies several measures for the AFOLU sector but does not provide quantifiable information concerning the impact of the measures, we do not assess the potential impact of the measures ourselves. Furthermore, where insufficient information was available to estimate AFOLU targets and in instances where quantitative NDC information was unavailable, it was conservatively assumed that the AFOLU targets would be the 2020 GHG emissions value for each sector. In other words, we assume that emissions and removals would remain constant over time. The rationale is not to influence the development of the aggregate global AFOLU emissions and removals over time because of the countries that have not officially provided an AFOLU estimate or have not quantified the impact of their mitigation actions.

### 2.3 LT-LEDS data

As of March 2024, 71 LT-LEDS have been submitted to the UNFCCC, corresponding to 70 countries and one region (European Union).

The information collected for long-term targets comes solely from the LT-LEDSs submitted to the UNFCCC; if a country makes a long-term commitment in any other report, it is not included in the dataset. Under the UNFCCC, no specific reporting methodology or guidance delimits the information an LT-LEDS should contain; therefore, each LT-LEDS presents information and data aggregation differently.

The data collected from the LT-LEDS includes their long-term cross-cutting target, the year to achieve it, the quantitative emission reduction target, or the expected sectorial emission value for the LULUCF, Agriculture or AFOLU sector by 2050, as reported by each country, and in case they include a BAU value, it is also collected. However, not all LT-LEDSs include quantitative

sectoral values; some LT-LEDSs only have crosscutting objectives but no sectoral pathways. For LT-LEDSs that did not include quantitative data for the sectors of interest, only the year and the crosscutting target were documented. In the case of including sectoral targets, those for the LULUCF and Agriculture sectors, or AFOLU if the country reported this category, were considered. When countries included all three reporting categories, it was ensured that there was no double accounting and that the values were consistent in the AFOLU category as an aggregate of the sectors LULUCF and Agriculture, see Supplementary Table 4.

When long-term commitment quantitative targets are reported as an absolute emission or removal value for the target year, they are included in the database as stated. However, if the target is reported in terms of an emission reduction value (e.g., expect to reduce emissions by 10 $MtCO_2eq$) or an increase in absorption value and no BAU baseline estimate is provided, the target value is calculated as the reduction or increase in absorption as compared to the 2020 GHGI estimate. In other words, in these cases, we use the 2020 GHGI as the BAU baseline estimate to calculate the net emissions or net removals for the target.

When countries report different pathways to achieve their long-term commitments, we collect the minimum and the maximum values reported per sector and estimate the average value for the analysis. Any assumption about the appropriate approach, the correctness of the value or their feasibility was made, and the data reported in the datasets shows the country information without any judgment.

## 3. Results

### 3.1 Data availability

One of the main proposes of collecting the GHG historical emissions, the NDC and LT-LEDS targets for the LULUCF, Agriculture and AFOLU sectors is to provide a consistent dataset to track countries' historical data in the light of their mid- and long-term commitments.

By March 2024, 196 countries and the European Union had submitted GHG inventories to the UNFCCC. Of these, 21% are Annex I countries and 79% are Non-Annex I countries. Almost three-quarters of the inventories were developed with the last reporting year in 2020 or later. Regarding the sectors, all the parties include the Agriculture sector except American Samoa and Monaco. The LULUCF sector is not included in Afghanistan, Egypt, Iraq, Kiribati, Oman, Qatar, Sierra Leone, Solomon Islands, and the Syrian Arab Republic. The AFOLU sector is estimated based on the sum of the LULUCF and the Agriculture sectors, according to the IPCC definition of the sector. Therefore, the AFOLU sector is included for all countries.

Regarding the 2030 commitments, all Annex I and most Non-Annex I countries have submitted their NDCs (having a total of 195 NDCs submitted) following the guidelines under the Paris Agreement (Table 2). Additionally, only 71 parties have presented their LT-LEDS to the UNFCCC (Table 2).

Table 2. Data availability by country type. Source: own elaboration based on UNFCCC, 2024.

| | GHG Inventory | NDC | LT-LEDS |
|---|---|---|---|
| Global | 197 | 195 | 71 |
| Annex I | 43 | 43 | 39 |
| Non -Annex I | 154 | 152 | 32 |

To avoid double counting and to maintain consistency, for all the analyses we consider only the European Union based on their regional reports, all State Members' information is included in the dataset for transparency, however, is not included in the quantitative analysis only uses the EU regional value. This means that the analysis includes 170 GHG inventories, 168 NDC and 51 LT-LEDS.

From the LT-LEDS 46% of these national climate policy documents come from industrialized countries and economies in transition; regarding the geographical distribution of all the countries in Oceania, 74% of EU27 member states (some with more ambitious targets than the EU27 LT-LEDS), 45% of non-EU27 European countries, 36% of Asian nations, 29% of American countries, and 17% of African countries have submitted their LT-LEDS. The objectives presented vary a bit, 47% of countries aim to achieve net-zero emissions, and 22% seek to reduce their emissions compared to a baseline year. Additionally, 16% aspire to Carbon Neutrality, 12% aim for Neutral emissions

or climate-neutral emissions, and two countries, Vanuatu, and Bhutan, aim to maintain carbon negativity.

The AFOLU sector, including the LULUCF and Agriculture sectors, is recognized as a crucial player in achieving long-term targets according to all LT-LEDS. However, only 36 of them provide quantitative values for any of the sectors of interest (LULUCF, Agriculture, and AFOLU). 68% of the countries have set separate targets for the LULUCF and Agriculture sectors, and 22% have reported only LULUCF targets. Additionally, the Marshall Islands and the United Kingdom included only an AFOLU target, Switzerland specified targets only for the Agriculture sector, and Armenia presented both AFOLU and Agriculture targets. The time frame to achieve the long-term target is mainly 2050; however, some countries such as Benin, Iceland, Sri Lanka, and Nepal define targets before 2050. China, Indonesia, Nigeria, and India have established targets after 2050.

### 3.2 Emissions and targets at global level

In 2020, globally the Agriculture sector accounted for 5,778 $MtCO_2eq$ of emissions and the LULUCF sector contributed -3,591 $MtCO_2eq$ of sequestration, giving a total AFOLU sectorial emissions of 2,233 $MtCO_2eq$ (Figure 1). This means that in 2020, the LULUCF sector compensated for almost two-thirds of the Agriculture emissions. Achieving a global net-zero AFOLU sector based on 2020 emissions would necessitate reducing Agriculture emissions and maintaining an increase in sinks by nearly 30%.

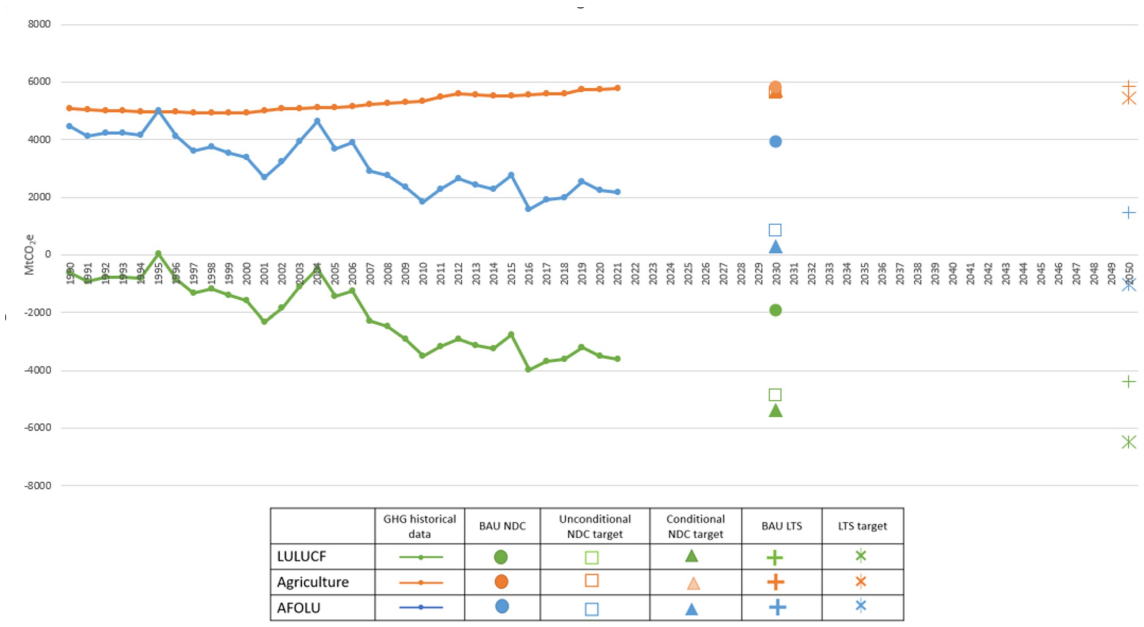


Figure 1. Global historical GHG emissions, 2030 and 2050 GHG emission targets.

From 1990 to 2020 the Agriculture sector has increased by 715 $MtCO_2eq$ in a relatively constant trend. On the opposite, the LULUCF sector showed a completely different trend an increase of -2,968 $MtCO_2eq$ by reducing its emissions, mainly by enhancing the absorptions by afforestation and restoration. However, considering that the Agriculture emissions in 1990 were around 5,000 $MtCO_2eq$, and the abortions in the same year were -623 $MtCO_2eq$, it is needed not only to increase the sink but also to reduce the emissions from Agriculture drastically.

For the 2030 targets, we have three types of values. Firstly, the global BAU value consists of the emissions level projected for 2030 if no mitigation action is taken, as reported by countries in their NDCs. For those countries not reporting this value, the emissions level from 2020 is used. Secondly, there are unconditional commitments, representing the actions that countries will undertake independently. And thirdly, there are conditional commitments, which are actions that countries will implement provided they receive international support. The highest emissions value is the BAU, followed by the unconditional commitments, while the highest mitigation commitment is presented

as conditional.

The GHG emissions from the Agriculture sector have been relatively stable in the last ten years and based on the NDC targets as submitted by the countries, it is expected that they will remain relatively stable also for the following years. Most of the NDCs recognize the importance of the Agriculture sector however only 34 out of the 195 NDCs have included quantitative targets for this sector. If globally the 2030 unconditional targets for the Agriculture sector are all fulfilled, the sectorial emissions will only be reduced by 71 $MtCO_2eq$, as compared to the BAU estimates. If the conditional targets are fulfilled, the sectorial emissions will be reduced by 100 $MtCO_2eq$, as compared to the BAU estimates.

On the other hand, the LULUCF sector reflects the largest commitments by countries globally, showcasing the sector's importance in absorbing emissions. If globally the 2030 unconditional targets for the LULUCF sector are all fulfilled, the sectorial absorptions would increase by 3,000 $MtCO_2eq$, as compared to the BAU estimates. This highlights the importance of the LULUCF sector in meeting the goals of the Paris Agreement. If additionally, all unconditional commitments for the sector are fulfilled, the sectorial absorptions would increase by another 500 $MtCO_2eq$. This implies that 75% of the expected absorptions of the LULUCF sector will come from country efforts as expressed in their unconditional commitments.

For the full AFOLU sector, it is noticed that conditional targets are not sufficient for reaching a balance of emissions and removals by 2030. Current commitments are as such not yet sufficient for the sector to reach net zero emissions and countries level of ambition and policy implementation must be increased for this to take place. If conditional commitments are achieved, net AFOLU sectorial emissions would remain at 284 $MtCO_2eq$. If only unconditional commitments are met, AFOLU sectoral emissions would be reduced to one-fourth compared to the BAU scenario, dropping from 3,895 $MtCO_2eq$ to 857 $MtCO_2eq$.

In terms of the LT-LEDS commitments, most countries (24) countries have committed to achieving net zero emissions, others are committed to Carbon Neutrality (6), Climate Neutral (6) or other similar objectives. Most countries have committed to achieving their targets by 2050, except for Sweden, Sri Lanka, Nepal, Iceland and Benin which have more ambitious targets of achieving them before 2050, and countries such as China, Indonesia, Nigeria and India, require more time committing to achieve these targets by 2060 and 2070 respectively. Achieving these targets is expected to require significant contributions from the LULUCF to increase absorptions and reduce emissions from the Agriculture sector.

Analyzing the Agriculture sector, in the BAU LT-LEDS scenario, global agricultural emissions are increasing from 2030 to 2050 by 24 MtCO2e. This is mainly due to increased food demand, of which the sector is the main provider (RTI, 2019; Ranganathan et al., 2018). By 2050, the global sectorial emissions are 5,841 $MtCO_2eq$ in the BAU scenarios, which could be reduced to 5,436 $MtCO_2eq$ if the LT-LEDS commitments are fulfilled. Therefore, fulfilment of the LT-LEDS commitments submitted by countries will only reduce Agricultural emissions by 405 $MtCO_2eq$ in 2050 compared to the BAU levels. Fulfilment of the LT-LEDS targets would result in a slight reduction of Agricultural emissions compared to the unconditional and unconditional NDC targets, thus ensuring that the sectorial emissions decrease over time. In term of policies, it's expected that the reduction of emissions will mainly come from the implementation of policies related to sustainable farming and improved livestock practices, which will only reduce the growing trend in the sector.

As for the LULUCF sector, the commitments as put forward by the countries in their LT-LEDS imply a continued increase in the sector's annual absorption rate. In the BAU scenario, the LULUCF sector is expected to reach a sink of -4,385 $MtCO_2eq$ by 2050, which is a doubling of the sink in 2030 in the NDC BAU scenario. If all the commitments as put forward in the LT-LEDS were to be reached, then the LULUCF absorption rate would even reach -6,461 $MtCO_2eq$ by 2050, mainly due to an integrated effort of reducing deforestation and enhancing carbon sinks by strengthening conservation or restoration activities.

Jointly, the commitments as put forward in the LT-LEDS would ensure a balance of emissions and removals for the AFOLU sector before 2050. Although the emissions from the Agricultural sector would only slightly be reduced over time, the continued increase in the absorption rate by the LULUCF sector would allow for achieving a negative net balance for the AFOLU sector before 2050. If all LT-LEDS commitments are successfully achieved, then the AFOLU sector will constitute a net sequestration rate of -1,024 $MtCO_2eq$ by 2050. Thus, globally the LT-LEDS targets for the

AFOLU sector could provide roughly 1 $GtCO_2eq$ of offsets to the overarching goals of the LT-LEDS commitments of achieving a cross-sectorial balance of emissions and absorptions.

The sectorial contributions to the global outcomes vary, influenced by historical emission growth trends, leading them to adopt different approaches in the medium and long term with distinct trends. We will focus on presenting the results separately for Annex I and non-Annex I countries.

### 3.3. Emissions and targets in Annex I countries

Annex I Parties include industrialized countries that were members of the OECD (Organization for Economic Co-operation and Development) in 1992, as well as countries with transitioning economies, including the Russian Federation, the Baltic States, and several Central and Eastern European States. As of today, there are 42 countries plus the European Union.

Historically, the Agricultural sector has shown a stable downward trend in emissions, decreasing from 1,713 $MtCO_2eq$ in 1990 to 1,494 $MtCO_2eq$ in 2020, representing 25% of the global emissions from the Agricultural sector (Figure 2). Mid-term commitments for this sector until 2030 imply a marginal reduction of 20 $MtCO_2eq$, meaning that by 2024, the commitment established by countries for the Agricultural sector, aiming to reach 1,480 $MtCO_2eq$ by 2030 as an unconditional goal (Annex I countries do not include conditional objectives), has almost been fulfilled. It is important to note that the BAU scenario projected for this sector in 2030 was 1,498 $MtCO_2eq$, virtually the same value as emissions in 2020.

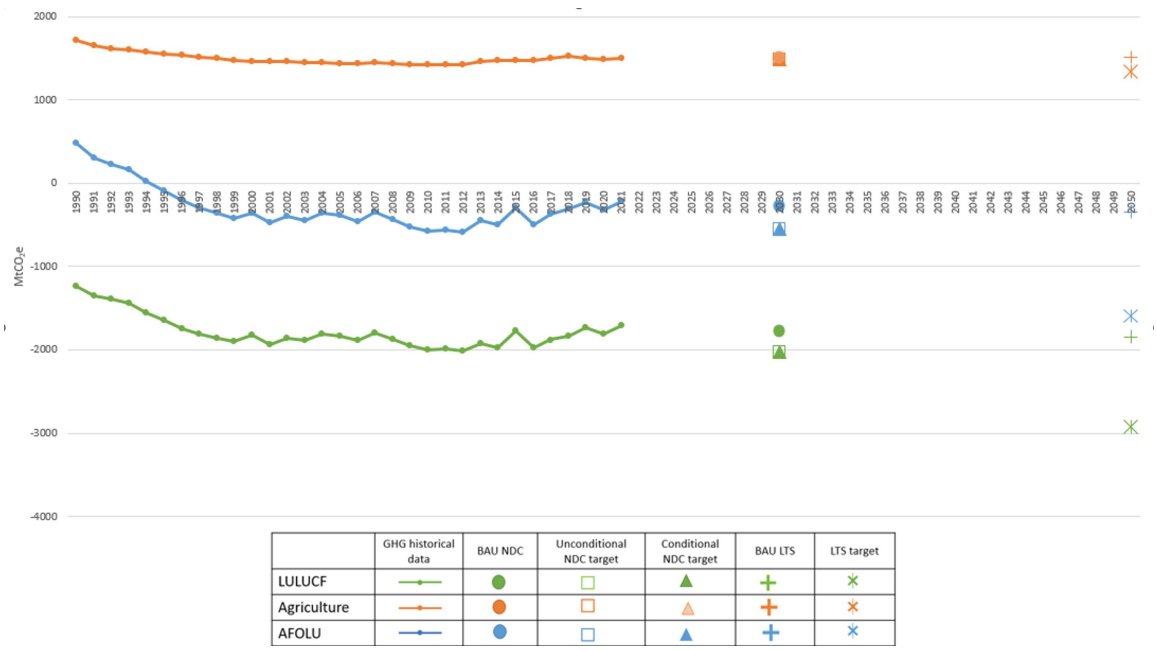


Figure 2. Annex I historical emissions, NDC and LT-LEDS targets.

For the Agriculture sector, regarding country commitments until 2030, there is no significant difference between the BAU scenario, the unconditional and the unconditional targets reported by the countries. In terms of the LT-LEDS commitments, Agricultural emissions are targeted to reach 1,331 $MtCO_2eq$ by 2050, representing a reduction of 149 $MtCO_2eq$ compared to 2030 emissions levels if the conditional goals set in the NDCs are met, and a reduction of 167 $MtCO_2eq$ compared to the 2030 NDC BAU emission levels, and 174 $MtCO_2eq$ compared to the LT-LEDS BAU.

On the other hand, the LULUCF sector shows fewer variations than those seen from a global perspective. Absorptions by Annex I countries (-1,237 $MtCO_2eq$) nearly double the global absorptions at the beginning of the time series (1990). However, by 2020, the contribution of absorptions is only half (1,707 $MtCO_2eq$) compared to global absorptions (-3,591 $MtCO_2eq$). Commitments established in the NDCs imply a 15% increase in absorptions compared to current levels. In 2050, absorptions are expected to increase by approximately one-third to reach -2,928 $MtCO_2eq$.

According to the GHG inventory data reported by the Annex 1 countries, the AFOLU sector

has been carbon-negative (i.e., removals are larger than emissions) since 1994. The challenge in these countries is to maintain and increase absorptions to cover the remaining emissions from other sectors and achieve carbon neutrality. It is essential to reverse the trend of decreasing absorptions observed since 2016 and increase commitments to reduce emissions from the Agricultural sector.

### 3.4. Emissions and targets in Non-Annex I countries

Non-Annex I countries are mostly developing countries with emerging economies. This leads to different fluctuations and behaviors in the emissions of the two analyzed sectors. The Agricultural sector shows an upward trend, with an increase of 933 $MtCO_2eq$ between 1990 and 2020, reaching 4,283 $MtCO_2eq$ (Figure 3). Around 30% of the NDCs mention that the peak of emissions from the sector is expected around 2027, followed by a trend of stabilization and a decrease in emissions. This aligns with the commitments established in the NDCs, where the unconditional commitment is to reach 4,235 $MtCO_2eq$, with a possible additional reduction of up to 119 $MtCO_2eq$ for conditional objectives. On the other hand, the BAU scenario for 2030 establishes an emission value of 4,318 $MtCO_2eq$. In the case of non-Annex I countries, the difference between the BAU and Unconditional scenarios is marginal, with a reduction of only 83 $MtCO_2eq$. In the long term, the sector aims to reduce emissions to 4,105 $MtCO_2eq$, implying a reduction of 178 $MtCO_2eq$ over 20 years.

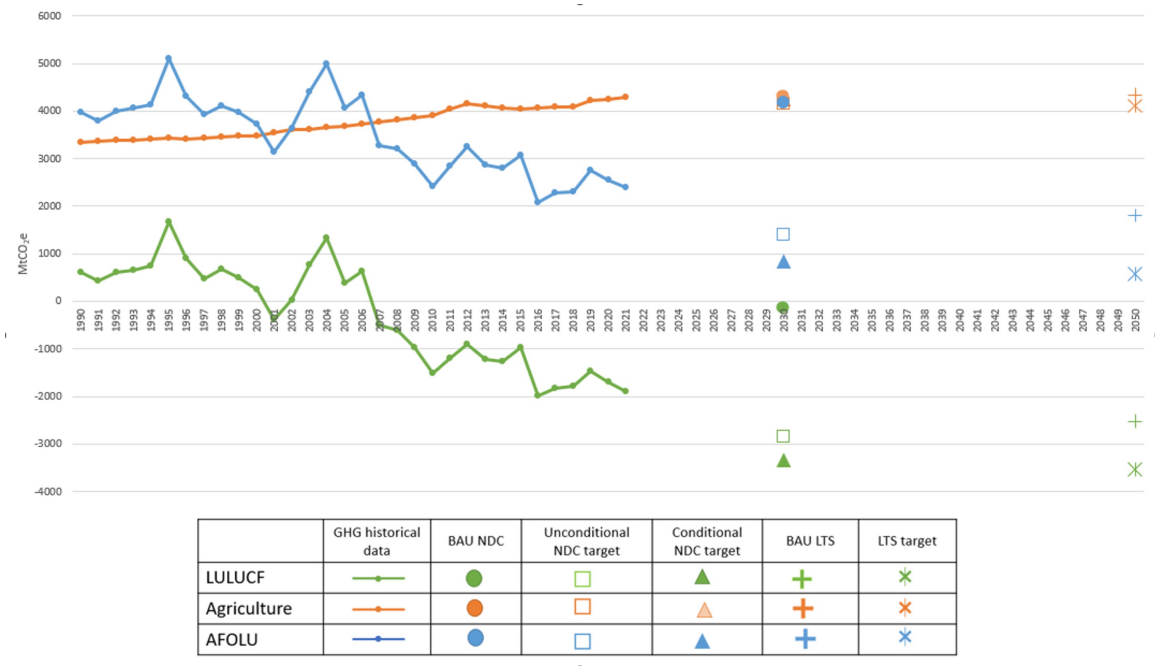


Figure 3. Non-Annex I historical GHG data, NDC and LT-LEDS targets.

As for the LULUCF sector, there is a positive trend in increasing carbon absorptions, albeit with high volatility. Between 1990 and 2006, the LULUCF sector was an emitter, with a brief sink period between 2001 and 2002. In 2007, it became a sink again (-1,883 $MtCO_2eq$). For 2030, absorptions are expected to be -2,834 $MtCO_2eq$ unconditionally, and possibly reach -3,336 $MtCO_2eq$ in a conditional scenario. This implies an increase in sinks of approximately 95 $MtCO_2eq$ per year between 2020 and 2030. These objectives are aligned with the 2050 target of -3,533 $MtCO_2eq$, implying average annual absorptions of 34 $MtCO_2eq$ if unconditional objectives are met.

When integrating the trends of the two sectors, in the case of Non-Annex I countries, absorptions fail to offset emissions generated by the Agricultural sector, keeping the AFOLU sector as a sink throughout the time series, including targets for 2030 and 2050. This could hinder countries from reaching zero emissions goals.

## 4. Discussion

Our analysis shows for the first time that on a global scale, the historical net emissions from the AFOLU sector have seen a gradual decline from 1990 to 2020, primarily due to increased removals in the LULUCF sector in non-Annex I countries. Agricultural emissions continue to rise in non-Annex I countries but may have peaked in Annex I countries. However, as of 2020, the global AFOLU sector has not yet become climate neutral. Developed countries have successfully achieved climate neutrality in this sector since 1994. On the other hand, AFOLU emissions in developing countries are on a downward trend, but emissions from Agriculture remain high due to the growing demand for food and biomass, particularly for biofuel production.

Of the 195 parties that have submitted an NDC, 80 parties have included quantitative targets for the AFOLU sector. This is an increase in the number of countries providing quantitative targets compared to previous estimates. Forsell et al. (2016) were able to document quantitative targets for 38 parties, but the assessment only reviewed targets for the LULUCF sector and focused on the first submissions of NDCs by the parties. Since then, numerous countries have updated their NDC submission and enhanced their ambitions. (den Elzen et al., 2022). Since LT-LEDS are not obligatory instruments according to the Paris Agreement, only 36% of the 193 parties that have signed the agreement (including the European Union) have provided them, and out of those, only 36 parties have included quantitative targets for the AFOLU sector. In the long run, their objectives frequently encompass attaining carbon neutrality or even reaching net-zero emissions for the AFOLU sector.

To attain the ultimate objective of zero emissions in the long run, it is imperative to adhere to the NDC targets, which will not only help stabilize Agricultural emissions but also enhance the net sinks from the LULUCF sector by 2030. By 2030, there is a possibility of reducing global net AFOLU emissions by 600–1,700 $MtCO_2eq$ compared to 2020 levels, with a potential further reduction of 2,300–3,400 $MtCO_2eq$ by 2050–2060. The AFOLU sector has the potential to achieve climate neutrality between the years 2035 and 2045 if all global targets outlined in the NDCs and LT-LEDS are successfully met.

Many countries continue to face challenges in estimating emission projections, as indicated by the absence of quantifiable estimates in both NDCs and LT-LEDS reports, which primarily concentrate on emission reduction commitments in the LULUCF sector. It is worth noting that when it comes to commitments, countries tend to prioritize the LULUCF sector over Agriculture. The commitments for Agriculture, as reported, are comparatively lower than those for the LULUCF sector, highlighting the necessity for international collaboration and capacity building in developing emission projections. It should though be noted that countries might be implementing strong measures but are unwilling or unable to estimate the potential impact of such measures. This assessment has taken a conservative approach by only considering quantitative estimates provided by the countries themselves. If all measures documented in the NDCs and LT-LEDS were to be considered, stronger mitigation for the AFOLU sector would be reported. It is also important to note that we are not accessing the likelihood, feasibility or costs for individual countries to reach their NDC and/or LT-LEDS targets. Numerous such global and regional assessments have been carried out at the economy-wide level and for individual sectors (Hof et al, 2017, Van Soest et al., 2017, Winning et al. 2019, Rogelj et al., 2023), but are currently lacking when it comes to the land-use sector. The data presented in this study thus offers a critical step towards the feasibility of carrying out such assessment in the future.

Going forward and as countries continue to submit their biennial transparency reports, it is anticipated that there will be improved transparency in reporting and a more ambitious implementation of commitments in the AFOLU sector. To align with emission pathways for 2 °C or 1.5 °C targets, the AFOLU sector is expected to reduce emissions by 8,300–9,100 $MtCO_2eq$ in 2050 (Roe et al., 2019). This would mean that the current commitment gap is in the order of 4,000–5,400 $MtCO_2eq$. Therefore, greater transparency in reporting and more ambitious implementation of commitments in the AFOLU sector are expected as countries submit their biennial transparency reports. Furthermore, the Paris Agreement presents stricter commitments for all countries, emphasizing the Enhanced Transparency Framework in a common reporting format that will facilitate the collection of data carried out much more easily with the common reporting tables of the Transparency Reports. However, the challenge will continue to lie in strengthening national capacities to provide the necessary information in these reporting mechanisms.

## 5. Conclusions

Clearly, it is needed to increase the efforts in the Agriculture sector to achieve the 2050 targets. It is necessary not only to increase the sinks but also to increase the emission reduction in the Agriculture sector, considering that the LULUCF sector seeks to compensate the emissions in a crosscutting approach. While significant progress has been made in documenting commitments through NDCs and LT-LEDS, there remain challenges in estimating emissions and prioritizing mitigation efforts. Greater transparency in reporting and international collaboration is essential for closing the commitment gap and achieving climate neutrality. As countries continue to submit biennial transparency reports, there is an opportunity to strengthen reporting mechanisms and enhance capacity-building efforts. By aligning commitments with emission pathways outlined in the Paris Agreement, there is potential to reduce emissions and mitigate climate change effectively.

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## Disclosure Statement

The authors declare that there are no competing interest.

## Data Availability

The data are available from the corresponding author upon request.

## Author Contribution

Conceptualization: NF
Funding acquisition: MC
Investigation: NF, ZAG
Methodology: NF, ZAG
Project administration: NF
Supervision: NF, MC
Writing - original draft: NF, ZAG, MC
Writing - review & editing: NF, ZAG, MC

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